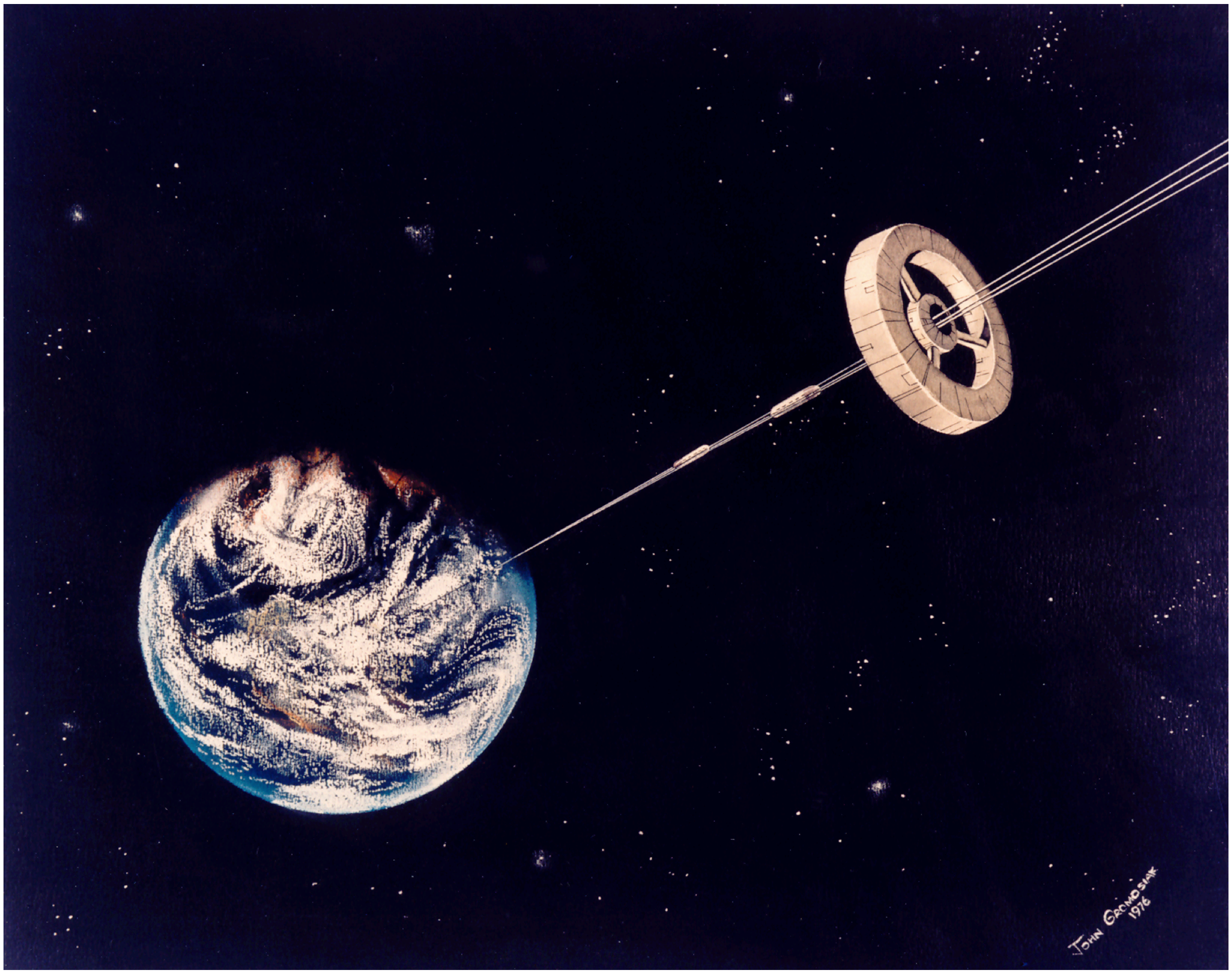
Space Elevators: A History



David Raitt, Editor

Prepared by the ISEC History Committee

Contributors: Mark Dodrill, Nicholas Martin, David Raitt, Ted Semon, Evan Smith, Peter Swan

ISEC

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Preface

The vision of the International Space Elevator Consortium (ISEC) is to have a world with inexpensive, safe, routine, and efficient access to space for the benefit of all mankind. As its name suggests, one of the principle elements of the ISEC action plan is to promote the development, construction and operation of a space elevator infrastructure as a revolutionary and efficacious way of getting into space.

ISEC is made up of organizations and individuals from around the world who share this vision of mankind in space. In their desire to record the progress of space elevator thinking over time, a number of these individuals formed the ISEC History Committee under the chairmanship of Dr Peter Swan. Their ideas and discussions have culminated into two main activities: one, oral interviews with major players, past and present, in space elevator research and development; and two, this book which attempts to document the history of the space elevator concept. The initial idea for the book emanated from Nicholas Martin in May 2014 who proposed many of the chapters and topics to be covered and these were then augmented by others in the History Committee.

Under the general editorship of Dr David Raitt, the work is a combined effort of several individuals including Dr Peter Swan (5, 6, 7, 9, 10, B), Dr David Raitt (all), Mark Dodrill (5, C), Nicholas Martin (1, 2), Evan Smith (4), and Ted Semon (7). The numbers and letters in parentheses after the names indicate the chapters and appendices for which they were largely responsible or a significant contributor.

The book is laid out in chapters close to chronological. The major topics are separated out such that the reader can look at the history is stages. This means that there is some degree of overlap between the chapters, which are thus largely self-standing. The three phases of the space elevator fall into the following categories (with chapters identified for clarification): Dreamers and Creators (Chapters 1 and 2); Modern Era Initiation (Chapters 4-8); and the Move towards Development (Chapters 9 and 10). These chapters are briefly outlined in the Introduction. The book is completed with a number of Appendices covering brief contributor biographies, a space elevator chronology, and selected summaries from the oral interview transcripts. [Additional transcript summaries, as well as a bibliography of references to space elevators, can be found on the ISEC website (www.isec.org).]

History is, of course, usually considered 'old', but, in fact, history is really anything before today! Hence a number of rather more recent developments, publications and events are included in the various chapters in the book. Although parts of the text herein were contributed by some who were not so involved in the formative years of the space elevator, efforts have been made to expand the material in an attempt to make it as complete and accurate as possible. This book should be considered as essentially a first edition and it is anticipated to bring out further updated issues as additional material becomes available, information is augmented or corrected, and more people are forthcoming with their own involvement in the concept of space elevators which will add to this book's historical richness. Please send insights and input to info@isec.org.

David Raitt
1 March 2017

Dedication

This book is dedicated to Dr. Bradley Edwards without whose remarkable work there would be no modern day achievable space elevator concept.

Acknowledgements

Thanks must go to the members of the ISEC History Committee for their continued involvement in the preparation of this book: Douglas Ahlquist, Margaret Alonso, Marc Boucher, A. J. Burke, Leonard David, Mark Dodrill, Mike Hall, Bruce Mackenzie, Nicholas Martin, Andrew McNichols, Jerome Pearson, David Raitt, Evan Smith, Paula Smith, Peter Swan and Chris Wimer.

The Editor would also like to give special thanks to Evan Smith, Ted Semon, Mark Dodrill and Pete Swan for their careful readings of the various versions of the manuscript which resulted in more than a few corrections, additions and amendments. Their assistance is much appreciated.

Thanks are also due to those, especially Mark Dodrill and Mike Hall, who not only conducted many of the oral interviews with those involved in the space elevator over the years, but also transcribed and summarized them. These interviews and their transcripts and summaries are to be found on the ISEC website (www.isec.org), though several are also included in this book.

A special thank you should also be given to Dr Peter Swan, Chairman and President of ISEC, who, as Chairman of the History Committee, is the main driving force behind the work of the Committee.

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Chapter 1: Introduction

1.1 Preamble

The International Space Elevator Consortium (ISEC) has the mission to promote space elevator development. This requires that one understands where the concept comes from and how far along the project is. This leads to understanding the key historical lessons learned and the recognition of the people who have contributed along the path of progress. This book lays out the history of space elevators in so far as it can be recalled and attempts to leverage this knowledge in a manner helping those dedicated to the mission of promoting space elevator development. The book expands on contributions by individuals (such as Jerome Pearson's paper on the real history of the space elevator (Pearson, 2006)) and identifies where groups combined people to advance the concept. The amazing thing about history is that it flows in random directions until someone stimulates activities and research in a specific direction. This kick start must be recognized and then recorded if the history is to be reflected correctly. As shown in most history texts, people are the key and their individual contributions are important and must be identified if there is going to be aggressive growth. The chapters presented herein reveal an insight into the incremental steps each phase in history provided, the contributors to each step along the way, and whether we are closer to an operational system after these contributions.

The International Space Elevator Consortium has produced many programmatic and engineering studies over the last seven years as small groups analyzed the issues and then recommended the next steps. Each of these studies dealt with the future. This book, however, sponsored by the ISEC History Committee, focuses on recognition of past successes and contributions from the small community of space elevator enthusiasts around the world. The purpose of this book is simple:

To ensure space elevator history is not lost as the project grows!

1.2 Why Space Elevators?

This key question must be answered each time ISEC produces a book or report as we must encourage, enthrall, challenge, explain, and provide hope for readers. To anyone who looks up from their chair periodically and searches the heavens for the future of mankind, it is obvious that we are moving off-planet in a major fashion, and in the near future. Besides regular American, Russian and European space activities, the Chinese have landed a rover on the Moon and are planning a space station, the Indians have orbited a spacecraft around Mars, and the Japanese have a module attached to the International Space Station (ISS). The National Aeronautics and Space Administration (NASA) Jet Propulsion Lab (JPL) has identified over 1,300 near-Earth asteroids that are compatible with rapid trips made from Earth. There are three companies investing in mining resources on asteroids while there are multiple companies preparing to create small habitats on the Moon. In addition, there is a rocket company (SpaceX) that plans on building a colony of greater than 10,000 people on Mars within its CEO's lifetime.

To ensure that these dreams are encouraged and made successful, there must be a change in the approach to travel within our solar system. The cost to orbit must become a very small part of the overall investment and the arena must support infrastructures that can be used many times, not thrown away each time they are used. When one looks at the concept of space elevators, the answer is obvious. The future of humanity's travel within our solar system requires space elevators that provide access to space and that have the following strengths:

- Routine [daily],
- Revolutionarily inexpensive [<$100 per kg]
- Commercial development similar to bridge building
- Permanent infrastructure [24/7/365/50 years]
- Environmentally sound
- Safe and reliable [no shake, rattle and roll]
- Low risk lifting
- Low probability of creating orbital debris
- Redundant paths as multiple sets of space elevators become operational
- Massive loads per day [starts at 20 metric tons]
- Opens up tremendous design opportunities for users
- Optimized for geostationary orbit altitude and beyond

The bottom line for space elevators and the solar system is that they open up humanity's hopes and needs to expand beyond the limited resources and environment of our planet Earth. A space elevator is the enabling infrastructure ensuring humanity's growth towards the stars. There are two main reasons why the human race needs space elevator infrastructures:

- The realization that chemical rockets cannot get us to and beyond Low Earth Orbit (LEO) economically
- The recognition that the 'Space Option' may enable solutions to some of Earth's current limitations (energy, resources, removing nuclear waste etc.)

1.3 What is a Modern Day Space Elevator?

For the purpose of this book, a space elevator is a tremendous transportation infrastructure leveraging the rotation of the Earth to raise payloads from the Earth's surface towards space and our solar system. In a mature environment where space elevators are thriving in business and commerce, there would be several (probably up to ten) spread around the equator, each with a capability of lifting off greater than 20 metric tons of payload per day, routinely and inexpensively.

For those who may be unfamiliar with the concept of a space elevator, it is precisely as its name implies; a ground terminal on the Earth's surface tied to a space station by an enormously long tether or cable on which climber cars could deliver crew and cargo to space. The orbital element would be located at roughly 36,000km above the equator, or, in other words, geostationary orbit (GEO). As its name suggests, anything placed in this type of orbit remains perfectly in step with the Earth's rotation, maintaining a fixed position relative to a point on the planet's surface. Communication satellites are often found at this location as it is more convenient for ground antennas to relay information to them. Imagine then, that from a space station maintaining an exact position above the planet, a line being dropped that would eventually make contact with a ground terminal on the Earth's surface, in turn providing access to space entirely rocket-free. Reaching outward from the space station, the line would also need to be extended to a distance of 100,000km, or more, where it would be attached to a Apex Anchor counterweight, whose purpose would be to keep the entire system taut. To put that distance into perspective, the Moon is 385,000km away, meaning that we are talking about the construction of a system that would extend to over 25% of the distance to Earth's age-old lunar companion. As difficult as it is to imagine that engineering effort, advocates of a space elevator estimate that putting payloads into orbit using this method would cost a mere $100 per kilo to GEO, as compared to NASA's current figure of $25,000.

The elements of a space elevator system (Figure 1) are considered to comprise:

- Marine Node: An ocean-going platform at the equator supporting movement of payloads to/from the space elevator climbers.
- Tether: A modern material that would extend from the surface of the ocean to an altitude of 100,000km. The material would be remarkably strong with a width and depth still to be determined (a width of about one meter with a depth of sub–micron were originally thought reasonable).
- Tether Climber: The 'box' for transportation of the payloads. Current models suggest it would climb the tether using wheels with sufficient friction to move up/down as needed when supplied with energy from outside.
- GEO Node: An altitude equivalent to modern day GEO satellites for off-loading payloads/satellites into the commercially significant orbit.
- Apex Anchor Node: This would be the terminus at the high end and capable of off-loading payloads as well. In addition, the Apex Anchor would be part of the system to control the dynamics of the ribbon.
- Headquarters/Primary Operations Center [HQ/POC]: This location would be where the day-to-day operations occurred for both the space elevator transportation activities and business operations.

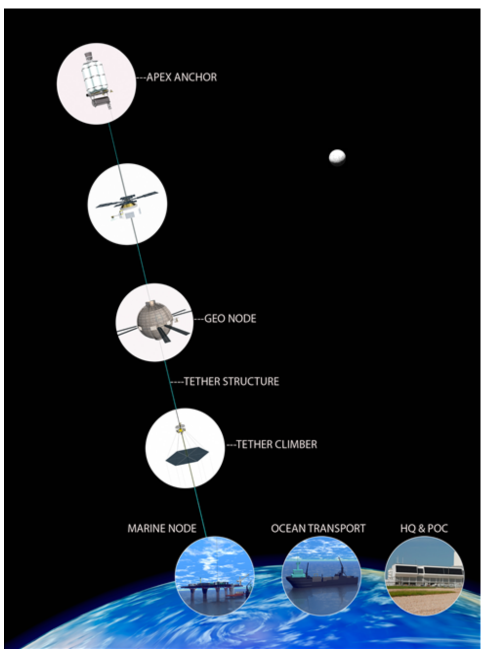

Figure 1: Space Elevator Architecture (a Frank Chase image)

1.4 Evolution from Rockets to Space Elevators

In reconciling human presence with outer space, the rocket remains unchallenged as the definitive icon of our link to the stars. Whether to the Moon, the routine trips to the International Space Station, or the delivery of instruments into space so that they may continue their journey on into the deepest reaches of our solar system, it is the rocket that gets us there. The question is, however, are these towering metallic colossi, which rely on equally massive expenditures of fuel to escape the relentless gravity of the planet, the only means by which we as a civilization might become active in space? Are they truly the only systems that might grant us access to worlds beyond our own? Many in the scientific community for a number of years have believed the answer to that question to be no, and in expressing such belief, feel that there might be a rather extraordinary alternative (Martin, 2015).

While no one could undermine the significant contributions that rocket technology has made to aerospace, nor to civilization as a whole, there are those who criticize the method as being exceedingly inefficient, dangerous, and far too expensive. In the waning days of the space shuttle, launches were estimated to cost more than $1.5bn each, totaling around $209bn when the shuttle Atlantis touched down on 21 July 2011, marking the retirement of the 30-year program. Using launch craft more akin to those of the shuttles' predecessors, NASA estimates that it currently costs around $10,000 per kilo to get into Earth orbit. [Note: to reach Geosynchronous Orbit or escape the Earth's gravity, the number is at least twice that, or $25,000 per kilo.] This staggering amount has made space travel a rather uneconomical venture that, historically, few have had the bankroll to finance, and what many would argue to be the most discouraging element of our extra-planetary activity. There is no doubt that space is expensive; however, as Dr David Raitt points out (in a paper co-authored with Dr Bradley Edwards) there are many megaprojects comprising major engineering constructions such as bridges and tunnels, towers and pipelines, railway tracks and high speed trains that also have tremendous costs and overruns, but they are not considered a waste of money because they provide added-value (Raitt and Edwards, 2004).

As next-generation rocket technology unfurls over the coming decades, many organizations, either government run or privately owned, hope to see a reduction in the cost of getting to space. Indeed, it would seem that the Falcon 9 launch service from SpaceX would cost around $7,500 per kilo to geosynchronous transfer orbit (GTO) and some $4,000 for the Falcon Heavy. To achieve such cost reductions, many feel the onus is largely on reusability and/or the mitigation of reassembly - in other words, putting the parts that are reusable back together in preparation for subsequent launches, such as the solid rocket boosters that were employed by the space shuttles. In fact if no reassembly were required at all, through the use of what are referred to as SSTO (Single-Stage-To-Orbit) craft, then getting to space via rocket could see a dramatic reduction in its overhead expense.

But while rockets are being retooled to better accommodate both government and corporate check books alike, one still has to wonder if there exists another way; another means by which we might provide egress from the gravitational binding of planet Earth via a system that did not employ any form of rocketry whatsoever. A cleaner, greener alternative that would be entirely reusable, and require only a one-time assembly. No-one could be blamed if they felt that such a system sounded entirely impossible, or at the very least, incredibly unlikely. However, a cadre of scientists and engineers, whose numbers have been growing steadily over the recent decades, firmly believes there is such an option that does in fact satisfy all of the aforementioned criteria; a completely unorthodox method whose absurdity has been increasingly diminished given its prolonged subjugation to scientific analyses. Though it would be the most monumental engineering endeavor humanity has ever known, a space elevator, as envisioned by both its creators and proponents, could theoretically provide humanity with cheap, routine, effective, daily, clean, and virtually risk-free access to space.

It must be admitted that the space elevator sounds like something straight out of a science-fiction novel, and yes, it does have tenaciously imaginative leanings. The idea of a monolithic bridge to the stars has been a common element in sci-fi literature, occupying significant roles in the works of authors such as Sir Arthur C. Clarke, Kim Stanley Robinson and others. Despite its prominence in fictitious renderings however, space elevators have also acquired tenancy in the minds of scientists and futurists alike, and for a much longer time than most might intuitively assume.

For some 120 years, a space elevator has been dreamed of, conceptualized, invented, reinvented, published in both media outlets and science fiction, and seen an increasing amount of supporters flock to the dream of cheap, daily access to space that it proposes. Since the 1960s, it has been the subject of increased scientific scrutiny all in an effort to determine whether or not it can be made real. Twenty or so years ago, much in-depth groundwork was done. Today, there are a multitude of organizations based in various nations that have built on this initial work and advocate its construction; and since 2008 annual conferences have been held by the International Space Elevator Consortium that address the prodigious amount of obstacles that impede the elevator's progress. The past decade alone has seen a variety of books published that spell out the engineering details relevant to an elevator's construction and operation, highlighting just how doable such an undertaking would be. One of the most recently published works, *Space Elevators: An Assessment of the Technological Feasibility and the Way Forward*, whose editors include major players in the space elevator community, was released in December 2013 under the auspices of the International Academy of Astronautics (IAA). The book emphasized the finding that space elevators do in fact, seem feasible (Swan, Raitt *et al*, 2013).

1.5 Overview of Chapters

Following this Introduction, the rest of the book is laid out in chapters that approximate a chronological sequence of space elevator evolution. It should be noted that there is some overlap between chapters. This is deliberate - both an attempt to be as comprehensive as possible and allow chapters to be self-standing (and for those readers who prefer to pick and choose), as well as to allow the varying viewpoints of different contributors to be revealed and thus afford greater perspective.

Chapter 2 examines the role of the early dreamers and creators of a space elevator. In doing so, three primary individuals can be identified as playing a critical role in its propagation. The story begins just prior to the turn of the 19th century with a well-known Russian scientist named Konstantin Tsiolkovsky (also spelled Tsiolkovski) who, even today, is still celebrated as being one of the most pervasive names in the early development of spaceflight and the father of rocketry. The story continues with the official invention of the space elevator which is recognized to have occurred in two separate locations at different times: first in Russia by Yuri Artsutanov in 1960 with the release of his work *To the Cosmos by Electric Train*, and then in the United States of America by Jerome Pearson in 1974 with his piece entitled *The Orbital Tower: A Spacecraft Launcher Using the Earth's Rotational Energy*. Though time and circumstances separated the two efforts by more than the 14 years, Artsutanov and Pearson have since agreed to be known as 'co-inventors' of the space elevator, despite never having collaborated. This chapter charts the ideas and concepts of these three men which laid the groundwork for how the space elevator became the object of extensive and systematic evaluation through the decades that followed.

The above three giants notwithstanding, the conceptual origins of this grandiose railroad to the stars, however, are believed to have occurred much earlier. In chronicling the space elevator's progress as an alternative to rocket powered flight, it is necessary to travel back to the imaginative foundations that begot its earliest incarnations - and this is the heart of Chapter 3. After briefly outlining the major milestones in the history of the space elevator, the chapter goes on to consider how the concept has been treated in science fiction, literature, art and films, and in competitions right from the start. Numerous examples are used to illustrate some of the depictions, technologies, applications and visions for space elevators as imagined by writers and artists over the years, including more recently.

Chapter 4 takes us out of the realm of science fiction and the theoretical work of the co-creators and into the very real world of NASA who had the clout and funding to move things along. Fully 40 years after Artsutanov and a quarter of a century after Pearson, David Smitherman organized a workshop in June 1999 at NASA's Marshal Space Flight Center to discuss the concept and potential of a space elevator. The published proceedings of this workshop is an important document in the history of the space elevator. Largely as a result of this, the NASA Institute for Advanced Concepts (NIAC) agreed to fund a two phase study (between 2000 and 2003) into the viability of a space elevator to be undertaken by Dr Bradley Edwards. This chapter discusses the workshop and the NIAC studies and describes how Edwards' work - his concept and approach - galvanized not only the space community, but also captured the attention of the public at large. The chapter also considers further NIAC studies for both a lunar elevator and a martian one.

The next chapter, Chapter 5, considers more deeply the contribution of Brad Edwards to the space elevator baseline concept. Based on his NIAC studies, Edwards wrote a book (with significant contributions from Eric Westling) entitled *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* (Edwards and Westling, 2003). The chapter essentially provides an overview of this seminal book and explores the background to the studies that inspired it, the reasons why a space elevator should be built, and the impact it has subsequently had. As part of the NIAC studies, Edwards had made a detailed assessment of the current state (at the time) of carbon nanotubes (CNT) and their suitability for the tether (ribbon) material. Accordingly, Chapter 5 goes on to further discuss the first preparation of carbon nanotubes in 1991 by the Japanese scientist Sumio Iijima and the progress being made in the field today where the material is still the material of choice for the ribbon.

Chapter 6 takes the view that out of chaos comes (relative) harmony! It is emphasized that Brad Edwards was not alone once he had outlined his concept for a space elevator in depth. Inspired by him, many people came forward and began to contribute and commit time, energy and resources toward common goals and future visions as they pertained to a space elevator. The task was huge – to motivate people and organizations to not only come together and push for change, but also to work together. The chapter considers the major events that have led to focused efforts across a broader set of players. These include: the creation of LiftPort by Michael Laine as the first commercial space elevator venture; Marc Boucher's Space Elevator Reference, Ted Semon's Space Elevator Blog and the Space Elevator Wiki all of which recorded the happenings, news and developments in the field for some ten years; the evolution of various space elevator associations in America, Europe and Japan; the progression of standalone individual conferences into symposia series under the aegis of major space entities; and the practical, as opposed to theoretical, efforts that are embodied by the Space Elevator Games/Challenges - initially in America, then Europe, and now continued in Japan.

This last strand is taken up in Chapter 7 which describes the various NASA Centennial Challenges between 2005 and 2009. It was Ben and Meekk Shelef of the Spaceward Foundation who approached NASA in 2003 with the idea of getting it to fund a Space Elevator prize. They were allocated a $400,000 prize purse for advances in tether strength and power beaming. The first games were launched in 2005 and were a great success (despite there being no winner) - so much so that

NASA raised the prize money to $4 million! Four Challenges were held (there was not one in 2008) before NASA decided to pull the plug in 2009. This chapter reviews each of the competitions for power beaming and strong tether together with the teams taking part and eventual winners. The chapter concludes with a look at other similar challenges around the world, notably in Japan, Europe and under ISEC in the United States.

Apart from the theoretical work by the original three creators (Tsiolkovsky, Artsutanov and Pearson) and subsequently Edwards, the bulk of further ideas and concepts, as well as resulting discussions, have taken place within the confines of meetings, workshops and conferences. Chapter 8 thus provides an overview of these major conferences and congresses since 1999, when NASA's David Smitherman held his workshop, that have had space elevators as a theme, either for the whole conference or for sessions within a broader congress. These events have taken place not only in the United States, Luxembourg and Japan, but also at major cities around the world at the International Astronautical Congresses. Besides briefly describing the context, sponsors and some participants of the conferences, the chapter also summarizes some of the research, developments, technologies, applications and visions for space elevators as covered by the various papers presented.

Although previous chapters (notably 4 and 5) cover early studies relating to a space elevator, Chapter 9 looks at how such studies have become much more specific. Since 2010, members of the International Space Elevator Consortium have addressed individual topics in year-long focused studies. Six such studies are discussed together with their significant findings. Two studies by members of the International Academy of Astronautics are similarly discussed. One was completed at the end of 2013 and resulted in a major book on the technological feasibility and way forward of the space elevator. The second, due for completion in 2018, is setting out a roadmap for projects that can be accomplished in the near future with minimum risk, but with enhanced technologies. The final part of this chapter describes the Obayashi Corporation's study and plans for a space elevator - with operations expected to commence around 2050. To date the Japanese appear to be the most active in the field as evidenced by their on-going tethered balloon and climber competitions. Mention is also briefly made of a couple of other studies that are worthy of comment.

Chapter 10 provides some semblance of a summary - not so much of the entire book and individual chapters, but rather additional thoughts and comments. In much of the writings about it, we refer to *the* space elevator - as if there is and will be only one. This is, of course, not correct, since an operational system is likely to comprise several elevators. And in any event, there have also been studies and stories about lunar and martian elevators. Accordingly, this chapter also describes some of the work done on these other types of elevators. There is also a brief overview to remind us of the baseline architectures and the consolidation of efforts in the space elevator concept and its further gradual delineation. Besides noting the benefits and applications of a space elevator, the chapter also takes a look at the future - which will be the history of tomorrow.

This final chapter is followed by a number of appendices giving brief details about the contributors, a space elevator chronology, and some selected summaries of the transcripts from oral interviews conducted with space elevator pioneers. Although appropriate references are provided at the end of each chapter in the book, it was initially considered to add as complete a list as possible of references and other sources to the space elevator as an appendix, but it was decided to place such a list instead on the ISEC website at www.isec.org, where in addition many more oral interview transcripts can also be found.

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Chapter 2: From Early Ideas to Co-Creators

2.1 Introduction

Rockets are reputed to have been invented by the Chinese in the 13th century and their technology, range and applications have been improved and adapted over many centuries. In the mid-to-late 19th century, writers such as Jules Verne and H. G. Wells, began writing adventure stories that featured interplanetary travel including manned spaceflight. In 1865, for instance, Verne's novel *From the Earth to the Moon* was a tale about an attempt to launch three people in a projectile to make a landing on the Moon. However, Verne was preceded in his imagination of spaceflight by a church minister from Monimail, Fife, Scotland who suggested in 1861 that rockets could fly to the Moon and go faster and smoother in the vacuum of space. Inspired by the powerful telescopes of the time, William Leitch set out his ideas in his book *God's Glory in the Heavens* published in 1862, though in an earlier essay, "A Journey Through Space" he had already written that the only machine independent of the atmosphere that could be conceived of would be one based on the principle of the rocket (MacDonald, 2015). In fact, though, both men were writing two whole centuries after Cyrano de Bergerac, whom Arthur C. Clarke credited with being the first to use rocket-powered spaceflight to the Moon! In his novel *L'Autre monde ou les états et empires de la Lune* published posthumously in 1657, Cyrano tried out a variety of ways to reach the Moon including strapping rockets or fireworks to a machine he had made to propel himself upwards. He also tried to focus solar energy through mirrors to generate bursts of air. Cyrano's satirical novel was, however, just pure imaginative (science) fiction, with no attempt to be accurate in detailing interplanetary spaceflight, unlike Leitch.

Like Cyrano de Bergerac, Verne was primarily a novelist and Leitch's ideas and accurate descriptions were largely ignored or missed, so this chapter, then, focuses upon later work - the transition from a dream of celestial castles to engineering looks at the concept of space elevators. The second half of the twentieth century was amazing with its transformation from a world at war to one where engineering successes revolutionized the planet. The remarkable change in transportation from only the rich voyaging on north Atlantic ocean liners at great expense, to routine cheap air travel across the Pacific for millions of vacationers occurred because scientists, engineers, builders, entrepreneurs, corporations and individuals saw a different future and invested their time, energy and money accordingly. The blossoming of space elevator ideas in the second half of that century depended on scientists and engineers putting their intellects to work and committing time to carrying out serious calculations and analysis. Their work has taken us into the 21st century ready to go forward with the concept.

2.2 Early Conceptualization – Tsiolkovsky and the Celestial Castle

Together with Robert H. Goddard and Hermann Oberth, Konstantin E. Tsiolkovsky (also spelled Tsiolkovski) is considered to be one of the fathers of rocketry. In Moscow, a statue in his likeness sits in front of the 'Monument to the Conquerors of Space,' a behemoth of a space-age obelisk built in memory to the USSR's accomplishments in exploring the final frontier. He is perhaps most famously associated with the Ideal Rocket Equation, sometimes referred to as the Tsiolkovsky

Rocket Equation, which provides the formula to account for the change in a rocket's velocity as its mass continues to reduce while expending fuel during flight. This equation, which serves to yield a rocket's delta-v, or the total change in velocity the craft is capable of producing, is still used in determining how much fuel is required to successfully propel a rocket-based craft of any given mass into orbit or beyond. Although he first described the formula in 1897, he did not publish it until 1903 in an article entitled "Exploration of the Universe with Reactive Machines" (Tsiolkovsky, 1903). (Along with other pioneers he is cited in the interesting and informative paper by Sokolsky (1971) who made a comparative analysis of the designs and implementation of vehicles based on reactive propulsion proposed during the nineteenth and beginning of the twentieth centuries.)

Significant as that contribution was, however, equations as they pertained to the yet-to-be invented rocket into space were not the only thing on Tsiolkovsky's mind when it came to conceptualizing avenues by which to gain access to space. As a professor of mathematics, he was particularly fascinated by the study of gravity, finding ways to simulate it, and also, ways to defeat it. To that end, his examination of the subject provided for a multitude of hypotheses that he included in his numerous written works. In 1926, Tsiolkovsky wrote *Plan of Space Exploration*; in 1929 he wrote *The Space Rocket Trains*; and in 1932 he wrote both *Cosmic Philosophy* and *Album of Space Travels*. However, it is within the pages of one particular collection of earlier essays from 1895, *Dreams of Earth and Sky*, that can be found what many regard to be the earliest abstract imagining of a space elevator (Tsiolkovsky, 1895).

In this piece, Tsiolkovsky speculated on a variety of methods as to how the pull of gravity could be diminished, shifted, or even reversed entirely providing the application of a sufficient amount of external force. In explaining his ideas, he invited his readers to imagine entering into a clay pot being spun on a potter's wheel, and how one would be able to stand on the inner walls as the pot was being spun due to the centripetal force. Many of us today have actually been able to enjoy this very simulation owing to the proliferation of amusement parks. It was known as the 'The Mineshaft' in some places, but the ride itself has no doubt been called by various other names - including the 'Wall of Death' which features motorcyclists going round and round. Regardless, the mechanics are precisely the same as Tsiolkovsky described with his spinning clay pot many decades prior. In the amusement park ride, individuals enter into, and line their backs along the wall of, a large cylindrical chamber. With the push of a button from the operator, the chamber begins to spin at increasingly faster speeds. The riders feel the generated force pressing upon their bodies, and find that when the floor is dropped out, they remain fixed to the walls of the spinning chamber. The rotation of the room generates an artificial gravity in a manner similar to Tsiolkovsky's clay pot hypothesis (Martin, 2015).

Further along in his essays, Tsiolkovsky took his speculations to even greater heights, for in calculating the centripetal force that would be required for one to be free of Earth's gravitational influence entirely, the Russian mathematician conceived of some rather unconventional means. He suggested that if one were to be riding a train that ran full circle around the equator at a speed of 30,000 kilometers per hour (kph), the pull of gravity would be entirely reversed, and any passengers on board would become secured to the ceiling. You do not have to be a train engineer to know that such speeds are nowhere near attainable as the fastest trains in the world currently can only reach around 500kph, although the Japanese maglev bullet train set a new record of 603kph in 2015. Continuing this line of thought, Tsiolkovsky contemplated on the change in conditions if one were not trying to defeat gravity on the surface of the planet, where it is at its strongest. Instead he thought, why not use centripetal force at a point where gravity is significantly diminished? Like space for instance.

Having been inspired by the Eiffel Tower on a recent trip to Paris, Tsiolkovsky imagined even grander towers situated at the equator that stretched far into the heavens, at the top of which sat what he called 'celestial castles'. With Earth's gravity seeming to vanish entirely at what he measured to be a distance of 34,000 versts (roughly 36,000km - or geostationary orbit), combined with the effects of the centripetal force provided by the rotation of the planet, he suggested that anyone standing inside his celestial castle would be looking up at the Earth, instead of down, as the pull of gravity would be effectively flipped.

Though the system he described in *Dreams of Earth and Sky* sounds incredibly familiar to what is now recognized as a space elevator, Tsiolkovsky was never acknowledged as the inventor per se (Pearson, 1997). The reason for this is that he never bothered to calculate some rather significant factors pertinent to the elevator's successful assembly and operation. Factors such as the material used for construction, how the line would need to double in width at certain intervals in order to support itself, how one would be transported to the top of the tower, or the need for a counterweight that extended much further than his castle at geostationary orbit to keep the entire system taut. Also devoid of any extensive numerical treatment, his ideas have often been chalked up to the musings of a highly imaginative mind, or what many refer to as a 'thought experiment'.

As described, Tsiolkovsky's tower would be able to launch objects into orbit without a rocket. Since the space elevator would attain orbital velocity as it rode up the cable, an object released at the tower's top would also have the orbital velocity necessary to remain in geostationary orbit. Unlike more recent concepts for space elevators, though, Tsiolkovsky's (conceptual) tower was a compression structure, rather than a tension (or 'tether') structure. But, according to an analysis by Landis and Cafarelli (1995), building a compression structure from the ground up would prove to be an unrealistic task as there was no material in existence with enough compressive strength to support its own weight under such conditions.

Although Tsiolkovsky's writings were in Russian, there is a fascinating translation into English of his works, together with some analysis and commentary. The book, *Call of the Cosmos* (Tsiolkovsky, 1960), contains chapters headed "On the Moon", "Dreams of Earth and Sky", "The Aims of Astronautics", "Science Fiction in Tsiolkovsky's Writings" and various supplements including "To Inventors of Reaction-Propelled Machines" and "Pages from a Young Man's Notebook" where many of his early ideas were jotted down. It is notable that Tsiolkovsky cited Jules Verne as an inspiration.

The gauntlet of scientific analyses that would champion the label of invention was yet several decades down the road. In fact, it would be more than half a century before the concept of a space elevator would even be conceived of yet again.

2.3 Space Age Alternatives – Artsutanov and the Cosmic Railway

Some six decades after Tsiolkovsky, a young engineering student in Leningrad named Yuri N. Artsutanov, came up with a more feasible scheme for building a space tower by using a geosynchronous satellite as the base from which to construct it. By using a counterweight, a cable would be lowered from geosynchronous orbit to the surface of the Earth while the counterweight was extended from the satellite away from Earth, keeping the center of gravity of the cable motionless relative to Earth. Artsutanov, unaware at the time of Tsiolkovsky's castle 65 years prior, independently conceived of what he called a 'cosmic railway,' the catalyst for which was an advancement in materials science that had recently been made in the United States. In 1957, he learned from a fellow graduate that a super-strong material (likely tiny graphite whiskers) had been invented whose strength-to-weight ratio could theoretically allow for the construction of a cable up to 400km in length without collapsing under its own weight. Artsutanov then took the idea of something even stronger; a fictitious super-material that could be used to extend a cable to an infinite length into the cosmos. That same material, as he imagined it, would serve as the rail in his cosmic railway. After attributing a great deal of thought to the concept, his idea eventually made its way into print, being later published in the daily Russian tabloid *Komsomolskaya Pravda* on 31 July 1960. His piece, "To the Cosmos by Electric Train", went into extensive detail regarding what is thought to be yet another earlier rendition of a space elevator (Artsutanov, 1960). [The English translation of Artsutanov's article mentions it was published in the Sunday Supplement of Young Persons' Pravda. This is a somewhat incorrect translation of the word Komsomolskaya and perhaps gives the wrong impression of who the article was aimed at. In fact, *Komsomolskaya Pravda* began in 1925 as the official organ of the Communist Union of Youth, or Komsomol, the youth wing of the Communist Party of the Soviet Union. As such, it targeted the same 14-28 year olds as its parent organization, focusing initially on popular science and adventure articles while teaching the values of the Communist Party. It would be more in keeping with the original to call it Young Communists' Pravda.]

Artsutanov began with criticizing the rocket as being too dangerous and having too lengthy of a preparation process prior to each individual launch. So much so, that he emphasized its inefficiency as a means of getting off the Earth. He then began to work with the previously established notion of 'celestial moorings', or orbital spaceports, that would allow for the docking and embarkation of large interplanetary vessels. These way stations would also employ smaller shuttles to ferry people to and from the planetary bodies they orbited. Artsutanov's permutation of this concept envisioned that instead of using smaller craft to transport people up from the ground, travellers would use railways that would extend into the sky, tying the ground terminals on the surface directly to their orbital counterparts above.

In many ways his system was similar to that of Tsiolkovsky's in that the elevator would have to be placed on the Earth's equator in order to utilize the centripetal force generated by the rotation of the planet. In explaining his concept, he drew a metaphor between a space station revolving around the planet and a stone being swung around on the end of a string. He explained that just as the centripetal force allowed the string to remain taut, so would the same be true for his cosmic railway. In some of the finer details however, his system differed from that of his unacquainted predecessor, particularly in that instead of a station placed at precisely the geostationary point at 36,000km, it would instead be located 50-60,000km out. His 'end of the line' as he called it, is from where he imagined interplanetary spaceships could depart on cosmic ventures into the solar system and beyond.

As a completely new element in the design, his model also employed the spaceport to serve a dual purpose in that it would simultaneously function as the counterweight for the entire system, helping to keep the line taut, thereby preventing its collapse. While subsequent analyses have provided for estimates of counterweights attached at distances of 100,000km and beyond, Artsutanov made it clear that he was well aware of this factor as a necessity in the system's overall design. Even today, the need for a counterweight is still considered to be a requisite in the most up-to-date models of space elevators.

"To the Cosmos by Electric Train" also afforded its readers a bit of narrative in that it invited them to imagine the experience of a passenger making his or her way up the railway from the ground terminal to the orbital station overhead. In doing so, it allowed for the visualization of some of the finer conceptual details within the elevator's design. After having left the surface, Artsutanov envisioned that at 5,000km up, the rider would pass through a solar station that would use large collectors to generate power for the entire drive system, which itself would utilize an electromagnetic field to move the climber upward. At 36,000km, where he estimated centrifugal force to overpower the Earth's gravitational pull, he explained that the climber would no longer need to expend its own energy to continue the ascension as the rotation of the system with the planet would provide enough energy to propel it further outward. As the rider reached his or her final destination at the spaceport 60,000km from the surface below, they would see a collection of structures that comprised, as Artsutanov imagined it, a small city held down by simulated gravity that diametrically opposed the influence of the Earth.

While ostensibly airing on the side of fiction at this point, Artsutanov was sure to adhere to the very practical requirements, later corroborated by others, that would enable the elevator's successful deployment. For example, he made it clear that construction would need to begin from a satellite placed at the geostationary point, where both the line being dropped to Earth and the one extending into space would need to be extruded simultaneously. This would be done in order to ensure that as the line reaching towards the surface became heavier with the increasing gravitational pull of the planet, the system could be kept in balance with the weight of the line reaching into space, which through the use of centrifugal force would negate the pull of the Earth.

He also drew attention to the need for the line connecting the spaceport to the Earth to exponentially increase in width as it was produced and slowly threaded towards the surface. With the thickest part of the line at the geosynchronous spaceport, this would ensure that it would not snap, as there would be an enormous strain placed upon it by the rotating station once anchored to the planet below. Those who would later come to work on the space elevator would reaffirm this stipulation in even finer detail.

But even for all of Artsutanov's unconventional concepts on constructing this revolutionary system, they were still predicated on a material that existed only in his mind. In 1960, there was no known physical substance whose strength-to-weight ratio could support such a gargantuan structure. Even today this still remains the elevator's primary obstacle in becoming realized (though the discovery of carbon nanotubes in 1991 have led to the conviction that these have the necessary characteristics for a space elevator), which leads many to argue that an elevator could be possible on the Moon, where the environmental conditions are far less demanding. In concluding "To the Cosmos by Electric Train", Artsutanov made mention of this and stated that if two elevators, one on the Earth and the other on the Moon, operated in tandem, the distance between the two bodies from surface to surface could be negotiated almost entirely without the use of fuel.

Super materials pending, Artsutanov's elaborate engineering approach was sufficient to later label him as one of two independent co-inventors of the space elevator. And though his ideas were lacking in any kind of mathematical treatment, his thought processes included enough conceptual detail to have him recognized as one of the space elevator's founding fathers. Despite this designation however, his piece was not received by a wide enough audience to gain any real footing in the scientific community, and for that reason, the space elevator remained in the shadows. Fortunately, it would not have to wait another 65 years before finally making its big debut.

2.4 Running the Numbers – Pearson and the Orbital Tower

In the five years prior to 1975, Jerome Pearson, an aerospace engineer for both NASA and the Air Force Research Laboratory, had been laboriously trying to persuade various scientific journals to publish his piece “The Orbital Tower: A Spacecraft Launcher Using the Earth’s Rotational Energy”. He was finally met with success when a 1975 volume of the journal *Act Astronautica* featured what became the definitive piece that heralded the space elevator’s entry into the scientific community and ultimately, the world (Pearson, 1975). Since then, this incredibly futurist means of Earth-to-space transportation has gained a following of scientists and enthusiasts alike who devote their time and energy to bringing the space elevator to reality. Just as Artsutanov had been unaware of the work of Tsiolkovsky before him, so too was Pearson unaware of Artsutanov’s, which led to Pearson’s being identified as the other independent co-inventor. That, and the fact that his paper was the first mathematical presentation of the elevator designed to convince scientists and engineers that such a grandiose alternative to rocketry was not only theoretically possible, but also the right way to go.

His assiduous number crunching provided for what can perhaps be seen as a kind of evolutionary analogue in that if Tsiolkovsky’s thought experiment can be compared to that of a single-cell organism, the concept in its most nascent phase, then Pearson’s elaborate numerical treatment can perhaps be thought of as a bipedal hunter. Continuing with that metaphor, Artsutanov’s piece in 1960 might then be the proverbial ‘missing link’ between the two. But even for its being laden with esoteric formulas undecipherable by the layman, Pearson’s “Orbital Tower” still contained plenty of intelligible content to fire the imagination of the average space buff.

Pearson began his assessment by imploring his readers to imagine a physical connection being made between a satellite at geostationary orbit and the Earth’s surface below. He suggested that through the use of this connection, the deployment and return of satellites and spacecraft to and from the planet would be much safer, and require far less energy, which as a consequence, would also make them cheaper.

Like Artsutanov before him, Pearson recognized many of the finer mechanical details pertinent to the elevator’s construction and operation. Details including the need for assembly to begin at the geostationary point so that the increasing weight of the cable reaching toward the planet could be counteracted by a separate cable extending into space. But, where as Artsutanov imagined his counterweight attached at a distance of 60,000km, where it would double as a spaceport, Pearson fastened his at the much further distance of 144,000km. As a matter of fact, Pearson’s design did not even call for a true counterweight *per se* as the sheer distance and mass of the line, and the outward force placed upon it by the spinning planet, would be sufficient to keep the structure standing. This enormously elongated line in Pearson’s model was of particular interest given that it paved the way to another major divergence in the designs of the two inventors.

Instead of interplanetary vessels departing from the station like ships from a harbor as proposed by his Russian counterpart, Pearson saw the elevator directly employing the inertia generated by the centrifugal movement of the rotating system to slingshot craft away from the planet. Essentially, it is like imagining the Earth as a giant discus thrower and any given spacecraft, the discus; the Earth rotates as a discus thrower would, thereby transferring the centrifugal force into the discus, or spacecraft, before releasing it at full arm’s length. By his estimates, anything launched in this manner from appropriate distances above the geostationary point would be able to reach as far out as Saturn without using any form of rocketry. This means that traveling to Mars, for instance, would require no more energy than what was needed to reach geostationary orbit. If craft were launched from even further up the tower, say more towards the end of the remarkably protracted tether, Pearson theorized that the spacecraft would not require any self-propulsion at all to escape the solar system entirely.

As for the power that would be needed to reach geostationary orbit from the surface, Pearson thought of that too. He suggested, again like Artsutanov, that perhaps this energy could be supplied by a solar power station attached to the elevator system. Either that, or through the capturing of energy from returning climbers as they descended the line back to Earth, generated via friction from braking that could be reabsorbed into the line.

This means that in 1975, Pearson associated sustainability with space travel on an entirely unprecedented level. His system would harness the rotation of the Earth to launch craft into space, thereby eliminating the need for rocket propulsion, while also generating its own power. Pearson backed up his explanations of a space elevator with countless calculations by which he thoroughly accounted for every technical aspect of his elevator's design and operation. Of those numerical computations, Pearson was certain to include those related to that one fundamental obstacle that continues to fetter the space elevator - the material, and its minimum strength-to-weight ratio.

Again, just as Artsutanov had done previously, Pearson identified the need for the elevator's cable to be tapered in order to prevent the line from snapping due to the enormous tension that would be placed upon the system from both the downward pull of the planet and the counterweight being spun around it. Were the elevator to be constructed using steel (which Artsutanov knew to be not the right material), the tapering factor would require that the diameter of the cable be increased at such frequent intervals, that its widest point at geostationary orbit would be impractically large. Wider than the planet's diameter in fact, given that the distance from Earth's surface to geostationary orbit is roughly 36,000km. With steel out of the equation, Pearson did theorize that a suitable candidate might be found with 'perfect-crystal whiskers of graphite', a material whose tapering ratio would require that the cable be only ten times larger in diameter at geostationary altitude than on the surface. At the time Pearson wrote "The Orbital Tower", this perfect rendering of graphite crystals could only be done on microscopic scales, a problem Pearson speculated could be rectified were they to be manufactured in a zero-gravity environment, say from the point of the elevator's construction at geostationary orbit. And though the production of super crystals in space is a project still pending, Pearson was certainly on to something in that the solution to this major hurdle might be found in the allotropes of carbon. It is also worth noting here that Pearson subsequently devoted his attention to a lunar space elevator (see Chapter 4.4).

2.5 Conclusion

This chapter has looked at the ideas and concepts of three men, at least two of whom are synonymous with exploring some form of stairway to the stars, or space elevator. The early work, first of Konstantin Tsiolkovsky, then Yuri Artsutanov, and later Jerome Pearson, was crucial to the understanding of the dynamics and structure of a space elevator system. Others had done some preliminary studies in between on, for instance, materials, but it was the work of this trio, particularly Pearson, who got the community (including science fiction writers) to the point that made it possible for Brad Edwards in the early 2000s, and then a plethora of others after him to conduct much more research into the design and development of a space elevator. Although Pearson is credited as the co-inventor of the space elevator, in fact, according to Arthur C. Clarke (1981), Pearson himself located at least three other independent originators of the concept, though none prior to Artsutanov's 1960 paper. These included G. C. Weiffenbach, G. Colombo, E. M. Gaposchkin and M. D. Grossi, who arrived at the concept as a result of their work on skyhooks and tethered satellites in 1975; and T.

Logsdon and R. Africano around 1970. To these could possibly be added Hans Moravec in 1977, and later Robert Forward, who investigated the physics of non-synchronous skyhooks, and performed detailed simulations of tapered rotating tethers that could pick objects off, and place objects onto, the Moon, Mars, other planets with little loss of energy. All these men, particularly the early threesome, helped lay the foundations for the subsequent research and development that was to follow a quarter of a century later. In fact, Robert Forward used Clarke's own comment (and third law) about advanced technologies for the title of his book *Indistinguishable from Magic* published in 1995 as an update from an earlier version written in 1988.

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Chapter 3: The Space Elevator in History, Media and Science Fiction

3.1 Introduction

The idea of a space elevator has captured the imagination of scientists and engineers and writers and artists alike. The space elevator, the subject of studies in the past by both the Russians and NASA, as well as the IAA, has been extensively refined and developed and is currently conceived as a 100,000km ribbon of carbon nanotubes extending into space up which climbers will travel to release payloads in different orbits. The space elevator was one of several concepts singled out for attention in the 'Innovative Technologies from Science Fiction for Space Applications' (ITSF) study, carried out under the aegis of the European Space Agency (ESA), which reviewed science fiction (SF) writings, artwork and films to ascertain whether any of the concepts and technologies mentioned in the (older) science fiction novels and magazines could be utilized for today's spacecraft and missions. The enormous public interest in the ITSF study stimulated the idea of a science fiction essay competition. The first competition was an overwhelming success and in view of the growing curiosity in the space elevator, it was decided that this should be the theme for a second competition. Following the major milestones in the history of space elevators, this chapter considers how the concept has been treated in literature, art and films, discusses the ideas behind the 2nd Clarke-Bradbury Science Fiction Competition on the space elevator and gives examples of some of the depictions, technologies, applications and visions for space elevators as imagined by writers and artists.

3.2 The Space Elevator in History

A space elevator, in various disguises, has been around for a very long time! The idea of building a structure from the surface of the Earth into space dates back to some of the earliest known manuscripts. In the 'Book of Genesis', the story of Babel is recorded where people there sought to build a city of bricks with a tower (ziggurat) with its top in the sky (commonly known now - but not then - as the Tower of Babel and said to have reached a height of some 207m). Later in the same Book, Jacob has a dream about a ladder set up on Earth, the top of which reached to heaven and on which angels were ascending and descending (commonly known as Jacob's Ladder). Two millennium further on, the children's fairy tale "Jack and the Beanstalk" which dates from the early 1400s might also be considered an early description of a space elevator! (In fact, "Jack and the Beanstalk" was apparently rooted in a group of stories classified as "The Boy Who Stole Ogre's Treasure", and can be traced back to when Eastern and Western Proto-Indo-European languages split more than 5,000 years ago.)

However, in 1895 Konstantin Tsiolkovsky, a Russian scientist, was inspired by the newly-constructed Eiffel Tower in Paris (300m in height) to consider a tower reaching all the way up into space. He thought of putting a 'celestial castle' at the end of a spindle shaped cable, with the 'castle' orbiting the earth in a geosynchronous orbit. Tsiolkovsky's tower would be able to launch objects into orbit without a rocket. Since objects would attain orbital velocity as they rode up the cable, once released at the tower's top they would also have the orbital velocity necessary to remain in geosynchronous orbit (Tsiolkovsky, 1895). However, building from the ground up for the height required proved to be an impossible task - there was no material in existence at the time with enough compressive strength to support its own weight under such conditions (Pearson, 1997). See Chapter 2 for more on Tsiolkovsky.

Some sixty years later another Russian scientist, Yuri N. Artsutanov, conceived of a more feasible scheme for building a space tower by using a geosynchronous satellite as the base from which to construct the tower. By using a counterweight, a cable would be lowered from geosynchronous orbit to the surface of the Earth while the counterweight was extended from the satellite away from Earth, keeping the center of gravity of the cable motionless relative to Earth. Artsutanov published his idea in the Sunday supplement of *Komsomolskaya Pravda* in 1960. He also proposed tapering the cable thickness so that the tension in the cable was constant (Artsutanov, 1960). See Chapter 2 for more on Artsutanov.

To make a cable over 35,000km long to reach geosynchronous orbit would prove difficult. In 1966, four American engineers (John Isaacs, Allyn Vine, Hugh Bradner and George Bachus) in discussing a very long tapered cable in space spun out in both directions simultaneously, determined what type of material would be required to build a space elevator, assuming it would be a straight cable with no variations in its cross section. They found that the strength required would be twice that of any existing material including graphite, quartz, beryllium and diamond (Isaacs *et al*, 1966).

Some 18 months after Isaacs and his colleagues published their work, Russian journalist Vladimir Lvov responded with a lengthy and detailed letter in *Science* to the effect that Leningrad engineer Yuri N. Artsutanov had already developed the concept they proposed and had published his ideas for a 'heavenly funicular' in 1960 (Lvov, 1966). The magazine published Lvov's letter together with a comment from Isaacs and his team in which they agreed that Artsutanov had proposed his sky hook six years before their paper was published. The matter was clearly important. In a biography of John Isaacs a whole chapter is devoted to 'Deep Sea Moorings and Skyhooks' where Isaacs discusses his ideas for a cable stretching from the bottom of the ocean to a high-altitude balloon and beyond (Behrman and Isaacs, 1992). The technical issues were worked out and culminated in the 1966 *Science* article. The chapter goes on to note the intervention of Lvov who brought Artsutanov's work to their attention and mentions that the idea was taken up by science fiction writers, notably Arthur C. Clarke, in *Fountains of Paradise*. What makes it even more interesting is that Clarke tells much the same story about Isaacs, Lvov and Artsutanov in a new and extensively-revised and expanded edition of his biography by Niel McAleer (2013). [The original, also by McAleer, was published in 1992.]

Then, in 1975, American physicist Jerome Pearson designed a tapered cross section that would be better suited to building the elusive tower. He suggested using a counterweight that would be slowly extended out to 144,000km as the lower section of the tower was built. His analysis included disturbances such as the gravitation of the Moon, wind and moving payloads up and down the cable. The weight of the material needed to build a tower with a base cross-sectional area of 50cm^2 and a taper ratio of 10, about 24,000 flights would be required of an advanced space shuttle with thirty times the payload of the presently proposed shuttle - although part of the material could be transported up the tower when a minimum strength strand reached the ground (Pearson, 1975). See Chapter 2 for more on Pearson's work.

Next, David Smitherman of NASA compiled a detailed study of the concept of space elevators based on the findings of a workshop on the topic in 1999 and concluded that, while not feasible then, this method of cheap transportation to geostationary orbit could become a reality and dramatically lower the cost of getting into space during the latter part of the 21st century. The plan was to capture a carbonaceous chondrite asteroid, drag it into a stable orbit around the Earth and mine it for the necessary material to make the cable, which would eventually reach down to the Earth's surface (Smitherman, 2000).

A few years later, in 2002, another American scientist, Bradley Edwards, suggested creating a 100,000km long paper-thin ribbon made of carbon nanotubes (CNT), which would stand a greater chance of surviving impacts by meteors. The space elevator, as conceived by Edwards, comprised an initial spacecraft, ribbon production unit, climbers, power beaming facility, anchor platform, debris tracking system and the CNT ribbon stretching up into space and along which the climbers would travel to release payloads into orbit at diverse points. It was expected that this international development would have a tremendous impact upon society and industry within the next twenty or thirty years when the space elevator was completed and launch-to- orbit costs are reduced to around an anticipated $100/kg.

The work of Edwards, financed in part by grants from the NASA Institute for Advanced Concepts (NIAC), was conducted in two phases: Phase I ran from May-October 2000 (Edwards, 2000), while Phase II ran from March 2001-January 2003 (Edwards, 2003). The study embraced all the engineering and scientific aspects including the deployment mechanism, ribbon production, climber design, power delivery system, orbital debris avoidance, and the anchor system. By positioning the anchor in the ocean off the coast of Ecuador, weather and environmental hazards as well as construction costs, could be reduced. Research and development (R&D) into CNTs was progressing apace and plans were advanced for possible construction of a first elevator, which was estimated to cost less than €10bn.

Brad Edwards' ideas, research and analysis culminated in not only reports for NIAC, but also coalesced into a book co-authored with Eric Westling entitled *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* and self-published in November 2003 (Edwards and Westling, 2003). This publication changed the landscape from one where the space elevator was mainly an idea in science fiction to one of potential execution in the foreseeable future. Edwards' engineering analyses and savvy insight into what was possible started a ground swell of innovation across the globe. The public embraced the idea which has been pursued in many arenas (newspapers, journals, popular magazines, and TV shows). Over the next ten years Edwards' concept was the baseline for the modern-day space elevator. This was focused around the belief that the materials industry would deliver a tether material of sufficient strength to enable the system of systems called a space elevator.

As more people began to put their minds to consider in earnest the concept of a space elevator, many questions and issues were being raised and discussed. These spurred Pete Swan and David Raitt to propose, in 2009, a detailed study assessing modern day designs and applications of a potential space elevator to be carried out under the auspices of the International Academy of Astronautics. In the four-year study, some forty experts from around the world studied the issues and analyzed the rationale for this unique transportation infrastructure and concluded that space elevators were a feasible option. Among the aspects researched were the major elements such as tether material, climbers and base and apex anchors; the systems design together with a technology assessment; the legal and regulatory frameworks; and market and financial projections. Although Edward's original idea of a carbon nanotube tether of 100,000km was retained together with much of his proposed infrastructure, it was believed that a more realistic price for access to GEO would be $500/kg (Swan, Raitt *et al*, 2013).

3.3 The Space Elevator in Literature

Konstantin Tsiolkovsky (see Chapter 2), besides formulating a rocket equation and writing several scientific and technical books about space, also wrote science fiction novels including *On the Moon* (1895), *Dreams of Earth and Sky* (1895) and *Beyond the Earth* (1920). However, it is his *Dreams of Earth and Sky* that is memorable and worthy of mention here as literature because of its depiction of an early space elevator. Read more about Tsiolkovsky and his ideas in Chapter 2.

Practicing scientists and engineers were not the only ones theorizing about a space elevator. Sir Arthur C. Clarke introduced the concept of a space elevator to a broader audience in his novel *Fountains of Paradise* (Clarke, 1979). Set in the 22nd century, in the story engineers construct a rigid connection between a point in geostationary orbit and Sri Kanda - a mountain on a fictitious island (Taprobane) closely resembling Ceylon (Sri Lanka) where Clarke lived. (The mountain in the book bears a strong resemblance to the real mountain Sri Pada on Sri Lanka and is also known as Adam's Peak.) One of the major problems for a space elevator is a suitable material able to withstand the mechanical tensile forces which would tear the cable apart. In the novel, Clarke envisions a microscopically thin but strong hyperfilament that makes the elevator possible. Although the hyperfilament is constructed from 'continuous pseudo-one-dimensional diamond crystal', Clarke later expressed his belief that another type of carbon, Buckminsterfullerene, would play the role of the hyperfilament in a real space elevator.

It is worth mentioning here that Clarke, also in 1979, in a presentation at the 30th International Astronautical Congress in Munich, Germany, touched on the nomenclature of space elevators. "The Russian inventor used the charming 'heavenly funicular'. American writers have contributed 'orbital tower', 'anchored satellite', 'beanstalk', 'Jacob's Ladder' - and, of course, 'Skyhook'. I prefer 'space elevator'; it is euphonious (at least in English) and exactly describes the subject" (Clarke, 1981). His presentation also gave a historical overview of the salient points and people in space elevator concepts and developments up to that point in time (1979). He further addressed the problem of materials, cable deployment, the mass anchor, catastrophes, elevators beyond the Earth, dynamic systems, power and propulsion, subsidiary problems, and a ring around the world.

As the Wikipedia entry on "Space Elevators in Fiction" shows, there are many novels which mention space elevators. A select few are mentioned below - further details about them and the others can be found at http://en.wikipedia.org/wiki/Space_elevators_in_fiction.

In Clarke's later novel, *2061: Odyssey Three* (Clarke, 1987), the possibility of a space elevator is realized after a groundbreaking discovery that Jupiter's core (now in fragments around the orbit of Lucifer, the small sun formed by the implosion of Jupiter) had been a solid diamond. As the hardest substance in nature, suddenly available in vast quantities, it facilitates the construction of a solid elevator rather than the more common tether structure previously envisaged. In Clarke's fourth and final book in his Space Odyssey series, *3001: The Final Odyssey* (Clarke, 1997), four gigantic space elevators are located evenly around the equator. The story follows the adventures of an astronaut murdered by HAL in *2001: A Space Odyssey* who is brought back to life. The astronaut then explores the Earth of the year 3001, one of the notable features of which is a large network of space elevators and habitats in Earth orbit.

In fact, Clarke wrote a short story in 1958, which was published under the same title as a novel published later in 1986. *The Songs of Distant Earth* (Clarke, 1986) tells the story of a utopian human colony in the far future which is visited by travellers from a doomed Earth, as the Sun has gone nova.

Although the term space elevator is not used, the story describes a kind of very strong cable that is used to pull massive blocks of ice from the surface up to a spaceship in orbit around a fictitious planet, Thalassa. [As an aside, in 1994 musician and composer Mike Oldfield released an album entitled "The Songs of Distant Earth" based on Clarke's SF novel.]

The Web Between the Worlds by Charles Sheffield (Sheffield, 1979), describes the construction of a space elevator and was published at the same time as Clarke's *Fountains of Paradise*. The story is a thriller centered around an engineer who builds the cable for the elevator. A recent paperback edition includes a contribution from Arthur C. Clarke on the history of the how the idea was brought to press, and a long appendix detailing the physics involved in building a 'beanstalk' (Sheffield's name for the elevator). The book is touted as a breakthrough novel, written by the President of the American Astronautical Society, about an idea whose time has come: a shimmering bridge between Earth and space, a veritable beanstalk that mankind will climb to the stars! In his introduction to the Baen Books edition of his novel, Sheffield informs us that Clarke sent an open letter to the Science Fiction Writers of America, stating that coincidence, not plagiarism, lay behind the fact that two books were to be published in 1979 with strikingly similar themes. Not just the space elevator, but each book had as main character the world's leading bridge-builder; and each one employed a device known as a Spider. Sheffield further muses:

"If Clarke had not published his *The Fountains of Paradise*, how would my *The Web Between the Worlds* have been received? Would my book have been hailed as the source of a big idea new to science fiction? Or would it have suffered instant obscurity, as a piece of science fantasy?" (http://www.baenebooks.com/chapters/0671319736/0671319736.htm)

The Mars trilogy, published in the 1990s, is a series of three science fiction novels (*Red Mars*, *Green Mars* and *Blue Mars*) by Kim Stanley Robinson, chronicling the settlement and terraforming of the planet Mars. An additional collection of short stories was published as "The Martians". The series features space elevators on Earth and Mars whose cables are made of jointed segments each of which is a huge single crystal of diamond. In the first novel, *Red Mars*, much of Mars' infrastructure, including the space elevator, is destroyed. However, all three books speculate on the possible long-term scenarios of space elevator operation (Robinson, 1994).

In 2008 Tom Terry published *City of Heaven* which tells of a terrorist attack on space elevators. The world (Terra) has strayed from the principles that led to humankind's greatest era: the Great Generation. The principal system of faith, Royalism, has become a politically oriented belief system. Responding to the growing threat to their beliefs, factions of the Royalist Social Movement seek to restore the principles and former glory of the Great Generation. High above Terra, connected by tethers stretching from the surface to sixty-four thousand kilometers in space, is the civilian space station City of Heaven - home to more than a million citizens - and humankind's greatest achievement. The Ar'chaists, a radical sect of Royalism, are determined to force the world to bend its knee and in a single act of terror, they sever the tethers connecting City of Heaven, killing nearly all of its inhabitants and sending the city on a collision course with Terra, where millions more will surely die (Terry, 2008).

In 2011 NASA's Goddard Space Flight Center announced it was teaming up with publisher Tor/Forge Books to develop and publish NASA-Inspired Works of Fiction. The program is designed to pair up scientists and writers to produce science-literate SF for a general audience, while making the public more aware of NASA's role. The books are intended to highlight concepts relevant to current and future NASA missions. Can anything be read into the fact that the first NASA-Inspired Work of Fiction book in the series, *Pillar to the Sky* by William Forstchen (the NASA engineer who consulted on the book was Dr Hohn Panek) was about a space elevator?! Published in early 2014, the novel follows the journey of Gary and Eva Morgan, a pair of married scientists at NASA's Goddard Space Flight Center. They dream of building a pillar to the sky (as their space elevator is known), not least to escape an Earth of pandemic drought, sky high oil prices, and dwindling energy supplies, with a view to mining the power of the sun to provide limitless energy for humankind. When the budget for their space elevator is cut by a skeptical and bureaucratic U.S. Congress, they have to find another way of making their dream become reality. A billionaire private investor comes to their rescue, however, the path to building a sustainable space elevator will not be easy with endless battles to fight and obstacles to overcome along the way (Forstchen, 2014).

It is worth pointing out that all of the later major players in the space elevator field, such as Smitherman and Edwards and others, were influenced or inspired to a certain extent by the ideas and writings of Arthur C. Clarke, in particular. In fact, in his *Phase I Final Report* for NIAC in 2000, Brad Edwards provided a brief overview of how he thought of using carbon nanotubes for his concept of the space elevator (Edwards, 2000). He noted that although Arthur C. Clark had put together an interesting tale of the construction of the first space elevator in *Fountains of Paradise* and Kim Stanley-Robinson had a different and well-thought out view on how the first space elevator might arise in *Red Mars*, these science fiction books pointed out many of the basic aspects and challenges of building a space elevator and keeping it operational, but their models for building a space elevator in reality were not really within the realm of practicality. In both of the novels a natural object, asteroid or moon, is moved into a proper orbit and mined for its carbon. This carbon is then used to build a very strong, very large cable extending both upward and downward. This approach was also considered a reasonable conceptual suggestion for one possible construction method in the David Smitherman's 2000 study on the space elevator for NASA. Edwards, however, believed this method of dragging an asteroid about was too expensive and too difficult to be a viable option outside of science fiction.

3.4 The Space Elevator in Art and Film

As noted above, Wikipedia provides a useful list of fictional works which feature a space elevator of some description. However, besides novels and fairy tales, the list includes anime, comics and manga; games; movies and TV series; and a few classed under Others. A select few are mentioned below, further details about them and the rest can be found at http://en.wikipedia.org/wiki/Space_elevators_in_fiction.

There are more than a few paintings that depict space elevators as any search on the internet will reveal. One of the earliest is illustrated on page 25 in a volume of paintings published in Moscow in 1967 with captions in Russian and English entitled the *Stars are Awaiting Us* by the Russians Alexei Arkhipovich Leonov and Andrei Konstantinovich Sokolov. Cosmonaut Leonov was the first person to conduct extravehicular activity taking a 12 minute walk in space. He was also an accomplished artist, who sketched his colleagues in space (including the American astronauts who flew with him on the Apollo Soyuz Test Project in 1975), and whose published books include albums of his artistic efforts as well as works, such as this, he did in collaboration with his friend Andrei Sokolov (Leonov and Sokolov, 1967). The painting mentioned here, was done by Sokolov, and is actually titled 'Space Elevator' and depicts an assembly of spheres, hovering apparently over Sri Lanka (surely not coincidentally since it was the home of Arthur C. Clarke who commented on this fact), from which a cable stretches down to Earth.

The English caption for this particular painting is as follows:

‘Space Elevator: Among the multitude of possible near-Earth orbits one is a very special one - the orbit of the so-called 36,000 kilometers satellite. If a satellite is launched to this altitude above the Equator it will orbit the planet every 24 hours, i.e. its period of revolution will coincide with the Earth’s rotation around its axis. And this means that the satellite will, so to say, stay fixed in a certain point in the sky. If a cable is lowered from the satellite to the Earth you will have a ready cable-road. An “Earth-Sputnik-Earth” elevator for freight and passengers can then be built, and it will operate without any rocket propulsion.’

Other, more recent, paintings were submitted to the 2nd Clarke-Bradbury Science Fiction Competition (see below), other paintings were commissioned as concept graphics for the early presentations and videos on the space elevator by Pearson and Edwards, amongst others. Although not nearly so many images as stories were submitted to the 2nd Clarke-Bradbury SF Competition, the artwork depicted a range of topics – some exhibiting detailed surrealism, others portraying a childlike quality. Some had been generated digitally on computers, others were real paintings in acrylic on canvas.

In other art works, there are at least two Anime series dealing with space elevators. In “Tekkaman Blade” (from 1992) six space elevators are located around the globe and are locked in space by an orbital ring structure. Every episode in the series deals with the space elevators. In the 2002 series, “Kiddy Grade”, a space elevator is used on every planet to transport people and materials.

An earlier anime science fiction television series from 1983 is “Super Dimension Century Orguss" set in 2065 where two superpowers clash over a space elevator which is in line to be destroyed by a new type of weapon.

More recent (2007) is “Mobile Suit Gundam 00”, an anime television series set in 2037, where all the superpowers have a space elevator (Permanent Orbital Station) of their own, linked to a Solar Power Satellite array used to harness solar energy for their use. Each elevator has two orbital stations: the lower orbital station functions as a spaceport and tourist attraction while the high orbital station houses the elevator's control facilities and provides physical access to the solar array. The partial destruction of the Africa elevator in the second season reveals that the elevators have ablative armor plates for protection against debris; purging these plates require the technical crew to jettison the counterweight at the orbital end in order to avoid the now-unbalanced elevator's complete destruction. They play a critical plot role in power balance and maintaining spheres of influence by denying electricity to rogue states.

While there are many novels that mention some form of space elevator, there are not so many films or television series (other than anime) that have yet covered the concept in any detail. The Wikipedia entry on Space Elevators in Fiction mentioned above lists a few.

“Mystery Science Theater 3000”, often abbreviated MST3K, is an American cult television comedy series which ran from 1988 to 1999. In one episode mad scientist Dr Clayton Forrester attaches a tether to the Satellite of Love (SOL) called the ‘Umbilicus’, turning the SOL into a space elevator. In subsequent episodes, experiments would be sent up the umbilicus for the show's weekly ‘Invention exchange’ skit. This tether is cut in the Season 7 finale, causing the satellite to drift off into deep space.

“The Great Space Elevator” was a new Dr Who adventure with the Second Doctor, as told by his companion Victoria Waterfield. Written by Johnathan Morris, it was the second story of Season 3 and released in August 2008 in the Companion Chronicles audio range by Big Finish. The synopsis tells that the Great Space Elevator is a marvel of human engineering; a transit tube stretching from the equator up to a space station held in geosynchronous orbit. When the TARDIS lands in Sumatra in the future, the Second Doctor, Jamie and Victoria are captured by guards just as the station loses power. Together with Security Officer Tara Kerley, the three travellers take a one-way trip on the elevator to fix the problem, and find themselves confronted by a powerful alien force that threatens to wreak chaos on Earth (http://www.drwhoguide.com/chronicles10.htm)

"Payload" is a short film about scavengers set in a space elevator town. Written and directed by Stuart Willis, and produced by Tom Bicknell in 2011, the world of Payload drew its inspiration from two very real places: the isolated Australian mining town of Kalgoorlie – full of men and brothels; and the Kazakhstan space launch facility town of Baikonur – where the locals scavenge the fallen refuse from a nearby Russian spaceport. It was important, however, that Clarke's Town (the setting of Payload) not be an allegory for either town but become its own imagined place. Clarke's Town is defined only by its function as a spaceport, it is isolated, weathered and indifferent (http://www.payloadfilm.com).

A team of filmmakers who love science and science fiction were inspired to share the story of the space elevator after learning that a group of scientists were working to make it a reality. For the past several years, the Going Up! Films team has been following the space elevator community as they pursue a seemingly impossible vision. From attending various scientific gatherings, to covering NASA's high-stakes Space Elevator Games, they got to know the major players and watch their successes and struggles, both personal and professional. The result of their efforts is "Sky Line: The Space Elevator Documentary", finished in early 2015, that covers where the idea of a space elevator came from, how it will work, and what it is like for people to work on the project (https://www.kickstarter.com/projects/1704207196/sky-line-the-space- elevator-documentary - see also http://spaceelevator.net and http://www.smithsonianmag.com/innovation/people-are-still-trying-build-space-elevator-180957877/).

Another film is "Shoot the Moon" - a story of sacrifice and a space elevator, directed by Benjamin Harrison. The film, originally due in 2015, is really about Michael Laine of LiftPort and his path over the past fourteen years towards building a space elevator. The film is supposed to feature vintage sci-fi effects depicting a trip from the Earth to the Moon on a lunar space elevator and shot with miniatures (http://www.shootthemoon.io). There is also another video from November 2016 entitled LiftPort Lunar Space Elevator Infrastructure Final from GCU at https://www.youtube.com/watch?v=fSzo6mY3LAA.

There are also a number of short films or rather videos on the space elevator concept available. Among those on YouTube are "The Space Elevator Why" movie - a three minute explanation as to why we want to build a "Space Elevator" by Alan Chan and the Space Elevator Visualization Group (https://www.youtube.com/watch?v=_eldlKDso9o). The "Space Elevator How" movie is a two minute introduction to what the space elevator is (https://www.youtube.com/watch?v=yP9yJHryNGk).

First shown on the This is Genius channel there is a short clip entitled "Space Elevators - Coming to You in 2025" - it is based on the recent IAA study report on the space elevator, *Space Elevators: An Assessment of the Technological Feasibility and the Way Forward* (Swan, Raitt *et al*, 2013) (https://www.youtube.com/watch?v=fkfYEJf8ieQ). More details on the space elevator are given in the short video on the same channel called Five Strangest Ways to Get into Space. Both these videos are voiced by Sam Datta-Paulin and have good imagery. The LipTV channel has a short news clip with Lissette Padilla and Gabriel Mizrahi in which they discuss the development of the space elevator following the announcement by the Japanese company Obayashi that they will have a space elevator constructed by 2050 due to the advances in carbon nanotubes. The elevator will reach 96,000km into space and will transport people and cargo to a new space station https://www.youtube.com/watch?v=33guUBZFxYQ. And in yet another video Markus Landgraf explains how to get to space via elevator. The twenty minute talk was presented at TedxRheinMain (https://www.youtube.com/watch?v=f8CpnKBnPC0). A space elevator tower can be viewed at https://www.youtube.com/watch?v=_ITW13KUWLI

YouTube does in fact have many other clips on space elevators, some featuring nice artwork, for example: https://www.youtube.com/watch?v=YdhM9MYcZeE. There is also a good, voiced, animated one, possibly aimed at younger viewers, with useful, simple to understand explanations and examples of the components, how it will work, dangers and so on. The "Space Elevator - Science Fiction or the Future of Mankind" by Kurzgesagt can be found at https://www.youtube.com/watch?v=qPQQwqGWktE. And also to be viewed for its detail is a nice video from 2012 set in the Galapagos entitled "Leaving the planet by space elevator" by Erdem Tuzun at https://vimeo.com/61671533.

There are, in addition, a number of games which also feature a space elevator. Sid Meier's Alpha Centauri strategy computer game, for instance, allows players to build a secret project called the Space Elevator. A number of artists have also depicted a space elevator in their work. Some have been captured in the Space Elevator Blog at http://www.spaceelevatorblog.com/?p=1894.

3.5 The Space Elevator as an Architectural Project

Architecture is also considered to be a form of art - the practice of carefully designing and constructing buildings and other structures. It is not for nothing that we refer to the baseline architecture of space elevators. Tom Phillips considers himself as an innovative, boundary pushing architect. That this is evident is apparent in his Master of Arts (MA) Architecture thesis submitted at the University of Greenwich in London which achieved Distinction and was nominated for the silver medal of the Royal Institute of British Architects. His proposal was said to have been strategically designed to combine the technicalities required with an architectural flare, a design that encompasses both function and form and intrinsically approaches the logistics through to the realization and design. The title of his thesis was *132,000,000:1 A Technological and Cultural Analysis of the Space Elevator* and it was published on the web in two parts on 30 August 2016. Part 2 focuses on the comparisons of fiction, science and his personal design project - *The London Space Elevator*.

Echoing similar sentiments to others, Phillips (2016) recognized that the realization of the space elevator concept would completely transform the ease and costs associated with satellite positioning, space exploration and intended future missions to Mars and beyond. Space tourism would become a reality and the construction of a space elevator is a critical requirement in mankind's future exploration. The focus of his architectural project for his proposed London Space Elevator is the Base Station and the logistics, zoning, design and integration of specific elements. The space elevator itself would be mobile, with its base acting as a large, maneuverable ship-like form that could dock into the permanent platform off the coast of Shoeburyness, in the Thames Estuary. This permanent docking platform would act as a large conglomeration of vital zones and would form an architectural exposition.

Phillips believes that the London Space Elevator, based in the river Thames estuary, brings science fiction to life by means of providing an efficient, intuitive and sustainable transport line to space. The two part base station with its detachable mobile element combines ground breaking technology with innovative design while conforming to an intrinsically considered series of functions and zones. With the current progression in technology, coupled with the need and benefit analysis of the space elevator project, its realization is imminent. That someone should choose to base his Master's dissertation on the design and operation of a space elevator is truly amazing. Phillips has made an excellent, detailed video of the London Space Elevator and its architecture, covering all the main issues, which can be viewed at https://www.youtube.com/watch?v=9tTe435YWCo.

3.6 2nd Clarke-Bradbury SF Competition

As evidenced above, science fiction literature, artwork and films are full of descriptions of space technologies and systems - often just pure imagination, sometimes based on some semblance of fact. Early science fiction authors, artists and illustrators described space concepts and spacecraft based on the limited scientific knowledge available at the time, whereas more modern writers generally portray the same basic systems as used in real-life spaceflight in their literature and art, even though artistic license is often employed. It still gives them the opportunity, however, to promote their ideas, which may not otherwise be possible through more formal scientific evaluation processes.

This idea that perhaps science fiction literature contained innovative technological ideas that could possibly be brought to the point of development with either today's technology or technology that was just around the corner was the driving force behind a European Space Agency study in 2001, conceived by Dr David Raitt, entitled Innovative Technologies from Science Fiction for Space Applications (ITSF).

The main objectives of the study were to review the past and present science fiction literature, artwork and films in order to identify and assess innovative technologies and concepts described therein which could possibly be developed further for space applications. In addition, it was hoped to garner imaginative ideas, potentially viable for long-term development by the European space sector, which could help in predicting the course of future space technologies and their impact (Raitt *et al*, 2001).

There was the possibility that older, overlooked, ideas might be now feasible with today's huge advances in space and other technologies and materials that were simply not available at the time when many science fiction works were being written in the 1920-50s. The enormous public interest in the ITSF study led not only to Raitt publishing two books (ESA publications) on the topic and organizing related technology events and exhibitions, but also stimulating a number of follow-on activities including a science fiction essay competition named in honor (and endorsed by them) of two great science fiction writers - Arthur C. Clarke and Ray Bradbury.

The 1st Clarke-Bradbury International Science Fiction Essay Competition, conceived by Dr David Raitt and launched in 2003 by ESA's Technology Transfer and Promotion Office (TTPO) and organized on ESA's behalf by the Maison d'Ailleurs, the OURS Foundation and MoonFront, was seen as a way to involve young people in thinking about space and becoming more interested in science and technology in general and in space activities in particular (Raitt *et al*, 2003). The main aims of the competition were to promote innovative ideas for future space technologies; recognize and pursue viable space technologies found in science fiction; provide a link between young writers and the space community; encourage young people to read and write science fiction; and share the ingenuity and creativity of young minds with the general public. Some 120 stories were submitted from 36 different countries and a number were selected for publication in a special book edited by Raitt and published by the European Space Agency.

Based on the success of the 1st Clarke-Bradbury SF Competition, Raitt decided to organize a second competition. Unlike the previous one, the second had a specific theme, was open to all ages, and encouraged images to be submitted as well as stories. The theme chosen was that of the space elevator which was one of the concepts identified and discussed in the ESA ITSF study as a potential innovative space launch capability and which had seized the imagination of scientists and science fiction writers in the past and was being transformed into reality today.

The 2nd Clarke-Bradbury Science Fiction Competition, announced in late 2004 and with a closing date of February 2005, had two categories - SF story and SF artwork – both of which had to relate to a space elevator and incorporate technologies and applications in some way. For example, imaginative use of a space elevator as a cheap means of access to space for launching oversize or fragile objects to distant planets, or for space tourism, or space exploration or terra-forming. Potential entrants were informed that their entries would be assessed in accordance with the following criteria: technology, imagination, structure, skills and visualization (Raitt, 2005). Dr Raitt invited Dr Brad Edwards to be involved in evaluating the entries and he indicated that he would like to present prizes to the eventual winners and be permitted to publish the resulting book of selected stories himself.

Altogether a total of 109 stories and images about space elevators were submitted from 29 different countries – a little under half being sent in from the USA. All the entries were evaluated by an international jury (which included Brad Edwards, David Raitt and Pete Swan) who eventually selected a Winner and Runner-up in each of the two categories. It appeared that most of the entrants were familiar with the space elevator - although a number of authors found themselves confined by the focus on technology, and many wrote lightly fictionalized descriptions of journeys up an elevator with no real thought of the problems, others though were really imaginative and thoughtful.

The entries threw up some very inspired names for their space elevator: ‘Finger of Allah’, ‘Big Bamboo’, ‘Silk Road’, ‘Archimedes' Lever’, ‘Big Rail’, ‘Rapunzel’, ‘Wick’ and simply ‘Beanstalk’. The climbers and elevator cars were often named after famous mountaineers. There were also some innovative uses – including using the elevator for sky diving and regattas – though none of the stories concentrated on taking real scientific payloads or freight up for release. A number of the stories focused on a breakdown and subsequent repair of the elevator, others used it as a rescue mechanism or to escape an overcrowded planet, and several concentrated solely on the ride itself, and more than a few of the stories concentrated on disasters which might befall it and several even saw it destroyed. There was also quite a lot of religious overtones in the stories. Almost all entrants who mentioned the facts also took the length to be 100,000km and the material to be carbon nanotubes – though the space elevators were located in very diverse places throughout the world including Africa, Canada, Brazil, Indonesia, Russia.

Just like the early science fiction writers who were constrained by the actual science and technology of the time, unlike today’s writers who have the benefit of sixty-odd years of spaceflight under their belts, so the Competition authors, having no actual operational space elevator to draw on, could only extrapolate from their own experience with real Otis-type elevators – so the inside and function of the space elevators in their stories was more like the lift in a department store or skyscraper – very little time taken to travel up or down and no spacesuit required!

Regarding the winning entries, the jury looked for stories and images which created a sense of drama or difference; and ultimately chosen by the organizers as winner in the story category was “Clever” by Christian Doan, a writer and artist living and working in Melbourne, Australia. The tale is about nanites – tiny alchemists able to construct anything from raw material. Injected into the body, protected by the saline, they could be carried anywhere – including up a space elevator – but when they escaped in a bead of sweat and the saline solution evaporated then they were free to do their work! This story was chosen because of the quality of writing, the technology idea behind the story and the thriller feel to the text. It was a convincing future technology and a fluently-written suspense story with a subtle, unstated twist at the end. The use of viewpoint was interesting and the way the scenario established itself rather than being just described was refreshing. The story was also short and stood on its own with no need for further explanation.

The winner of the image category was Frank Lewecke from Nuernberg, Germany for his image entitled "Africa Tower - the African Space Elevator". The artist was directly born into the space generation, growing up in times when men walked on the moon and this is reflected in his art work. Appropriately, the artist was inspired by Arthur C. Clarke's novel *3001: The Final Odyssey* and the science fiction concept of an elevator into space is combined with detailed and realistic painting to produce a powerful, captivating translation on canvas.

The runner-up in the story category was Scott Rolsen from Denver, USA for his work entitled "Ervin's Watch". This was a story of opposites – female soldier and monk; different times and places – where a long forgotten elevator is used to return to Earth. The writer skilfully managed to give an idea of the length of time that passes on the trip in his tale.

The runner-up in the image category was Richard Bizley, an artist from Lyme Regis in England, for his image entitled "Rising at Dusk". The painting depicts an elevator car (named 'Clarke Clipper') travelling upwards as the sun is setting. This setting sun is casting a long shadow of the elevator ribbon on the clouds which show the immense length of the structure.

Altogether, 35 of the stories plus three images (including both category winners and runners-up) were published in *Running the Line - Stories of the Space Elevator*, edited by Brad Edwards and David Raitt and published with Lulu in 2006. (Edwards and Raitt, 2006). The winning stories and artwork are also included on the website created for the competition at http://www.itsf.org (regrettably this site is no longer maintained, but can be accessed through the WayBack Machine at archive.org).

3.7 Conclusion

The intention of this chapter was to provide an overview of the space elevator in a historical setting and as a science fiction concept and to show how it has evolved from science fiction to technology fact. The chapter has thus given a brief overview of the history of the space elevators and its portrayal in novels, films and works of art. It has also described an international competition, in which a space elevator was the theme, which was an outcome of a remarkable study on Innovative Technologies from Science Fiction for Space Applications. The chapter gives some commentary on how the science fiction approaches for constructing the space elevator, particularly the cable, were not considered practical and how the discovery of carbon nanotubes seemed to be the material of choice. This discovery brought the minds of many more scientists and engineers to bear in the space elevator camp. Besides enabling people to contribute imaginative and creative ideas and well-thought out stories, the genre of science fiction novels, films and videos, as well as competitions and games focusing on the space elevator, are fostering a greater interest by young people in science and technology in general and space activities in particular. It is to be hoped that the curiosity thus engendered in the concept of space elevators will stimulate further interest and investment.

As shown above, there are many different types of media that offer fresh perspectives on space elevators - even if they are simply fiction. And what better way to end this chapter than to mention one fictitious offering that looks further ahead than most - a light-hearted talk by John Knapman and Peter Robinson given on 25 January 2017 at the British Interplanetary Society headquarters in London. Their presentation was entitled ‘Space Elevator History: 2017-2057’ and after providing a quick overview of space elevator history to date, they launched, tongue-in-cheek, into giving what they considered to be the milestones in space elevator development and operations at five-yearly intervals starting in 2019. Important dates are suggested for technologies, material availability, prize competitions, deployment and operation of lunar and martian elevators, and fully functional Earth elevators. Time will tell whether they have the scenarios correct!

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Chapter 4: NASA and NIAC Funding for Space Elevators

4.1 Introduction

In the 1990s NASA was researching a wide variety of breakthrough space transportation concepts to bring down the cost of launch into space and was investing in many technologies, systems and infrastructures with significant development funding. And already in the 1980s it was carrying out applications of tethers in space. But it is interesting to note that the first NASA publication to actually mention a space elevator was a technical report, dated 1 January 1992, on 'The First Mission of the Tethered Satellite System." The 'Further Reading' section in the report lists Arthur C. Clarke's 1981 paper "The Space Elevator; 'Thought Experiment,' or Key to the Universe?" The section also lists Pearson's work on "The Orbital Tower", Artsutanov's "Into Space Without Rockets" and Moravec's "Skyhook" (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920024495.pdf).

It is probably fair to say, however, that the modern era of space elevator development was initiated by David Smitherman of NASA after he had read an article on Fullerene nanotubes appearing in *American Scientist* in 1997, which noted Arthur C. Clarke's description in *Fountains of Paradise* and a strength requirement for the cable of 63GPa (gigapascal), and indicated that Fullerene cables for a space elevator might be possible some day (Yakobson and Smalley, 1997). Smitherman was working in space transportation planning at the time and realized that if the promise of carbon nanotubes came about there would be tremendous potential for space tethers and space elevators. His proposal to NASA for a workshop on the subject led to an engineering analysis looking at a 'big government' approach with tremendous amounts of development and large funding ending with a design that was not feasible in the foreseeable future. However, this initial step was remarkably critical as the new millennium approached. The workshop was attended by several people who were enamored with the concept of space elevators and wanted to take it to the next level with the belief that it could be accomplished in a reasonable time with an affordable budget.

This chapter shows the modern day space elevator gestation with the NASA workshop organized by David Smitherman in 1999 and then the two Brad Edwards studies for the NASA Institute for Advanced Concepts (NIAC) from 2000-2003. These studies resulted in a "doable" design for reasonable funding with the reliance on a new material discovered 12 years previously and then under development. In addition, further ideas are presented, briefly, about other space elevators, including those for the Moon and Mars.

4.2 Advanced Space Infrastructure Workshop

The modern space elevator began with a workshop orchestrated by David Smitherman at the NASA Marshall Space Flight Center in Huntsville, Alabama from 8-10 June 1999. From this 'Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether Space Elevator Concepts' came one of the first major space elevator documents, based on its findings. Subsequent consultation and review of the document with the thirty or so participants of the workshop (who included such people as John Mankins (NASA HQ), Joe Carroll (Tether Applications), Bob Cassanova (NIAC), Geoffrey Landis (NASA Glenn), Jerome Pearson (Star Technology and Research, Inc.), Paul Penzo (Jet Propulsion Lab), Enrico Lorenzini (Smithsonian Astrophysical Observatory), Richard Smalley (Rice University) and others) was made prior to publication to clarify technical data and ensure overall consensus on the content of this NASA conference publication (Smitherman, 2000).

The overall conclusion from the workshop was that in the latter part of the 21st century, the space elevator concept could become a reality and offer cheap transportation to geostationary orbit, dramatically lowering the cost of getting into space. A key finding was that materials technology for space elevators was already in the development process, and continued work was likely to produce high-strength carbon nanotube material. The document also pointed out that, although the tallest current structure at the time was 629m tall, buildings or towers could be constructed that were many kilometers tall using current construction materials and methods, but there just had not been a demonstrated need. With new materials and methods, however, it would become possible to construct towers tens, hundreds, or even thousands of kilometers in height. The workshop concluded that the most efficient and technically feasible method for space elevator construction appeared to be a tether hanging from geostationary Earth orbit (GEO) connected to a tall tower constructed up from the Earth. Equatorial locations were desired for the ground anchor point of such a space elevator. The workshop also made the point that climate conditions at the equator were mild since the Coriolis force vanishes and thus strong winds were not physically possible. Another important finding was that the space elevator would be flexible enough over its length that it could be designed to avoid major hazards. Minor hits from meteoroids were inevitable and would require standard repair procedures. A simple analogy was to think of the space elevator structure as a 36,000km-long highway that would require ongoing maintenance and repair.

A baseline concept for a space elevator was created during the workshop to illustrate its purpose, scale, and complexity. This baseline plan was to capture a carbonaceous chondrite asteroid and move it into a stable orbit around the Earth, then mine it for the necessary material to make a cable reaching down to the Earth. In addition to the obvious benefit of cheaper access to space, the work provided several other incentives. Using materials from near-Earth asteroids would help to depopulate these potential threats to Earth. A space elevator extending beyond GEO (toward the ballast mass) would provide escape velocity for propellant-free transfer orbits to the Moon, Mars and other planets. A manufacturing complex built at GEO could be used for metal fabrication in orbit, reducing the amount of pollution on Earth. A space elevator would simplify the construction of massive solar-powered systems in orbit that could carry power to Earth, thus overcoming problems of large-scale power production in the biosphere, ending strip mining for coal, reducing power plant emissions, reducing greenhouse gas production, and likely having a positive impact on global warming concerns. The space elevator would be environmentally friendlier than burning the amount of rocket fuel in the atmosphere needed to lift the same tonnage. A space elevator was believed likely the only feasible way to build large space-based cities and colonies for continued expansion into space. And GEO was a good location for massive space cities, so as to minimize collision probabilities with other spacecraft.

The conference publication from the workshop was very comprehensive, covering not only the key findings, but also future directions and technology demonstrators. It discussed space elevator concepts, history and basics; noted technology development paths in materials, tension and compression structures, propulsion and supporting infrastructure; and issues such as environmental and safety. The document also briefly summarized lunar and martian space elevator concepts. The conclusions and recommendations included a good overview of pros and cons for building a space elevator, and concerns and possible solutions.

Shortly after Smitherman published the results from his workshop, NASA prepared a news item based on the publication and an interview with him. Written by Steve Price, the news item, published on 6 September 2000, suggested that NASA scientists were seriously considering space elevators as a mass-transit system for the next century. The opening lines of the article welcomed people aboard NASA's Millennium-Two Space Elevator which had a first stop at the lunar-level platform before continuing on to the New Frontier Space Colony development. The entire ride would take about five hours. The news item then went into Smitherman's plans that could turn such an elevator from science fiction (as envisioned by Arthur C. Clarke) to reality in 50 years or so. The article notes briefly the work by Tsiolkovsky, Artsutanov, Pearson and others and then discusses the five primary technological thrusts that Smitherman thought were critical to the development of the elevator. These were: the development of high-strength materials for both the cables (tethers) and the tower; the continuation of tether technology development to gain experience in the deployment and control of such long structures in space; the introduction of lightweight, composite structural materials to the general construction industry for the development of taller towers and buildings; the development of high-speed, electromagnetic propulsion for mass-transportation systems, launch systems, launch assist systems and high-velocity launch rails; and the development of transportation, utility and facility infrastructures to support space construction and industrial development from Earth out to GEO (Price, 2000).

4.3 NASA's Innovative Approach - NIAC Studies

The NASA Institute for Advanced Concepts (NIAC), an independent entity funded by NASA and operated by the Universities Space Research Association (USRA), was formed in 1998 for the explicit purpose of functioning as an independent source of revolutionary aeronautical and space concepts that could dramatically impact how NASA developed and conducted its missions. The entity was discontinued in 2007, but later resurfaced as the NASA Innovative Advanced Concepts Program, thus keeping the same acronym. Like the old NIAC, the new NIAC nurtures visionary ideas that could transform future NASA missions with the creation of breakthroughs - radically better or entirely new aerospace concepts - while engaging America's innovators and entrepreneurs as partners in the journey.

Dr Bradley Edwards was not satisfied with the end result that emanated from David Smitherman's 1999 workshop, nor with other concepts that had been put forward for space elevators. He believed that he could design a less robust space elevator that could be built within 15 years with current technologies, with the caveat that he must wait for carbon nanotube development. This belief drove him to apply for, and win, NIAC study funding to advance his developing concepts. The NIAC support allowed him and his small team to explore the arena and propose a space elevator infrastructure that would work in the near future.

In his NIAC Phase I and Phase II studies, Edwards (2000, 2003) spelled out an approach to his space elevator using a 100,000km paper-thin ribbon made of carbon nanotubes (CNT). This vision included an initial spacecraft, ribbon production unit, climbers, power beaming facility, anchor platform, debris tracking system and the CNT ribbon stretching up into space which would stand a greater chance of surviving impacts by meteors. Climbers would travel up the ribbon to release payloads into orbit at various points. Edwards expected that this international development would have a tremendous impact upon society and industry within the next 20 or 30 years when the space elevator was completed and launch-to-orbit costs were reduced to around an anticipated $100/kg.

Edwards' work encompassed all of the engineering and scientific aspects - which will be covered more extensively in the next chapter. This is essentially the material included in his 2003 book, co-authored with Eric Westling, but the important point to note is that Edwards presented a revolutionary change in approach. The earlier Smitherman workshop expected a much longer development schedule, including 20 to 30 years to develop the necessary ribbon materials. Now, Edwards was suggesting that CNTs, discovered in 1991, were already available and thus an operational space elevator could be developed in this same timeframe. So, when Edwards released his book, this leapfrogged beyond NASA and NIAC and took his case into the public domain. There were conferences, follow-up meetings, papers and presentations. There was mainstream media coverage - newspapers, journals, TV shows, even late-night talk shows. He created an industry - low-cost access to space - a space elevator infrastructure that could work. He brought this concept to the public in a manner well beyond what NASA could have done alone.

Brad Edwards showed how a space elevator offered the opportunity to break free of our complete dependence on rockets to get into space. By positioning the anchor in the ocean off the coast of Ecuador, weather and environmental hazards, as well as construction costs, could be reduced. CNT research and development efforts were progressing and plans were presented for construction of a first space elevator at an estimated cost of less than $10bn. No other advanced propulsion systems being examined by NASA could or can provide the high-volume, low-cost transportation system required for future space activities that mankind can imagine. A space elevator, a cable stretching between Earth and space, is unlike any other transportation system for getting into space. Edwards' NIAC Phase I report provided the technical groundwork, but was not able to test many of the proposed designs and scenarios. Even Edwards admitted surprise at the apparent feasibility of the space elevator, the availability of nearly all of the necessary technology, and the affordability of the first elevator.

His NIAC Phase II study offered a critical next step. It started to answer many of the remaining questions, give direction for future research and spell out crucial future funding and programmatic decisions. Research began towards the construction of cable segments from carbon nanotube composites, and testing their general characteristics, such as resistance to meteor and atomic oxygen damage. Critical aspects of the space elevator design were further expanded, such as the anchor and power beaming systems, cable production, environmental impact, the budget and the major design trade-offs. Both Phase I and Phase II results were then introduced into the NASA mainstream effort through a conference and publication – and then the release of a self-funded book (Edwards and Westling, 2003).

4.4 NIAC Studies: Lunar Elevators

The idea of a lunar space elevator idea was introduced in a 1979 paper by Jerome Pearson. This was an extension of the classical space elevator idea, using the Earth-Moon Lagrangian points as balance points instead of the stationary orbit around a single body. The concept of a lunar anchored satellite offered the promise of bringing lunar materials into high Earth orbit, much more cheaply than with rockets (Pearson, 1979). As a side note, Yuri Artsutanov (1979) published a paper on a lunar space elevator about a month later, without either author being aware of the other!

With a NIAC grant, Pearson and colleagues released a Phase I final technical report in 2005 (Pearson, 2005). The lunar space elevator was proposed as a revolutionary way to facilitate development of cislunar space. The lunar space elevator used solar-powered robotic climbing vehicles to bring lunar resources from the lunar surface to the L1 Lagrangian point, where spaceships would transfer the lunar material into high Earth orbit. The lunar space elevator would thus serve as a highway linking Earth orbit and the Moon, bringing lunar products to Earth orbit, and carrying supplies from Earth orbit to lunar bases. There would be surface tramways connecting the elevator ribbon with lunar mineral deposits and with ice deposits in craters near the pole. Solar-powered robotic vehicles would carry minerals and propellants along the tramway and up the ribbon to beyond the L1 balance point. At this point, the payloads would be released into Earth orbit and used for construction of space complexes and for propellant depots for spacecraft leaving Earth orbit. The report envisioned an initial lunar space elevator using existing high-strength composites with a lifting capacity of 204kg at the base. With solar-powered capsules moving at 100km/hour, this configuration could lift 584,000kg/yr of lunar material into high Earth orbit. With rocket launch costs estimated at about $1,000/kg, this system would be worth more than half a billion dollars per year. These greatly reduced costs were believed to create a new paradigm for space development.

The report indicated some key enabling technologies. One was the use of advanced composites with better strength/density values. Key cost savings could be provided by use of lunar materials. Another key technology was the use of robotic construction on the lunar surface, again with additional reduction in construction costs if indigenous lunar materials were used. Another challenge would be mastering the dynamics and control of the lunar space elevator structure. The length of the lunar space elevator would exceed even the expected length of the Earth space elevator and this greater length presented some dynamical issues. The structure would have very low frequency modes of vibration with low natural damping, and thus be prone to forced excitations. There would also be forced oscillations induced by the libration and orbit eccentricity of the Moon, and even from gravitational effects of the Sun. Motion and release of the climbers would also induce oscillations, as well as the capture and release of payloads traveling between the top of the tower and high Earth orbit. The report noted that these natural frequencies and mode shapes had to be analyzed and thoroughly understood. Active damping control would be needed to augment the natural damping of the space elevator ribbon. And a final key technology was that the lunar space elevator and its components must be autonomous, minimizing the need for human operation or intervention.

The proposed lunar space elevator would provide a new way to create a lunar base for robotic and human operations on the surface. It would revolutionize the way to operate in cislunar space, and would allow for development of the Moon and the use of its resources for advanced space development. It would provide lunar materials to Earth orbit at substantially lower cost than launching from the Earth, providing a virtually unlimited supply of construction material in Earth orbit. It would pave the way for continuous supplying of lunar installations, creating a new paradigm for robotic construction and development on the Moon. Pearson's Phase I results show the feasibility of the lunar space elevator, in that it could be constructed with available materials, technological advances commensurate with current plans for return to the Moon, and fitting into the timeframe of the NASA Moon-Mars initiative. It would provide lunar material for constructing large solar power satellites and shielded habitats in Earth orbit. Using lunar polar ices, the lunar space elevator could provide large quantities of propellant in Earth orbit for use by vehicles bound for the Moon or Mars. And it would provide a low-cost means for transporting the infrastructure components from Earth orbit to the lunar surface. (It can perhaps be mentioned that Pearson has recently (2017) submitted another proposal to NIAC for a lunar space elevator.)

Even earlier than Pearson though, from November 1998 to 30 April 1999, Robert P. Hoyt of Tethers Unlimited, Inc carried out a Phase I study funded by NIAC into a "Cislunar Tether Transport System". This was followed up by a further NIAC Phase II study from August 1999 to July 2001 into "MMOST - Moon and Mars Orbiting Spinning Tether Transport". The Phase I effort developed a design for a cislunar tether transport system that used one tether in elliptical, equatorial Earth orbit and one tether in low lunar orbit. Numerical modeling verified that this system could provide round-trip travel between LEO and the surface of the Moon with near-zero propellant requirements. Using currently available tether materials, such a system would require a total mass of less than 28 times the mass of the payloads it could handle. Because a rocket-based system would require a propellant mass of at least 16 times the payload mass to perform the same job, the fully-reusable tether system would be competitive from a perspective after only two trips, and would provide large cost savings for frequent round-trip travel. The Phase I effort also developed a conceptual design for a tether system for rapid Earth-Mars travels. In the Phase II effort, these system designs were combined and improved to develop a tether transportation architecture could provide low-cost transport to the Moon, Mars, and elsewhere in the solar system (Hoyt, 2001).

4.5 NIAC Studies: Martian Elevators

Although NIAC does not appear to have actually funded studies for martian elevators *per se*, there are a couple of NIAC studies that do discuss the concept, including the Phase 1 and Phase II studies by Hoyt (see above), the six-month study (Phase I) conducted by Brad Edwards in 2000, and also his Phase II study conducted from 2001-2003. In the manuscript report for Phase I, Edwards noted that an additional aspect of a space elevator was that it could be used as a sling to launch payloads to more distant destinations. A cable length of 91,000km would allow access to Mars (as well as Venus and Jupiter). Edwards provided a possible scenario for deploying a martian elevator - the Mars cable could be produced in Earth orbit alongside an Earth elevator and then released as a single unit on a trajectory to Mars. This would permit a 20,000kg capacity Earth cable to be used to build and launch a 100,000kg (or larger) Mars elevator. The Mars elevator would have a different taper profile and would not have to concern itself with lightning or man-made space debris. However, studies would have to be done to address possible Mars specific problems such as dust storms and the avoidance of Mars' moons (Edwards, 2000).

In his Phase II study, Edwards noted again that he had also considered elevator applications beyond Earth orbit (Edwards, 2003). Initial calculations showed both common perceptions (a Mars elevator would require a small cable, and the Moon a large one due to rotation rates) as well as other interesting details (asteroids and smaller moons of planets would require the smallest cables and Venus and the Moon would require extremely long cables.) Edwards also expected a solar system exploration and development market to emerge with both unmanned and manned segments, based loosely on Robert Zubrin's 'Mars Direct' scenario, and commencing early after elevator operations begin. The exploration market would include exploratory and mining claims missions to asteroids, Mars, Moon and Venus; in-situ resource production on Mars and the Moon; and large mapping probes for Mars and the asteroids. Edwards also believed that one exciting possibility that would become reasonable with the Earth space elevator would be the colonization of Mars in the near future. To accomplish this would require several fully operational space elevators on Earth and an investment in a martian elevator.

In his report, Edwards stated he had produced an initial Mars elevator design which included: 1) a power beaming system using L'Garde's inflatable solar concentrators, 2) a deployment scenario minimizing the propulsion requirements, 3) an overall system with modules on each end of the ribbon, 4) a self anchoring module on the lower end of the ribbon, 5) a power beaming, propulsion, and capture system at the upper end, and 6) an anchor location on Olympus Mons to avoid both the moons and the dust storms. He also provided an illustration of a martian elevator showing grappling anchor, cable spool and cable, focusing concentrator, solar concentrator, fuel for plane stages and stopping, and station, supplies and counterweight. In his discussion of the media frenzy surrounding his NIAC Phase II effort, he mentioned that he had created several animations showing the deployment of an Earth space elevator as well as a Mars elevator.

4.6 Conclusion

NASA and/or its Institute for Advanced Concepts provided funding for the Smitherman, Edwards, Pearson and Hoyt studies of space elevator (including lunar and martian) concepts. The results demonstrated a practical methodology for constructing space elevators, and advanced material research has improved the prognosis while shortening the forecast for successful establishment of this capability. The Earth space elevator has the most demanding tensile strength requirements for the cable. Also, all low Earth orbit satellites constantly intersect with the equator, so would require active avoidance strategies to avoid collision with the space elevator cable. The lunar space elevator may be more practical in the near-term, as the tensile strength requirements for the cable are substantially lower. Calculations suggest that a lunar space elevator could be constructed with existing composite materials without the need for the super strength provided by carbon nanotubes. A lunar space elevator offers a revolutionary advance in efforts to develop lunar resources and facilitates communication with the lunar far side. The retrieval of Earth-crossing asteroids for use in these endeavors helps support the goal of planetary protection by getting rid of objects that could possibly collide with Earth. The modern space elevator era can be said to have been initiated by NASA. It was kicked off with an exploratory workshop that led to acceptance of a two Phase advanced concept study conducted by Brad Edwards who was convinced that the answer was possible and achievable in a much earlier timeframe. By bringing this idea into the public domain and thus broadening the concept beyond the space community, Edwards encourage others to jump into the fray as will be seen in the next chapter.

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Chapter 5: The Edwards Concept and Carbon Nanotubes

5.1 Introduction

Without a doubt, Dr Bradley Edward's book *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* (co-authored with Eric A. Westling) was a major turning point in the modern history of the development of the space elevators (Edwards and Westling, 2003). This book was based on the work Edwards completed during two studies funded by the NASA Institute for Advanced Concepts (NIAC) - a Phase I study running from May-October 2000, and a follow-up Phase II study running from March 2001-January 2003. The effort was led by Edwards, then at Eureka Scientific, and involved more than 20 institutions and 50 participants at some level. In the Introduction to the book, Edwards comments, "I read a statement that the space elevator couldn't be done, and I set out to find out why.", which speaks to his initial motivation. Essentially, Edwards revolutionized the approach to a space elevator by showing that it could be done in the near term, that it was affordable, that it could be powered by lasers from the ground, that its optimum location was the equatorial Pacific, and that hazards could be overcome. He went further to opine that not only should we do it, but we should start now!

This chapter provides an overview of the contents of the reports emanating from the two NIAC studies Edwards carried out and explores the background that inspired his first book and what effects it has had on the modern development of space elevators. In addition, since Edwards was mindful of the best material most suitable for the space elevator and turned his attention to carbon nanotubes, the chapter also addresses that topic.

5.2 The 1st NIAC Study

The first step in the development of Dr Edwards' ground-breaking book started in 2000, when he published the results of a six-month study (May-October 2000) financed by NIAC into the feasibility of a space elevator. Titled simply *The Space Elevator*, this NIAC study report contained the results of his investigation into all aspects of the design, construction, deployment and operation of a space elevator. As Edwards (2000) noted in the Preface to the report the study was far from simple and his manuscript covered only the technical aspects of building a space elevator, with no political aspects being considered. The first of the 14 chapters in the report discussed what a space elevator was (mentioning the earliest people who conceptualized it in their writings whether scientific or science fiction such as Artsutanov, Clarke, Isaacs, Pearson and others), why we would want to build one, and what was the bottom line. The other chapters discussed the cable design and production (including carbon nanotube development); spacecraft and climber designs; power beaming; deployment of the initial cable; the anchor location; the destinations (including Mars); safety factors; design options; the many different environmental challenges to be faced; budget estimates; schedule; and future work. The report was copiously illustrated with tables and figures, and contained a lengthy list of references.

The study report lists the strongest available materials, prior to 1991, as being candidates for building a space elevator (steel, kevlar, carbon whiskers, spider webs). But Edwards contended that the discovery of carbon nanotubes in 1991 by Sumio Iijima in Japan changed the entire game for possibilities for the space elevator. Edwards posited a way to construct the space elevator using carbon nanotubes, by starting with the smallest possible elevator 'string' extending from geosynchronous orbit down to the Earth, and then repeatedly building up the string larger and larger to get to the desired size and capacity. This was a previously unheard of approach to the construction of a space elevator, and is the construction method that all serious parties are currently planning to use. Edwards coined the term 'climber' for the physical machine that will move up and down the string (now called a ribbon), adding to the ribbon, moving cargo up and down, and performing any necessary maintenance. The concept of 'power beaming' is also introduced as a way to give power to the climbers to make their ascent. Edwards catalogs all the different destructive influences that the space elevator ribbon will be subject to by the nature of its path from the Earth to geosynchronous orbit. But he notes that all of those destructive influences appear to have reasonable solutions and none are show stoppers. Edwards also introduces the notion of the ribbon being curved (not flat) and an ideal location for the Earth base station - off the coast of Ecuador. At the end of his summary of the space elevator concept, Edwards added that during the study they did not find one killer problem that made the design impossible. This is an astounding statement for a concept thought to be solely in the realm of science fiction.

After this introduction, Edwards discusses the many different reasons why we should build a space elevator. He suggests that the space elevator could be the catalyst for cascading progress in many different parts of society. One of the primary and easiest to understand reasons is to drastically reduce the cost and risk of getting things into space (reduction of 50% to 99%), and the resulting new space industries (like space-based solar power and tourism) that would be created. The initial estimate for the cost of the space elevator was put at $40bn. Edwards thought it might be hard to grasp the magnitude of impact the space elevator would have on society, but he hoped it would be clear from his discourse that it would dramatically advance society both immediately and in the distant future.

In chapter 2, before talking about the structure and design of the cable, Edwards provides a detailed discussion of the current state of carbon nanotubes, and what the current research has created, before moving on to more detailed design proposals of what the ribbon would look like, and how the design would handle partial failures of the ribbon material. In the next chapter of the report, the design of the initial spacecraft used to deploy the first ribbon is discussed in detail, along with a table of projected mass of the various components. Also in this section, the climber design and function (along with a mass table) is explained for all the jobs it must perform. In chapter 4, the design of the power beaming system, along with some formulas and math for computing efficiencies and determining overall power requirements for lasers as well as microwaves, is covered. The problem of the initial deployment of the ribbon is tackled in chapter 5. This section makes extensive use of physics and mathematical formulas to determine how the ribbon can be deployed from geosynchronous orbit and successfully make it down to Earth in the correct position with the correct orientation. Chapter 6 discusses the Earth-based portion of the system, called the anchor node. Edwards believed that one of the major tradeoffs of the space elevator program, and one of the most critical, would be the location of the anchor. He goes on to describe the desired characteristics of the Earth side of the system, and why an ocean location 1,500km west of the Galapagos islands is likely the best choice. He also proposes the use of a floating platform like Sea Launch as the type of vessel for this purpose.

Chapter 7 of the NIAC Phase I report describes how the design and length of the space elevator ribbon influences what extra-Earth destinations can be targeted. The space elevator could be used as a sling to launch payloads to more distant destinations. In this respect he considers the construction of a Mars space elevator. In Chapter 8, the safety factor for all components, and the pros and cons that have to be considered during system construction are discussed. In the proposed system a standard safety factor of 2 was selected - which implies that the cable theoretically has twice the strength at any point along it. The tradeoff on the safety factor is between the probability of catastrophic damage and what can actually be built. In the design, deployment and use of the space elevator there are various choices that have to be made and each of these has an impact. Chapter 9 contains a high-level table of the different options (modifications from the baseline) and the positive and negative impacts of each. The primary influences on space elevator design come from the environment in which it must survive. In the following chapter, Edwards examines each of the natural challenges (such as lightning, meteors, low-Earth orbit objects, wind, atomic oxygen, electromagnetic fields, radiation damage, induced oscillations, and environmental impact) of the entire project and the possible ways to deal with each of them. Next, is a chapter laying out the budget estimates for each part of the system, with a total projected budget for both the first ribbon and the second one (once the first is completed). A projected realistic schedule for the deployment of a space elevator, based on the proposed design, is outlined in chapter 12, with a number of assumptions present in the time projections. It is emphasized that the schedule is based on the technical aspects of the program only, and assuming sufficient funding is available at the start. Then there is a short chapter which identifies the additional work that needs to be done to move forward with the space elevator project as a whole - it comprises predominantly of a list of follow-on studies in critical areas like nanotube production; small scale cable design; damage to the cable and so on. The final chapter, 14, is simply a short summary of the manuscript (as Edwards termed his report).

5.3 The 2nd NIAC Study

Edwards' second NIAC study documented the initial design for the first space elevator, using current (as of that time) technology. *The Space Elevator Phase II Final Report*, dated 1 March 2003, in combination with the book *The Space Elevator: a Revolutionary Earth-to-Space Transportation System* (Edwards and Westling, 2003) summarized the work done under the NIAC grant to develop a space elevator. The objective of this work, which started in March 2001 and continued until January 2003, was to produce an initial design for a space elevator using current or near-term technology and evaluate the effort yet required prior to construction of the first space elevator. In the Introduction to the report, Edwards stated "What we hope to do in our publications is to put forth a convincing case that we have indeed defined a viable, defendable space elevator design and completely addressed the challenges that its construction and operation will face." His book, co-authored with Eric Westling, contains additional technical information generated by the study that was not included in the final NIAC report.

The proposal Edwards made to NIAC in November 2000 for the Phase II follow-on study listed the primary areas of effort. These were: large-scale nanotube production; cable production; cable design; power beaming system; weather at the anchor site; anchor design; environmental impact; placing payloads in Earth orbit; elevators on other planets; possible tests of system; major design trade-offs; budget estimates; and independent review of program. As work progressed, the detailed plans needed to be modified as is noted in the report. The contents of the final report are thus based on the results and implications of these study areas, but also include other aspects such as organizational and administrative; health issues; ribbon dynamics; legal issues; applications of the space elevator; and dissemination of data. In particular the design studies cover the climber, ribbon infall, the ribbon itself, propulsion, orbital objects, market, cost, checking data, and the Leonid meteor shower.

The first part of the report details the state of the art in carbon nanotube design, production, and testing, using data generated from actual samples of carbon nanotubes. Edwards noted that the raw carbon nanotubes themselves have limited use and they need to be included in a composite to be useful. Based on the research collected for the study, and the projected advances in CNT research, carbon nanotubes with the required 100GPa should be available in 2004. Advances in laser power beaming technology are also discussed, with specifics of a laser design from Lawrence Berkley National Laboratory, using a 15m wide beam director. Several issues related to human health are described, along with some of the testing and studies that have been done to verify no ill-effects of carbon nanotubes in the environment and atmosphere. Edwards and team (which involved more than 20 institutions and 50 participants at some level) were able to secure more complete weather information for the projected anchor site (125 degrees West and 3 degrees South), and the data for wind speed, maximum wave height, and cloudiness are all in reasonable bounds for the anchor site.

In essence, over the three years of the Phase II study, all aspects of the space elevator concept were examined. A completely new design was proposed for a space elevator, which incorporated few characteristics of the earlier designs. The design was broken down into component parts and each was attacked individually. The ribbon was designed to optimize performance and stay within the limits of the materials being developed. The deployment was reduced to conventional large rockets and standard spacecraft hardware. The climbers utilized off-the-shelf technology to achieve a high payload fraction and to enable build-up of the ribbon. The power problems and anchor questions were addressed along with proposed solutions, as were each of the operational challenges. All the results were put into a complete package with scheduling, testing, development and cost estimates. After initially concentrating on the technical aspects and laying out a viable plan for constructing, deploying and operating a space elevator system, Edwards and his team proceeded to fill in the details, clean-up and optimize the design and push into the non-technical areas like legal, health and finance. Although colleagues stated that based on the team's effort an elevator could be operational in 30-50 years, the team's own estimate was that the space elevator could be operational in 15 years for $10bn.

At the end of the report, there is the following statement. "Three years ago [i.e. in 2000] the space elevator was science fiction. Because of NIAC funding the space elevator is now a viable system that is well on its way to becoming reality. The return on the $570k NIAC investment could eventually become trillions of dollars annually and provide an energy-starved world with clean unlimited power, dramatically improved communications, new resources, new worlds to live on and the ability to understand our planet and the solar system around us at a level impossible with conventional rockets."

It is worth observing that James Cline, who proposed a Mooncable to NASA in 1971-72 (see Chapter 10.2.1) made some comments in 2002 on Edwards' original concept which he believed might enable the project to have new features. His Mooncable would have been built up from a small 'seed' tether, much like Edwards' 'crawlers', but he thought the properties of the new tether material (carbon nanotubes) suggested a possible easier construction technique. He provides a fairly detailed summary of his ideas on the tether, complete with calculations (Cline, 2002).

5.4 Material Suitable for the Space Elevator Ribbon

The early writings had worked out the physics of the space elevator and discussed some of the components such as the optimal cable being one of tapered design. But further research on the space elevator concept languished because of a general pessimism that no material in existence was strong enough to build the ribbon which was the core component of the space elevator system. There was clearly a need for the discovery of a suitable material for it. Already in 1966, four American engineers had determined what type of material would be required to build a space elevator, assuming it would be a straight cable with no variations in its cross section. They found that the strength required would be twice that of any existing material including graphite, quartz and diamond (Isaacs *et al*, 1966). Some ten years later, Pearson (1975) opined that the solution might be found in carbon allotropes - namely perfect-crystal whiskers of graphite. Steel, kevlar, carbon whiskers, spider web or any other material known at the time simply would not work. Very small diameter (less than 10nm) carbon filaments had been prepared in the 1970s and 1980s, however no detailed systematic studies of such very thin filaments were reported in these early years. That all changed with the discovery of carbon nanotubes.

It was the year 1991 that saw the birth of that elusive material previously relegated to science fiction alone - carbon nanotubes (CNTs), or the strongest arrangement of a carbon molecule ever known. In November 1991, Japanese physicist Sumio Iijima announced in *Nature* the preparation of nanometer-size, needle-like tubes of carbon - now familiar as nanotubes - that seemed to have unlimited potential (Iijima, 1991). (Independently, and about the same time, Russian workers also reported the discovery of carbon nanotubes and nanotube bundles, but generally having a much smaller length to diameter ratio.) It was Iijima's observation of the multiwall carbon nanotubes that heralded the entry of many scientists into the field of carbon nanotubes, stimulated at first by the remarkable one-dimensional quantum effects predicted for their electronic properties, and subsequently by the promise that the remarkable structure and properties of carbon nanotubes might give rise to some unique applications. Indeed, these structures gave the promise of being the strongest material yet discovered. The long molecular tubes of carbon were theoretically stronger per kilogram than any other material by a factor of 40. As an example, a fiber made of carbon nanotubes 3mm in diameter could support 41,000kg. This strength combined with the low density of the material made it critically important when considering the design of a space elevator. Using any material other than carbon nanotubes it was estimated to require 750,000 space shuttles to place a space elevator in orbit - a task outside the realms of possibility. And this is the reason for the science fiction scenario of building the elevator cable on-orbit using materials naturally existing in space. However, many believed there was a better way - assuming we could get all the carbon nanotubes we needed to build a space elevator, then we could build it in a similar way to how difficult bridges were built in the past. The major problem was that carbon nanotubes were not available in the required lengths to construct a structure some 100,000km long.

In 1997 NASA Ames Research Center asked a group of scientists to look into molecular nanotechnology applications to NASA missions. Their report was published in 1998 and, interestingly enough, included a brief section on space elevators which mentioned the proposals for a space elevator by Isaacs and colleagues in 1966 and Pearson in 1975. In the report, researchers noted that the maximum stress on a space elevator cable is at geosynchronous altitude so the cable must be thickest there and taper exponentially as it approaches Earth. Any potential material may be characterized by the taper factor - i.e. the ratio between the cable's radius at geosynchronous altitude and at the Earth's surface. For steel the taper factor is tens of thousands and thus clearly impossible. For diamond, the taper factor is 21.9 including a safety factor, but diamond is, however, brittle. Carbon nanotubes have a strength in tension similar to diamond, but bundles of these nanometer-scale radius tubes should not propagate cracks nearly as well as the diamond tetrahedral lattice. The authors concluded that if the considerable problems of developing a molecular nanotechnology capable of making nearly perfect carbon nanotube systems approximately 70,000 kilometers long could be overcome, then the first serious problem of a transportation system capable of truly large scale transfers of mass to orbit could be solved (Globus et al, 1998).

5.5 Promising Progress in CNTs

Since their discovery, carbon nanotubes have made big waves in material science, appealing to multiple fields and engineering megaprojects. Space elevator advocates, including Brad Edwards, were no exception to the interested parties as CNTs were found to not only meet, but far exceed the strength-to-weight ratio required in the tapering factor of the elevator's lengthy cable. The problem however, similar to the perfect-crystal whiskers of graphite in the 1970s, is getting them to lengths beyond that of the nanoscale, an achievement for which those who engage in CNT research hold 'competitions'. Indeed Edwards, though still a strong proponent of the space elevator, eventually discontinued his work on the concept to focus on the further development of carbon nanotubes and their properties, applications and uses. His new company, Plasma Ten, produces carbon nanotubes for strengthening plastics and epoxies. (It might also be worth mentioning here that another early proponent of the space elevator, Dr Bryan Laubscher, also set up a business venture, Odysseus Technologies, to advance the use of carbon nanotubes in engineering materials design and use.)

Theoretical studies suggest that a single CNT can have a tensile strength of 100GPa, making it one of the strongest materials around, but efforts to spin multiple nanotubes into a practical large-scale fibers have only produced ropes with strengths of 1GPa. Recent research, though, has shown that material strengths properties would be available in the laboratory by about 2016. The design of a macro-tether could be tested in the late 2020's. The major hurdle for a successful space elevator is material availability with strength-to-weight ratio far better than steel. CNT material, in the laboratory, has been grown in centimeter lengths with sufficient strength to hold a space elevator against the gravitational field. The projections were that: a) the material would be available around 2016, in the centimeter to meter length, with appropriate strength to achieve operational space elevators, and b) growth to thousands of kilometers of woven strands of this material could be available during the late 2020s (Swan, Raitt *et al*, 2013).

However, despite the enthusiasm for the wonder of carbon nanotubes, as reported in the *New Scientist* (Aron, 2016), research by a team at Hong Kong Polytechnic University has indicated that a single out-of-place atom in the hexagonal arrangement can cut their strength by half since it causes a kink in the tube (Zhu, 2016). Simulations showed this change had a profound impact on the tensile strength of the CNTs, causing the strength to go from 100GPa to 40GPa. Since CNT manufacturing processes are thought to be flawed in mass production, then it is difficult to produce high-quality CNTs in large numbers. And as the tensile strength of the cables required for the space elevator are estimated to be some 50GPa (though Ben Shelef has shown that depending on the efficiency of the power supply used, a cable with a strength of 25-30GPa is feasible - see section 5.6 below) then the ribbon would not be strong enough to support it. In fact, we had been here before. Consensus had been reached in 2009 among experts that a space elevator could be built only if it was based on the flaw tolerant design proposed by Professor N. Pugno in 2006, abandoning earlier unrealistic proposals, which ignored the role of defects and assumed a mega cable strength even larger than 100GPa (Pugno & Klettner, 2009).

The discussion surrounding the use of carbon nanotubes for a space elevator usually concentrates on the lengths and strengths that can and must be achieved. Little is said regarding their cost. The price of CNTs varies widely, depending on their quality and purity, but can be as low as around $200 per kilo and as high as $750 per gram. This, however, is the cost for just the raw material, which then needs to be processed into a composite. In 2012 it was reported that a group of researchers from the Universiti Sains Malaysia had successfully created a new continuous production method for producing carbon nanotubes. The new method was capable of reducing the price of carbon nanotubes from $100-700 to just $15-35 for each gram, much lower than world market prices (https://www.sciencedaily.com/releases/2012/04/120412105109.htm). However, it should be pointed out that these CNTs are nowhere near the strength needed for a space elevator.

5.6 Recent Extrapolations for CNTs and Space Elevators

Over the years, many strength numbers have been used to describe the needed basic space elevator tether strength. Early in the 21st century, Ben Shelef of the Spaceward Foundation came up with a definition of specific strength to better understand how one relates strength of materials and their mass. Shelef measured strength-to-weight using a unit called a Yuri (after Yuri Artsutanov, one of the original inventors of the space elevator). One million Yuris is a MegaYuri (MYuri) and the value is equal to tensile strength divided by density of material. As most of the CNT densities are around 1.3g/cc and tensile strength given in gigapascals (GPa), the value comes out as GPa-cc/g (also seen as N/Tex). In 2008 Shelef wrote the "Space Elevator Feasibility Condition", which related many factors and compared engineering values to propose appropriate strengths needed. He showed that a strength of approximately 30MYuris would be required for a working space elevator. For reference, the specific strength of steel is about 0.5MYuris (Shelef, 2008). Though there are many high strength materials used around the world, ongoing research points to carbon nanotubes as being the strongest candidates for success. Shelef's chart was complex, but his results compared acceptable specific strengths to the taper ratio of the tether [taper ratio is the relationship of the mass at maximum stress location (GEO altitude) and the surface of the Earth.] Basically, a tether specific loading of 40MYuri and a taper ratio of 3.4 gave the desired level; a tether specific loading of 30MYuri and a taper ratio of 5.0 gave an acceptable level; while a loading of 20 and a ratio of 7.0 was not sufficient as 25MYuri was probably the minimum strength required. In the IAA study report, Shelef's numbers in his feasibility condition were used to provide Finding 3-1 that space elevators could be developed with 30MYuri tethers (Swan, Raitt *et al*, 2013)

As Mark Haase (2016) points out, construction of a space elevator requires several engineering and scientific advancements, probably the most critical of which is development of materials with a high specific strength. Haase then goes on to identify and review advances in high tensile strength materials for space elevator applications. His conclusion is that extrapolating from current data, it seems plausible that a carbon nanotube material meeting the minimum strength requirement for a space elevator will be produced in a laboratory setting within the next 5-10 years. A boron nitride nanotube based material should reach that threshold about 7-10 years later. Once developed, it will take some time to adapt the technique from the lab to industry - perhaps 10 or 15 years, if the adaptation occurs over a time frame similar to other novel materials.

5.7 Conclusion

It is telling that in his Phase I Final Report for NIAC in 2000, Brad Edwards provided a brief overview of how he thought of using carbon nanotubes for his concept of the space elevator. (Edwards, 2000). He noted that although Arthur C. Clark had put together an interesting tale of the construction of the first space elevator in *Fountains of Paradise* (1978) and Kim Stanley-Robinson had a different and well-thought out view on how the first space elevator might arise in *Red Mars* (1993), these science fiction books pointed out many of the basic aspects and challenges of building a space elevator and keeping it operational, but their models for building a space elevator in reality were not really in the realm of practicality. In both of the novels a natural object, asteroid or moon, is moved into a proper orbit and mined for its carbon. This carbon is then used to build a very strong, very large cable extending both upward and downward. This approach was also considered a reasonable conceptual suggestion for one possible construction method in David Smitherman's 2000 publication on the space elevator for NASA. Edwards, however, believed this method of dragging an asteroid about was too expensive and too difficult to be a viable option outside of science fiction. Hence his foray into carbon nanotubes. However, unless great breakthroughs in CNT synthesis and production are achieved in the near future, then using carbon nanotubes as the material of choice for the space elevator might be challenging and put back its construction and deployment for quite some further years. However, as Mark Haase has concluded (see above) a material that can be produced on an industrial scale, with a specific strength sufficient for a space elevator tether, should be available in 15-25 years.

Essentially, this chapter has put forward the argument that Dr Bradley Edwards can be considered to be the father of the modern day space elevator for all his ground breaking activities during the first decade of this century. His ability to visualize and lay out the design of a feasible space elevator, address many of the sizeable issues with proposed mitigation activities, and then popularize the concept around the world ensured that hundreds (even thousands) of engineers and scientists of many disciplines joined together to enhance his design - and not simply start over. Besides his book with Westling, Edwards wrote another, less technical, book together with Philip Ragan (with a Foreword by Sir Arthur C. Clarke) three years later. *Leaving the Planet by Space Elevator* was aimed at the more popular market and covered in simple-to-understand and practical terms what a space elevator was, how it would be constructed, how and why it would work, where it would be located, and why it was such a great idea (Edwards and Ragan, 2006). Interestingly, Clarke in his foreword to the book notes that Brad Edwards was presented with the Arthur C. Clarke Innovator Award 2005 by the Arthur C. Clarke Foundation. He also goes on to mention that co-author Phil Ragan had identified Perth, Western Australia as an ideal space elevator base (following his research into Indian Ocean meteorology) and this idea was incorporated in the novel *Sunstorm* that Stephen Baxter wrote in 2005 based on Clarke's ideas and drawing on material included in *Leaving the Planet by Space Elevator* (in fact, Clarke appears to be the first-named co-author of the novel - and again on a second novel with Baxter entitled *Firstborn*, published in 2007, which mentions the 'Aussievator' - a space elevator being built in Perth.) As a final word, it is worth mentioning that there exists a rather old historical interview by Keith Curtis which took place during a chance meeting with Brad Edwards in Seattle on 14 October 2005. The interview, which elicited 85 comments can be found at http://keithcu.com/wordpress/?p=17 gives additional insights into Edwards' thinking.

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Chapter 6: From Chaos to Consolidated Organization

6.1 Introduction

The idea of a space elevator has had multiple creators with curious results. The original idea posited in 1895 by Konstantin Eduardovich Tsiolkovsky excited a few, but failed to take hold. The co-inventors of the modern space elevator, Yuri Artsutanov and Jerome Pearson, were able to momentarily establish the concept in small communities; but, once again, they could not expand its audience. The one exception was the cooperation between Jerome Pearson and Sir Arthur C. Clarke, on his novel *Fountains of Paradise*. His science fiction audience was huge, but fleeting. The Japanese covered the topic well in anime, but this also failed to stimulate massive funding for the development for a space elevator infrastructure. It seemed hopeless and not worthwhile as the century turned over - a project with no focus.

Then Dr Bradley Edwards took a concept that a NASA study had shown could not work for a century or so, and made it seem possible within a reasonable timeframe (see Chapters 4 and 5). His marvelous engineering ingenuity and his technological savvy resulted in a space elevator design that could work. This amazing achievement, under NIAC grants, led to the definitive book, co-authored with Eric Westling, entitled *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* (Edwards and Westling, 2003) and indeed, the modern space elevator concept was born.

This fever did not die down as the other false starts had. Edwards realized that his book alone would not result in a developmental program. There had to be much more effect to fan the fires of fervor over the potential of space elevators. He noted that after having completed a thorough study of the concept and all the implications he and his team began promoting the idea. He added that the media and public appeared to be excited about the concept and the publicity had spread globally through very reputable channels. His efforts resulted in many positive, transient and ongoing activities trying to gain footholds across the spectrum of potential stakeholders. Reaching across many domains, his communications skills ensured others would buy-in and commit their own energies and efforts towards the goal of having a space elevator infrastructure.

The task was huge - to motivate people and organizations to come together and push for change! Some successes followed, but the chaotic behavior of organizational and major space players around the world argued against this elegant solution to so many problems. However, inspired by Brad Edwards, many individuals, including his co-workers, in the years following his work in the early 2000s, have contributed and committed time, energy and resources toward common goals and future visions concerning a space elevator. Indeed, actively joining and playing important roles in parallel with Edwards were, and still are, people such as:

- Michael Laine – a parallel business approach with hardware testing
- Bryan Laubscher – increased the energy with supplemental conferences
- Pete Swan and David Raitt – initiated international sessions and studies on the concept
- Ben Shelef – leveraged NASA Centennial Challenges into Space Elevator Games
- Marc Boucher - established Space Elevator Reference

- Ted Semon – initiated the Space Elevator Blog
- Markus Klettner – organized space elevator activities in Europe
- Martin Lades – contributed greatly to space elevator games in the USA and Europe
- Shuichi Ohno – organizer of Japanese Space Elevator Challenges
- Yoji Ishikawa - leading Obayashi's space elevator construction concept
- The small team forming the International Space Elevator Consortium

The problem was that by 2005, Brad Edwards had run three conferences but there was minimal other activity beyond his energetic travels around the world. A few activities took the situation in hand and changed it from a single person-driven arena to one where many contributed and expanded the reach of enthusiasm on space elevators. The chaotic behavior of a developmental mega-project (in this case, well prior to any funding or serious investors) continually pushed the participants into individual actions optimized with short-term goals. This is very understandable and a good path to follow during the creation of any major mega-project. However, the issue becomes who will invest first and who will jump into the arena with a commitment to develop future access to space.

In the first few years of the 21st century many people had hopes and invested time and energy towards space elevators. The problem was that while individual efforts were herculean, the sum of the parts was not sufficient to break into programmatic funding levels. At the end of 2005, there were many diverse and intermittent activities that began the effort to come together and discuss concepts. The space elevator conferences were wonderful stimulants to consolidate efforts and focus, even if they were only for a few days. Even though the funding opportunities had not yet surfaced, this small community leveraged Brad Edwards' global windstorm of marketing and started to contemplate more structured approaches to space elevator development.

This chapter will discuss the major events that lead from organizational chaos to more focused efforts across a broader set of players. These include: an initial approach into commercial ventures; the Space Elevator Reference, Space Elevator Blog and Space Elevator Wiki; evolution of various space elevator associations; moving from individual conferences to symposia series; and consolidation from an initial idea to Space Elevator Games. Each of these segments define events that were unfolding during the nebulous times of the last half of the first decade of the 21st century. Each individual contributed as they moved forward, with the second decade unveiling a much more organized and unified approach.

6.2 An Initial Approach into Commercial Ventures

LiftPort (www.lifport.com) is a privately held Washington State corporation founded in 2003 by Michael Laine as a spinoff from NIAC following Brad Edwards' Phase II study. The final report outlined exactly how a space elevator could be built, said that indeed a space elevator was possible to build and concluded that there were many reasons to build one. And Laine intended to do just that. The focus of his company in the early days was upon a space elevator using new materials, specifically carbon nanotubes. The company concentrated on learning how to build robotics, large tethers and carbon nanotubes that could be used to construct a space elevator. In 2006, LiftPort launched a proprietary observation and communication platform on a 1,600m long tethered balloon while robotic climbers moved up and down the tether multiple times. The tether was made by sandwiching three carbon fiber composite strings between four sheets of fiberglass tape. LiftPort hoped to go on to test a 3.2km tether with robots scaling to at least half that height (https://www.newscientist.com/article/dn8725-space-elevator-tether-climbs-a-mile-high/).

When the economy crashed in 2007 LiftPort collapsed with it, only to bounce back again in 2011 when the company announced it was going to develop a lunar elevator. The reasoning was that it could be built now, with current technology, and would be a vital precursor to an Earth elevator. In 2012, Laine set up a Kickstarter project to raise funds for LiftPort's Earth space elevator, tethered tower and lunar space elevator infrastructure. The modest goal was \$8000, but over \$110,000 was pledged from nearly 3,500 backers (https://www.kickstarter.com/projects/michaellaine/space-elevator-science-climb-to-the-sky-a-tethered).

Like others, Michael Laine has spent many years working on the space elevator concept – first an Earth version and now a lunar one. He has contributed to the field extensively, improving the chances that one or the other will be initiated in the near term. With his business background, he was instrumental in looking at a space elevator from a commercial and financial perspective. In fact, what is often overlooked these days, is that prior to founding LiftPort, Laine was co-founder (together with Brad Edwards) and president of HighLift Systems, a Seattle-based company that along with Eureka Scientific received the funding from NIAC to research building an elevator to space. The company was set up in 2002, and it was HighLift Systems that was the sponsor of the first space elevator conference in Seattle that same year. Brad Edwards had teamed up with Michael Laine, who ran the business side of the company, in an effort to raise funds to develop an operational elevator, but the two HighLift Systems principals later parted ways because of financial disagreements. In March 2003, Edwards moved to West Virginia to take a position as director of research at the Institute for Scientific Research (ISR), an R&D corporation that worked closely with NASA and other federal agencies. Edwards and a number of other ISR employees worked on various aspects of the elevator concept, and sought NASA support to continue their work.

It was following the split up of their company, that Michael Laine established LiftPort to commercialize a space elevator. The company's initial business plan evolved to become a group of affiliated companies, one attempting to develop and commercialize carbon nanotube technologies, another to provide public outreach and education services, and a third to provide venture funding for other companies developing space technology. All were tied together to commercially develop a space elevator within 15 years (from 2003). An interview with Michael Laine appeared in the October 2004 issue of *Nanotechnology Now* and it gives an interesting historical perspective of his views and aims - http://www.nanotech-now.com/Michael-Laine-Oct2004.htm. There is another nice video, entitled 'Arthur C. Clarke's Space Elevator' featuring Michael Laine reviewing his ideas of a space elevator and with commentary from Arthur C. Clarke, Kim Stanley Robinson and others at https://www.youtube.com/watch?v=Xdr6zXXrTbg.

6.3 Space Elevator Reference, Blog and Wiki

In 1999, entrepreneur, technologist, software engineer, writer and a builder of the Mars Society, Marc Boucher co-founded SpaceRef Interactive Inc. SpaceRef is a media company focused on the space sector that as well as news aggregation also creates original content. In August 2003, Boucher established Space Elevator Reference as a subset of SpaceRef and covered anything and everything that had to do with space elevators - papers presented at conferences, news items in the press, study reports, events, talks, new books and so on. The site at http://spaceref.com/space-elevator is an invaluable historical (as well as current day) record of space elevator developments. In March 2008, the Space Elevator Reference announced the launch of a new Twitter community dedicated to space elevators aimed at advocates, professionals and enthusiasts taking it from concept to reality by providing news and information. One of Boucher's first actions for this new service was to ask Ted Semon (see below) if his posts from the Space Elevator Blog could be fed into this new Twitter community. The company also set up a page on FaceBook in 2012, but it does not appear to be currently active.

Ted Semon, a retired software engineer, wanted to contribute, somehow, someway, to making the space elevator a reality. To this end, he initiated the Space Elevator Blog in 2006 as a means to become a part of the effort to promote the idea of a space elevator. His nine years of recording events surrounding space elevator development was instrumental in ensuring that its history is preserved. In his closing remarks as he announced he was quitting (at least for now) at the end of March 2015, he stated that being involved with the NASA-sponsored Space Elevator Games, run by Ben Shelef, was one of his highlights. His insight into the activities of space elevators reaches across the entire community with an early focus upon creation of the International Space Elevator Consortium, of which he was President and a member of the Board of Directors. (In an interesting historical note, Brad Edwards was the first President of ISEC, but he left after only a month or two, and then Ted Semon took over and was President for four years.)

Over the years, the Blog, like the Reference, covered anything and everything about space elevators: news, articles and reports, events, images, key people and websites, discussions, reports on conferences and meetings, book reviews, competitions, materials, videos and much more. In his final blog, Semon included an episode from 'The Lonely Astronaut' series from TwistedMojo. In the series, an astronaut is stranded on the Moon where he has somehow survived for several decades. The humorous episodes cover his trials and tribulations as well as various rescue attempts. Episode 8, from 2014, posted on the blog is about another rescue attempt, this one based on the idea of a lunar and Earth-based space elevator! Watch it at https://www.youtube.com/watch?v=i0-C9D2CrBw&feature=youtu.be.

Although the Space Elevator Blog is no longer being written, it remains an invaluable source of knowledge about space elevators and can still be searched and consulted for historical items at www.spaceelevatorblog.com.

One other website which should be mentioned here, even though it also appears to be no longer regularly updated, is the Space Elevator Wiki (spaceelevatorwiki.com) which was created in July 2008 by Keith Curtis, with administrative assistance from Brad Edwards and Ben Shelef. Intended to be a repository of information and a baseline for research of the space elevator, the site provides such things as the baseline designs and status of all the elevator components, the major technical challenges being faced, detailed calculations, simulation software, individuals involved, as well as news. There is an archive of detailed work containing images and renderings; and also a section called Open Work Space which is intended to provide a place for people to use for space elevator development work. Within the Work Space, there are collaborative pages for such topics as economics; space debris removal; space catapult; and companies involved in space elevator technology development. The site is rather dated, but it does provide another useful and interesting historical take on the space elevator in its formative years.

6.4 Evolution of Space Elevator Associations

One of the significant activities that ensured continuity, as well as unity, in the development of space elevators was the creation of national and international associations in the United States, Europe and Japan relating to the concept. These entities enable volunteers to educate themselves while contributing towards a larger goal. To date there have been four such bodies: the International Space Elevator Consortium; the Japan Space Elevator Association; the Spaceward Foundation; and the Eurospaceward Association. These are discussed below in the order in which they were founded.

6.4.1 Spaceward Foundation

'Governed by the famous Rocket Equation, space-bound rockets must always be composed of at least 95% fuel, and will likely never carry more than 1% or 2% payload, so rocket travel will likely never be safe or affordable. The space elevator is the only viable alternative on the drawing boards today, offering very scalable, low-cost, and safe transport to space. Mankind has clearly outgrown its habitat, and it's time to move on.' This is what the Spaceward Foundation believed when it set the goal of breaking the space program out of Earth orbit and into worthy destinations. The Spaceward Foundation was a non-profit organization, co-founded by Ben and Meekk Shelef in 2003, dedicated to furthering space science and technology in education and in the public mindshare. They approached NASA with the idea of funding a Space Elevator prize and were allocated a $400,000 prize purse for advances in tether strength and power beaming. The first Space Elevator Games were launched in 2005 less than a year after their proposal was accepted and were a great success - so much so that NASA raised the prize purse to $4m! The competitions for tether strength and power beaming, organized by the Spaceward Foundation, were held in 2005, 2006, 2007 and 2009. Full details of these Games, participants and results are given in Chapter 7.

In 2008, Ben Shelef developed and set out ideas for the Space Elevator Feasibility Condition (http://www.spaceward.org/documents/papers/SEFC.pdf) and proposed a solar-based space elevator architecture that satisfied the condition (http://www.spaceward.org/documents/papers/SEPSAO.pdf). The Space Elevator Feasibility Condition paper tied together parameters pertaining to tether specific strength and to power system mass density to arrive at an inequality that determines whether a space elevator system is viable. The principle for the feasibility condition was that a space elevator must be able to lift its own weight fast enough - i.e. fast enough to grow by bootstrapping, fast enough to replace ageing material, and fast enough to have a significant margin for commercial cargo beyond these housekeeping tasks. The feasibility condition therefore set a 3-dimensional design space comprised of tether material specific strength, power system specific power and system time constant. After developing the feasibility condition, real life limitations on specific power and specific strength were plugged in, and the resultant viable design space was examined - resulting in a design architecture that satisfied the feasibility condition. The second paper laid out the basics constraints for a space elevator power system, performed parameter optimization, and compared the results with real-life technology parameters. The paper also considered the special case of solar climbers that had the additional constraint of a once-per-day launch rate.

The combined effect of these two concepts was that the higher power level possible with solar power translated into lower requirements on the CNT tether. Two other upshots were a great reduction in the requirements of the power beaming system, and the built-in free creation of very large arrays of solar-collectors in orbit. Although no longer updated, there is a wealth of interesting historical information and photographs, of the Space Elevator Games established by The Spaceward Foundation, at www.spaceward.org.

6.4.2 European Spaceward Association

Taking its cue from The Spaceward Foundation in America, the European Spaceward Association (known more simply as EuroSpaceward) was established in 2007 with Dr Brad Edwards as its President and Markus Klettner as the Executive Director. Other directors included Dr David Raitt from the European Space Agency. The Association was formed to consolidate discussions about space elevators within Europe and to encourage participants in tether climber competitions. EuroSpaceward organized the 1st European Workshop on Space Elevator Climber and Tether Design in the city of Luxembourg on 10-11 November 2007. The 2nd International Conference on Space Elevator Climber and Tether Design was also held in Luxembourg on 6-7 December 2008. In addition to EuroSpaceward, the event was organized in cooperation with the National Research Fund of Luxembourg, the Spaceward Foundation, the Japan Space Elevator Association, and various universities. A 3rd International Conference organized by EuroSpaceward with the theme Space Elevator, Carbon Nanotube Tether Design and Lunar Industrialization Challenges was again held in Luxembourg from 5-6 December 2009. And, on 4-5 December 2010, the European Spaceward Association hosted the 4th International Conference on Carbon Nanotechnology and Space Elevator Systems in Luxembourg. More information on the conferences can be found in Chapter 8.5.1. Although short-lived, EuroSpaceward and its series of conferences (which also had a Climber Competition element - see Chapter 7.7) provided an extremely useful forum for European advocates of a space elevator to discuss realistic and even breakthrough technologies and developments. Although the EuroSpaceward website at www.eurospaceward.com is no longer accessible, snapshots at various points in its life can be found via the WayBack Machine at archive.org.

6.4.3 Japan Space Elevator Association

The Japan Space Elevator Association (JSEA) (jsea.jp) was started after a team, led by Akira Tsuchida of the Japanese Aerospace Exploration Agency (JAXA), and comprising many of its future founding board members, participated in the NASA Power Beaming Space Elevator Challenge in Salt Lake City in October 2007. In 2008, those members founded JSEA (with Akira Tsuchida as Director) with the established principle to have similar activities in Japan including an annual conference comprising presentations, lectures and discussions and exchange of views on the latest technologies, materials and developments in space elevators. In most years there was also an accompanying art competition. JSEA started in 2009 with the Japan Space Elevator Technology and Engineering Competition and this has continued every year since with high hopes for the future as more and more progress is made in design and construction. The main purpose of the Japanese Challenges is to increase concept development among engineering students and enthusiasts and to understand more about tether climber designs as well as power issues with a view to attain an altitude of 30km in the next few years. The Challenges are also in line with the intention of the Obayashi Corporation to have an operational space elevator by 2050 (see Chapter 9.4). Some further brief details about JSEA activities can be found in Chapters 7.7 and 8.5.2.

6.4.4 International Space Elevator Consortium

After the 2008 Space Elevator Conference, there were many committed space elevator participants who lacked leaders and direction. A small team started casting around for Board Members for a new organization that would pull together like-minded professionals from all disciplines. The decision was to have an International Space Elevator Consortium (ISEC) with a President and a few active board members. The thinking was that there was a need for visible direction and leadership in taking space elevator activities forward, particularly in the United States. In addition, the small-dedicated community needed a location to meet periodically and help each other compile and develop information. ISEC was created to handle national and international aspects of space elevator development and provide a vision for other countries as their involvement grew. The tasks identified as necessary in the near future were: 1) To continue to leverage NASA's Centennial Challenges for spreading the word and pulling people together, 2) To ensure that conferences continued to bring people in for technical and professional discussions, and 3) To enable a small set of board members to grow the industry through the power of information and vision.

With interest and enthusiasm for a space elevator having reached an all-time peak, and with space elevator conferences scheduled in both Europe and Japan, it was felt that the time was right to formalize an organization. An initial set of directors and officers were elected and they immediately began the difficult task of unifying the disparate efforts of space elevator supporters worldwide. ISEC's first Strategic Plan was adopted in January 2010 and became the driving force behind the organization's efforts. The initial focus was on the Centennial Challenges and the annual Seattle Conference (see Chapter 8.3). The latter was given a tremendous boost when Microsoft Corporation decided that the topic fitted within its sponsorship criteria. Although there were more than a few ideas about what else needed to be accomplished in parallel with the conference and the tether and power beaming competitions, the bottom line was that the small core of participants could not achieve much beyond these two events. The next four years were thus devoted on maturing ISEC while continuing to excel in the Centennial Challenges and conferences.

After several successful yearly conferences and the award of $900,000 to a team racing up a tether for NASA, ISEC was in a position to change its approach to include more activities. The first thing it did was to create a single research topic for each year. The aim of this was to ensure that players within the space elevator community channeled their energies into a single topic for a year with a resulting focus in energies and outputs. Each topic generated a study report, was included in the ISEC journal *CLIMB*, and also provided a ready-made theme for the annual conference with papers and mini-workshops. The topics to date have been: 2010 - Space Elevator Survivability and Space Debris Mitigation; 2011 - CNT Material Development for Tensile Strength; 2012 - Space Elevator Concept of Operations; 2013 - Design Considerations for Tether Climbers; 2014 - Architectures and Roadmaps; 2015 - Earth Port Design Characteristics; and 2016 - GEO Node, Apex Anchor and Communications Infrastructure Designs. The topic for 2017 is Design Considerations for Space Elevator Simulations. The topics are discussed in more depth in Chapter 9.2. All these study reports can be downloaded from the ISEC website (www.isec.org).

These study research activities have led to greater conference attendance and more ideas for topics being put forward by the elevator community. Besides *CLIMB*, the space elevator journal, ISEC also publishes a space elevator magazine named *Via Ad Astra*. In addition the organization since 2011 of a Space Elevator Family Science Fest with its Robo Climb Competitions whereby middle- and high-school robotic teams build and program an autonomous, tether-climber, has increased the interest and involvement of young people (see also Chapter 7.7). As support has grown, so the internal structure, layout and aims of ISEC have became more mature and robust. The ISEC Vision is: A world with inexpensive, safe, routine, and efficient access to space for the benefit of all mankind, while the ISEC Mission is to promote the development, construction and operation of a space elevator infrastructure as a revolutionary and efficient way to space for all humanity. Because of common goals and hopes for the future of mankind, off-planet, ISEC became an Affiliate Organization with the National Space Society in August 2013.

6.5 From Individual Conferences to Symposia Series

After the initial NASA workshop in 1999, the topic of space elevators diverged from a government program, estimated to be achievable by 2400, to a more realistic commercial project with smaller engineering challenges which were aired at various other conferences over the years. This section briefly outlines the development of these various conferences which are all discussed at length in Chapter 8. After Brad Edwards' first NIAC study, together with his partner Michael Laine, HighLift Systems sponsored the first international space elevator conference in Seattle in 2002. After those initial two space elevator conferences, future conferences split up into two categories: individual conference events; and symposia series (although it must be noted that there were several papers on space elevators being presented at much larger, general space conferences.) The former were motivated by Edwards and provided an early refinement of his body of work. After Seattle in 2002, two more such conferences were organized there by Edwards. The mantle was then taken up by Dr Bryan Laubscher's Albuquerque Sessions – as part of a larger space conference. Periodic meetings were also organized by the European Spaceward Association (see above and Chapter 8.5.1). The symposia series are dominated by sessions, organized by the International Academy of Astronautics, at the annual International Astronautical Federation Congresses held around the world; and by the yearly conferences in Seattle organized by the International Space Elevator Consortium. There is also an annual space elevator conference organized by the Japanese Space Elevator Association.

6.5.1 Individual Conference Events

The early conferences on the space elevator were almost just one-off events with no guarantee that they would reoccur. Brad Edwards was the principle force behind the space elevator concept and its development and refinement during the first five years of this new century and his sponsorship, attendance, and challenge ensured many critical participants showed up, contributed, and advanced the concept. At the end of the first three conferences (2002 in Seattle; 2003 in Sante Fe; and 2004 in Washington DC), the modern day space elevator had been established as a doable concept that must be pushed ahead to ensure humanity moves off-planet. And the conferences provided a forum for those interested in the concept to advance and discuss ideas and progress. The continuation of space elevator focused conferences in Albuquerque in 2005 and 2007 moved into a smaller community setting and Bryan Laubscher's guidance at this critical time ensured that the topic continued to be studied and reported upon.

6.5.2 Establishing Symposium Series

After the initial space elevator conferences and sessions, there was a recognition that more consistent opportunities must be made available for presentation of space elevator concepts as they developed. Accordingly, at the instigation of Dr David Raitt and Dr Peter Swan, sessions were proposed, accepted and organized, under the aegis of the International Academy of Astronautics (IAA), at the annual International Astronautical Congress (IAC) - jointly run by the International Astronautical Federation (IAF) and the IAA. The IAA has sponsored at least one session (occasionally three, usually two, plus a poster) at each International Astronautics Federation Congress since 2004. The focus has always been global participation in space elevator development as shown by their locations: 2004 Vancouver; 2005 Fukuoka; 2006 Valencia; 2007 Hyderabad; 2008 Glasgow; 2009 Daejeon; 2010 Prague; 2011 Cape Town; 2012 Naples; 2013 Beijing; 2014 Toronto; 2015 Jerusalem; 2016 Guadalajara; 2017 Adelaide.

However several members of the core space elevator community recognized that there should be a continual and separate annual conference (rather than just the odd session at the IAC) specifically devoted to the space elevator. Dr Laubscher was successful in gaining sponsorship from Microsoft, a venue (initially at Microsoft's facility in Redmond, Washington, but currently at Seattle's Museum of Flight) and content providers. These conferences started out as individual efforts to pull together a program and morphed into a full-blown International Space Elevator Conference sponsored principally now by the International Space Elevator Consortium (ISEC), Microsoft, and the Museum of Flight. The event was established for late August each year in Seattle and each has been highly successful. As the years progressed, the individual leadership moved to a community effort led by David Horn, as conference chair, to focus on specific topics.

6.6 Space Elevator Games

The concept of empowering small teams to design, build, test and then compete with their own tether climbers has expanded from a simple concept to a successful series of events around the globe. They include primarily; the NASA Centennial Challenges, the Japanese Tether Climber competitions, the European Space Elevator Challenges and the ISEC Robo-Climb competitions. Indeed space elevator challenge competitions have been held, with varying results, since 2005 (see section 6.4 above and Chapter 7) - earlier ones usually having both a competition of tether and climber, and later ones mainly focusing on climbers. A fairly comprehensive list can be found at https://en.wikipedia.org/wiki/Space_elevator_competitions. The NASA Centennial Challenges are fully covered in Chapter 7 together with mention of competitions organized by the International Space Elevator Consortium, the European Spaceward Association and the Japan Space Elevator Association. Each of these events around the world motivates young scientists and engineers, as well as the established elevator community, and engages the public in the process of advanced technology development with individual motivations such as prizes. The events have definitely helped change the movement of space elevator development from the early concept stage to one where systems engineering, advanced technologies and new techniques and materials are needed and practical demonstrators are *de rigueur*.

6.7 Conclusion

The development of the space elevator arena from the beginning of the first decade of this century until the middle of the second decade was somewhat personal or individualistic with people pursuing their own concepts, albeit often based on that of Brad Edwards. But there has been an amazing and astonishing transition in the last ten years or so from this semblance of chaos in ideas, gatherings, and relationships. The creation of various space elevator associations has enabled better organization and cooperation to surface around the globe. Investigative research and studies have moved from the scientific towards commercial viability. The occasional paper on the space elevator at diverse large conferences, followed by the occasional stand-alone conference on space elevators, have evolved into regular annual events. The internet has enabled dedicated reference and blogging websites on space elevators that can be tapped for historical details, and the creation and continuation of space elevator competitions has brought a new surge of young enthusiasts into the space elevator community. The maturing of each of these concepts was due to individuals who committed their time and energy towards space elevator development and the result has been a welcome shift from one of individual efforts to one more of global cooperation and teamwork.

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Chapter 7: NASA's Centennial Challenges and Other Competitions

7.1 Introduction

From the beginning of widespread interest in the space elevator, involvement with advanced technology and inclusion of youth were important. One of the major contributions that greatly increased the visibility of space elevators to the general public was the Space Elevator Games, a series of four competitions held over a seven-year period which were dedicated towards advancing technologies needed to build a space elevator. While other competitions have been held elsewhere since then, it is probably safe to say that these Games are still the 'gold standard' against which all other competitions must be measured. In 2005, the National Aeronautics and Space Administration (NASA) launched the Centennial Challenges with the following announcement (Semon, 2015):

"NASA Centennial Challenges were initiated in 2005 to directly engage the public in the process of advanced technology development. The program offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. The program seeks innovations from diverse and non-traditional sources. Competitors are not supported by government funding and awards are only made to successful teams when the challenges are met."

There were several of these Challenges: Astronaut Glove, Regolith Excavation, Green Flight, Power Beaming and Strong Tether. However, since two of these Challenges, Power Beaming and Strong Tether, involved technologies having a direct application in the construction and operation of a space elevator, Ben Shelef, an Israeli-American engineer and co-founder of the Spaceward Foundation (along with its President Meekk Shelef), had the grand idea to leverage these two challenges into an event they titled 'The Space Elevator Games'. An interesting piece appeared on 27 August 2004 written for Space on NBCNews.com by Alan Boyle under the heading 'Space Elevator Contest Proposed'. It appears that the original name for the Ansari X Prize-inspired competition was Elevator:2010 because the Shelefs firmly believed that the set of technologies that underlie the infinite promise of the space elevator could be demonstrated, or proven infeasible, within a five-year time frame - hence the name. Elevator:2010 (http://www.nbcnews.com/id/5792719/) - see also https://en.wikipedia.org/wiki/Elevator:2010).

NASA awarded the Spaceward Foundation (www.spaceward.org) a license to organize these two Challenges [NASA called all of the competitions 'Centennial Challenges', but Spaceward always called the Strong Tether and Power Beaming competitions the 'Space Elevator Games'.] In accordance with how NASA organized these Challenges, Spaceward would devise the rules for each Challenge, procure a competition venue, recruit the competitors and coordinate all of the activities for each event. NASA would review and approve the rules and, if there were any winners, award them prize-money based on the Challenge results. NASA also provided administration and consulting expertise and some advertising as well. In Media Advisory M05-044 dated 22 March 2005, NASA announced the first two Centennial Challenges would be released by NASA and its partner the Spaceward Foundation on 23 March in Scottsdale, Arizona and they would conduct a media teleconference on 25 March. In its Media Advisory M05-083 dated 23 March 2005, NASA announced the first Centennial Challenges' Prizes (https://www.nasa.gov/home/hqnews/2005/mar/HQ_m05083_Centennial_prizes.html).

During this agreement, several sets of competition events were held. The Power Beaming Challenge event was held in 2005, 2006, 2007 and 2009, while the Strong Tether Challenge was held in 2005, 2006, 2007, 2009, 2010 and 2011. In 2005 both Challenges were held at the NASA Ames facility in

California. In 2006, both Challenges were held in Las Cruces, New Mexico, initially as part of that year's X Prize competition. In 2007, both Challenges were held at the Davis County Event Center in Layton, Utah. In 2009, the Power Beaming Competition was held at the NASA Hugh L. Dryden Flight Research Center (renamed the Neil A. Armstrong Flight Research Center in 2014), while the Strong Tether Challenge for 2009, 2010 and 2011 was held at the Microsoft Conference facility in Redmond, Washington, along with the annual Space Elevator Conference hosted by the International Space Elevator Consortium (ISEC).

For the 2005 event, NASA provided a $100,000 prize purse ($50,000 for each of the two Challenges). In 2006, NASA increased this to $400,000 ($200,000 for each Challenge). In 2007, NASA further increased this to $1,000,000 ($500,000 for each Challenge) and for 2009, 2010 and 2011, NASA provided a total prize purse of $4,000,000 ($2,000,000 for each Challenge).

As with all technological challenges, winners are not guaranteed and the rewards are not easy to come by. In the first three events, no winners were declared (though one team from Canada came very close to winning in the Power Beaming Challenge – twice!). In the fourth and final Power Beaming event, the team from Lasermotive LLC, an American engineering company based in Seattle, Washington, won the first level of the Power Beaming Challenge and with it, a $900,000 prize.

During the development of the Centennial Challenges and then the execution of each one, the information was shared with everyone through Ted Semon's Space Elevator Blog (http://www.spaceelevatorblog.com). In his blog, Semon kept abreast of all the events that supported the development of the space elevator, including the Spaceward Foundation Games.

7.2 The 2005 Challenges

The inaugural Space Elevator Challenge event was held in October 2005 at the NASA Ames Research Center, located in Mountain View, California and was a four-day affair. For this first set of Challenges, NASA put up a total prize purse of $100,000 - $50,000 for each Challenge.

The 2005 Power Beaming competition

Climbers were mounted on a 50m-long, 10cm-wide, tether suspended from a crane at the height of 5m and had to climb to the 50m level at an average speed of at least 1 meter per second (m/s) to be eligible for the prize. There were also other requirements; for instance, climbers had to descend within a maximum length of time, and they had to do so under control. If only one team succeeded in meeting all of the requirements, it would win the full $50,000. If multiple teams succeeded, the prize purse would be divided according to a set of criteria set out in the rules. The climbers could not carry any fuel, they had to be beam-powered, i.e. power transmitted to them wirelessly. For this first competition, all of the beam power was generated by 70kW portable searchlights provided by the Spaceward Foundation.

Six teams entered this competition (Table 1) and every team except Star Climber used photovoltaic cells on their climber to convert the light beam to electricity to power their climbers. Star Climber used a Stirling Engine which was powered by the heat generated from thermoelectric cells. Only the two climbers from the Canadian teams were able to successfully make a beam-powered climb on the ribbon. The Snow Star team was first to actually succeed in climbing, ascending about 6m before stalling out. Starting a tradition that was to carry forward to future competitions, USST performed the best, ascending about 12m, but not quickly enough to be eligible for any prize money.

Team Name	Where from
USST (University of Saskatchewan Space Design Team)	University of Saskatchewan, Saskatchewan, Canada
Snow Star	University of British Columbia, British Columbia, Canada
MClimber	University of Michigan, USA
Star Climber	Private group from Maryland, USA
SpaceMiners	Private group from Texas, USA
Centaurus Aerospace	Private group from Utah, USA

Table 1: 2005 Power Beaming Teams

The 2005 Strong Tether competition

For the Strong Tether competition, NASA provided a separate $50,000 prize purse. The rules were simple. Tethers had to be in the form of a closed loop, had to weigh a maximum of 2.5 grams, had to be at least 2.5m long and could be no wider than 20cm. Each team also had to provide four identical tethers. Once a tether was measured and certified as being within specifications, it was placed on a competition apparatus, nicknamed the 'Tether Torture Rack' (TTR). The TTR allowed two tethers to be placed on separate rollers which, when the competition started, were simultaneously forced apart with hydraulic pressure. Whichever tether broke apart first was the loser. A strain meter was attached to the TTR to provide a numerical value of the force applied to it.

When a tether would break, it was eliminated and the team with the winning tether would move on to the next round. This would continue until only one team was left. This team's tether was then matched against a 'House Tether', a tether made of COTS (Commercial, Off-The-Shelf) materials which was identical in form to the competition tethers except it weighed 50% more. If the competition tether was able to defeat the House Tether, it would mean that it was at least 50% stronger than the House Tether and would therefore be eligible for prize money. Four teams (Table 2) entered this competition. The tether from Centaurus Aerospace won both of its matches and was then matched against the House Tether. Centaurus Aerospace lost the bout but its tether broke at a very respectable 550kg. The House Tether was then tested itself and broke at nearly 600kg so the Centaurus Aerospace tether came very close to winning.

Team Name	Where from
Centaurus Aerospace	Private group from Utah, USA
Fireball	Private group from New Mexico, USA
Tethers Unlimited	Company from Washington, USA
Carbon Neanderthals	Private group from Washington, USA

Table 2: 2005 Strong Tether Teams

7.3 The 2006 Challenges

This event was held at Las Cruces International Airport, New Mexico in conjunction with that year's X Prize Cup. The Power Beaming Challenge was held there over two days. One of the teams, however, had a microwave-powered climber and the Airport refused to allow it to compete on its grounds. So on the third day, the Space Elevator Games moved to the nearby County Fairgrounds and finished up there. Coverage of the 2005 Challenge had drawn worldwide interest and resulted in 20 teams registering for the 2006 event, including the first non-North American entries. For this year's Challenges, NASA put up a total prize purse of $400,000 - $300,000 in 'new' money plus the $100,000 left over from the 2005 event - a total of $200,000 for each challenge.

The 2006 Power Beaming competition

The Power Beaming rules had many similarities to the 2005 competition; the racecourse was still a 50m-high, 10cm-wide ribbon suspended from a crane, competitors would still mount their climbers on the ribbon and start their timed climb at 5m and the goal was still 1m/s. However, the teams now had to provide an end-to-end solution, i.e. they had to bring their own beam source. Also, NASA increased the prize purse to $200,000. Six teams passed the qualification runs and were able to compete (Table 3).

Team Name	Where from	Power Source
USST (University of Saskatchewan Space Design Team)	University of Saskatchewan, Saskatchewan, Canada	Searchlights
Snow Star	University of British Columbia, British Columbia, Canada	Reflected sunlight
MClimber	University of Michigan, USA	Searchlights
TurboCrawler	Max Born College, Germany	Searchlights
Kansas City Space Pirates	Kansas City, Kansas, USA	Reflected sunlight
Lite Won	Campbell, CA, USA	Searchlights

Table 3: 2006 Power Beaming Teams

In addition, there were several other teams that registered and showed up, but were unable to compete for various reasons. These were:

- Recens – A team from Spain. Their equipment got caught up with a customs issue in Germany and ultimately did not arrive at the competition.
- SpaceMiners – They burned out four cells on their photocell array on a qualification attempt and ultimately were unable to repair their climber in time.
- Star Climber – They suffered an ultimately fatal mechanical problem with the ribbon gripping mechanism and the gears driving it trying to qualify.
- Beamer1 – When their climber was being weighed in, it somehow got disconnected from the scale and crashed to the ground. The lens fractured and became unusable.
- PunkTaurus – This was a combination of the PunkWorks and the Centaurus Aerospace teams. The PunkWorks climber was powered by microwaves, but the team could not get their equipment working and it looked like they would not be able to compete. At the last minute, however, the Centaurus Aerospace team arrived and they too, had a microwave-powered climber. The two teams decided to combine forces and thus PunkTaurus was born. As mentioned earlier, the Power Beaming competition was eventually moved to the local County Fairgrounds to give them a chance, but in the event they could not get their equipment working.

All climbers of the competing teams were able to successfully climb to the top of the tether except Snow Star and the Kansas City Space Pirates (KCSP), which did, however, successfully negotiate a significant portion of the course. MClimber had the distinction of being the very first climber to ascend the entire length of the ribbon while USST completed the course in by far the best time of 57 seconds, just two seconds too slow to claim the prize. USST's time was so close that the Spaceward Foundation had to re-measure the ribbon for elastic and plastic elongation to determine if a winning run had been made. One other note about the entry from USST is worth mentioning - they came very close to winning with their second choice of beam power. They had brought a laser and hoped to power their climber with it, but were ultimately unable to get it working properly and had to resort to using searchlights.

The 2006 Strong Tether competition

The rules for the 2006 Strong Tether Challenge were similar to those from 2005, but the weight requirement was reduced from 2.5g to 2g and the length requirement was reduced from 2.5m to 2m. NASA also increased the prize purse for this Challenge to $200,000. Four teams registered for and competed in the Challenge (Table 4).

Team Name	Where From
Astroaraneae	Private group from California, USA
Snow Star	University of British Columbia, Canada
Centaurus Aerospace	Private group from Utah, USA
Fireball	Private group from Washington, USA

Table 4: 2006 Strong Tether Teams

While tethers from all four teams met the 2g limit qualification, only the tether from Astroaraneae met the 2m limit qualification. This meant that Astroaraneae won the competition among the individual teams by default, something which caused much heartache from the disqualified teams. In the spirit of competition, however, the Fireball and Snow Star tethers were matched against each other in a "non-title" match. Snow Star won when Fireball's tether parted at 240kg. Snow Star then took on Centaurus Aerospace in another friendly competition. Centaurus Aerospace won when the Snow Star tether parted at about 400kg. The Astroaraneae tether was then matched against the House Tether to see if it would qualify for prize money. Alas, it did not, breaking at about 600kg. And as it turned out, this was the strongest measurement of any competitor's tethers in the entire Games. Once that was completed, the House Tether was then matched against some rope, just to see what level the House Tether would break at. Unfortunately, both tethers proved to be too strong for the TTR and they broke the machine – a fitting end to a disappointing competition!

7.4 The 2007 Challenges

This year's Challenges were held at the Davis County Event Center in Layton, Utah. Originally scheduled to run from 19-21 October, they were extended by several days due to weather-caused delays and also to accommodate additional competition runs.

The 2007 Power Beaming competition

The rules for the 2007 competition again were similar to the 2006 rules, but the height of the racecourse was doubled to 100 meters and the speed necessary to win a prize was also doubled to 2m/s. The prize purse was also significantly increased to $500,000. While some 20 teams registered for the competition, only seven actually showed up (Table 5).

Team Name	Where from	Power Source
USST (University of Saskatchewan Space Design Team)	University of Saskatchewan, Saskatchewan, Canada	Laser
LaserMotive	Professional group from Washington, USA	Laser
Punkworks / McGill	Canada	Microwaves
E-T-C	Japan	Searchlights
Technology Tycoons	Campbell, CA, USA	Searchlights
Kansas City Space Pirates	Kansas City, Kansas, USA	Reflected sunlight
Snow Star	British Columbia, Canada	Reflected sunlight

Table 5: 2007 Power Beaming Teams

All the competing teams were able to mount climbers on the ribbon and attempt runs, but three of them, LaserMotive, Punkworks and Snow Star, were unable to make it to the top of the ribbon. The Kansas City Space Pirates had the fastest measured climb rate over a significant portion of the ribbon, well over 3.5m/s, but unfortunately could not keep this up over the entire climb. Their best time to the top of the ribbon averaged out at 1.25m/s. USST had the fastest climb to the top of the ribbon (and they were able to make multiple climbs to the top, the only team to do so) but their best time, 1.8m/s, was just slightly under the required 2m/s necessary to be eligible for a prize. This was the third Power Beaming competition in a row where the USST Climber had the best performance.

The 2007 Strong Tether competition

The rules for the 2007 Strong Tether Challenge were very similar to the 2006 Challenge; the tethers had to be at least 2m in length, they could weigh no more than 2g and they had to beat the House Tether (which could weigh 50% more) in order to be eligible for prize money. The prize purse in this Challenge was also increased to $500,000. Only two teams entered tethers for this Challenge: Delta-X from MIT, Massachusetts and Astroaraneae, the private group from California.

While the tether composition from Astroaraneae was unknown, Delta-X brought the first carbon nanotube tether ever entered into the Strong Tether competition but it was so new that they had not had time to form it into a true loop and so they wound up tying the ends together in a knot. The tethers from both teams met the qualification criteria, so they were matched up in a head-to-head competition. It was a foregone conclusion that the Delta-X entry would separate at the knot and this was, in fact, what happened - it was a rather anticlimactic victory for Astroaraneae. They were then to be matched against the House Tether to see if they would be eligible to win a prize, but they inexplicably refused to do so. So, once again, there was no prize winner this year.

7.5 The 2009 Challenges

It had originally been hoped to have the next set of Challenges in 2008, but several factors, most significantly that of trying to find a venue which could handle the new Power Beaming Challenge requirements, conspired against this. After a lot of searching, the venue selected was the NASA Dryden Flight Center located in southern California near Mojave. The Power Beaming competition was first scheduled in early 2009, and then in August but it was finally held in November of that year. The Strong Tether Challenge was held in conjunction with the annual Space Elevator Conference held by the International Space Elevator Consortium in August.

The 2009 Power Beaming competition

The rules for the 2009 Power Beaming Challenge were similar to those of the 2007 competition but the requirements to win any money were made significantly more difficult. The prize purse for this Challenge had been increased by NASA to $2,000,000. Teams had to have their climber ascend the competition tether with a minimum speed of 3m/s to be eligible for the first-level prize of $900,000. If a team could make the run with an average speed of at least 5m/s, they would then be eligible to win the entire $2,000,000. The racecourse for this event was a one kilometer long steel cable held aloft by a helicopter. The starting point was at 100m so the timed run was 900m long. Because of the difficulty in satisfying these requirements, only teams with laser-powered climbers joined this competition. There were three of them, all veterans of previous years' events, namely USST, LaserMotive, and KCSP.

Each team used a different tracking mechanism to keep their laser pointed at the photovoltaic cells on the climber. USST used a GPS-based system, the Kansas City Space Pirates team used an automatic beam tracking system, while LaserMotive tracked their climber manually with a camera and a joystick. LaserMotive was the only team to be able to climb the entire length of the cable and they did so multiple times. In addition, they were able to climb the cable in a best time of 3 minutes, 48 seconds, which worked out to a speed of about 3.95m/s, more than enough to win the $900,000 prize. Once they had qualified for that prize, they then stripped off every gram they could from their climber in an attempt to win the $2,000,000 prize, but it failed during the ascent. KCSP was able to climb several hundred meters multiple times, but different failures kept causing them to be unable to travel the full distance. And, in something which remains inexplicable, the USST climber was barely able to climb any distance at all. They were the most experienced team (all-round and with lasers) and they had performed the best in the previous three competitions, but this time around it was just not to be. Still, these Challenges were finally able to award some prize money with $900,000 going to the LaserMotive team.

The 2009 Strong Tether competition

For this year's Challenge, NASA had increased the prize purse to $2,000,000 and, concomitantly, rules to win prize money were even more difficult than in previous years. A competition tether still had to meet the 'no less than two meters long and weigh no more than two grams' requirement and then would have to beat the House Tether in a head-to-head match. If successful, it would then have an absolute measurement made of its breaking strength. If this exceeded 5MYuris (5GPa-cc/g or 5N/Tex), then it would be eligible to win prize money. There was only one entrant in this year's competition, namely Shizuoka University from Japan having a tether composition of carbon nanotubes.

This was only the second carbon nanotube tether that had been seen in a Strong Tether competition and, unfortunately it did not perform any better than the one from Delta-X in 2007. While it looked like a thin ribbon and was formed as a true loop without a knot holding it together, it parted at a very low load, barely registering on the strain meter.

7.6 The 2010 and 2011 Challenges

In 2010 and 2011, only the Strong Tether Challenges were held. As with the 2009 Strong Tether Challenge, both of these events occurred during the annual ISEC Space Elevator Conference held at the Microsoft Conference Center in Redmond, Washington. The rules for both of these Challenges were identical to the 2009 Strong Tether Challenge, as was the prize purse of $2,000,000.

In 2010, three teams entered. A tether of pure carbon nanotubes was submitted by Bryan Laubscher of Odysseus Technologies, LLC (out of Washington). Chris Cooper, an independent inventor out of Vermont, submitted an entry (composition unknown), while a third entry, combining carbon nanotubes and glass fibers, was submitted by Professor Gilberto Brambilla, a scientist from Spain. None of these tethers performed well - all of them broke at a strain level well below values of common string. This competition was noteworthy, however, because it was attended by both Yuri Artsutanov and Jerome Pearson. The results were so disappointing that, at one point, Yuri light-heartedly offered his tie as a competitive entry.

In 2011, only two teams entered. Odysseus Technologies brought another carbon nanotube tether, while Flint Hamblin, an independent inventor, brought a tether that was, as far as we know, made from some commercially available fiber which may have been 'salted' with carbon nanotubes. Again, both of these tethers broke at a very low strain level - below the 5MYuris threshold, a truly disappointing result.

7.7 Demise of the Two NASA Challenges

There was some interest in holding one more set of competitions in 2012, but ultimately this did not happen. Unfortunately, NASA decided not to renew these two particular Challenges, despite persistent efforts from the International Space Elevator Consortium to get them to renew the Strong Tether Challenge. NASA does, though, still run a Centennial Challenge program and currently there are four Challenges: 3D-Printed Habitat; Cube Quest; Space Robotics; and Vascular Tissue. Details on these, as well as past Challenges can be found at https://www.nasa.gov/directorates/spacetech/centennial_challenges.

7.8 Challenges Elsewhere

The idea of holding annual or, at least, regular space elevator challenges or competitions was not put on hold after NASA decided to no longer support such events. There were already overlapping events in Europe and Japan as entities there commenced organizing similar challenges and competitions. The International Space Elevator Consortium did hold one more in America and Israel also introduced a one-off competition as part of a broader annual technology competition (Swan and Raitt, 2016). These challenges are described below.

United States of America

Since 2011, in conjunction with its annual conference in Seattle, ISEC has held a youth robotics competition known as Robo Climb. The aim is to motivate teams from schools to build and program autonomous robots that are able to climb a tether and that simulate space elevators carrying payloads into orbit. Prizes are awarded for best performances as well as innovative robotic designs and climbing mechanisms (see the ISEC website at www.isec.org). Rules were established for the competitions - in 2016, for instance, the robots had three minutes to carry as many 'satellites' up a very short taut woven nylon ribbon (1.8m long and approximately 8cm wide) and leave them at the top. The weights of the satellites varied between approximately 110g, 225g and 450g. There were two classes of robots: LEGO Only, and (Almost) Anything Goes and each class was judged separately. LEGO Only are robots built completely from LEGO, using standard LEGO building techniques (no gluing, cutting, melting, etc.). As many motors or sensors as necessary could be used and any programming language was permissible. Robots in the (Almost) Anything Goes class could be built with anything else - any processor and any materials. The only restrictions were that the power source had to be electric batteries, and all processing had to be done on the robot.

Europe

The European Spaceward Association (EuroSpaceward) held two climber competitions in Luxembourg in 2007 and 2008 and there was talk of organizing a third in 2009. Unfortunately, the details have been lost as the EuroSpaceward website (www.eurospaceward.org) is no longer accessible, though snapshots can be found via the WayBack Machine at archive.org. However, with the demise of EuroSpaceward, the organization of the European Space Elevator Challenge (EuSPEC) has been taken up by WARR e.V., the Scientific Workgroup for Rocketry and Spaceflight at the Technical University of Munich (TUM) in Germany. Founded in 1962, the aim of WARR is to provide its members with the opportunity to accomplish scientific work and gain experience in practical projects related to their studies. Accordingly, the Challenge (euspec.warr.de) is to establish a climber structure in compliance with predetermined requirements, bearing in mind the idea of a real space elevator. The focus is on the efficiency of the climber, the technical implementation of the climber (especially the payload system), and aspects which directly impact the development of the 'real' space elevator (Swan and Raitt, 2016).

To date there have been three such competitions in **Europe**:

- EUSPEC 2011, a climber competition for 25m held at TU Munich, Germany with six entries: Aoki Bravo A (Nihon University, Japan); Aoki Bravo B (Nihon University, Japan); Earth Track Controllers (USA/Japan); Egami Lab, (Kanagawa University, Japan); Irie Lab. (Nihon University, Japan); and WARR Space Elevator (TUM, Germany). Teams from Cambridge, England and Macedonia cancelled and the team from Iran was unable to obtain visas. The winner of both Level 1 and Level 2 was Earth Track Controllers. The Technology Award went to Aoki Bravo B and the Innovation Award went to Egami Lab.

- EUSPEC 2012, a climber competition for 50m held at TU Munich Germany with six entries: Aoki Lab. A (Japan); Aoki Lab. B (Japan); Earth Track Controllers (USA/Japan); Egami Lab of Kanagawa University (Japan); Irie Lab. (Japan); and WARR Space Elevator (Germany). The winner of Level 2 was Aoki Lab. B. The team also took the Technology Award; while Irie Lab took the Innovation Award.

- EUSPEC 2016 took place from 12-15 September at the Garching Campus of TU Munich. The drive height was doubled to 100m and there was a new category for high school teams and beginners. The Advanced level competitors included only three team: Aoki Lab. A (Nihon University, Japan); Aoki Lab. C (Nihon University, Japan); last.minute space elevator (TUM, Germany). Aoki Lab. B (Nihon University, Japan); Caterpillar (University of Stuttgart, Germany); and Team ORION (Indian Institute of Space Science and Technology, India) all cancelled. At the Beginners level were two teams: Space Group Hof (Schiller Gymnasium Hof, Germany); and Meier's Eleven (Gutenbergschule Wiesbaden, Germany). Three teams cancelled: ESEF (Tallinna Reaalkool, Estonia); GOTech (Gymnasium Ottobrunn, Germany); and TURAG Space (TU Dresden, Germany).

Japan

The Japan Space Elevator Association (JSEA) (jsea.jp) has been holding climber and tether competitions since 2009, each with an increasing level of difficulty (much the same as the NASA-Spaceward Space Elevator Games which the Japanese had attended), but the climbers in these two competitions are electric battery-powered. The purpose of the Space Elevator Challenge in Japan is to provide an actual chance for researchers, engineers and young people to study and enhance their understanding of space elevator related systems. Such a Challenge also offers good chances to spread the basic concepts of the space elevator to a larger audience. Whereas the Spaceward Foundation used a crane in 2007 and a helicopter in 2009 to hang the tether, JSEA uses helium balloons due to the lower cost and other potential uses of such a tethered balloon system. During 2012, JSEA changed the concept from one of competition to one of understanding the evaluation of climbers and how they should develop as well as the tether. The tethered balloon systems provide the platform to evaluate not only different materials for the tethers themselves, but also differing climber technologies as well as providing basic knowledge about the function of a real space elevator tether.

The Japanese Tether Climber competitions have two types, JSETEC/SPEC and LASER. The former competitions are the serious ones, with balloons outdoors and battery-powered climbers. There is a practical aspect behind the competitions - the plan to scale-up and build a 30km-high tethered balloon system with multi-powered durable climbers by 2020. One of the purposes is to increase not only the knowledge and issues of tether climber designs, but also the investigation of batteries and power issues. In what is probably the first text in English to cover the JSEA Space Elevator Challenges, Ohno (2016) provides a complete overview of the competitions and challenges for tethers and climbers in Japan since 2009 and summarizes the results and lessons learned of each.

Israel

On 18 June 2014, a space elevator competition was scheduled at Technion, Tel Aviv, Israel for the latest in the annual Technobrain Competitions, held at Technion, which have the aim of driving engineering students towards academic goals, through a design, build, test and race process. The challenge for the teams in this twelfth Technobrain competition was:

> 'to build a device capable of climbing in a nearly vertical manner (at an 80 degree angle to the ground), to a height of 25 meters (for this purpose the Technion has ordered a huge crane), and then slide down from this height while lifting a 'space elevator' carrying practical cargo from the other side of the pulley (the position of the pulley will signify the location of the Space Station in space, while the mission course will emulate the movement of the space elevator).' (http://www.technion.ac.il/en/2014/06/space-elevators-technobrain/)

Yuri Artsutanov was invited to be one of the judges, and among the competitors were three father and son teams comprising Technion graduates and students. Ishai Zimerman and Ronen Atzil won the prize.

7.9 Conclusion

No-one yet knows, of course, how and when we are actually going to build a space elevator, but when that day comes, it is fair to say that the Space Elevator Games and Challenges in America, Europe and Japan, will be seen as an important early step in the process. Most, if not all of the technologies used in the Power Beaming competition will probably be relevant, even if lasers are ultimately replaced with another power source.

The need for a material to create a strong tether, is, of course, absolutely crucial to building an Earth-based space elevator. And the goal of the Strong Tether Challenge was to develop a strong but lightweight tether. As noted in Chapter 5.6, the unit of MYuri (N/g/km) takes into account strength and weight of the sample being a measure of force carried per gram per length of tether sample. A strong but heavy tether may have a lower Yuri value than a weaker but lighter sample. For a space elevator tether that may be 100,000km in length, then both strength and weight are obviously important. It has been estimated that the minimum tether strength to build an Earth-based space elevator is in the range of 25-30MYuris about an order of magnitude above the material we have today. It is fortunate that there are now several possibilities for ultra-strong materials in the lab (boron-nitride nanotubes, carbyne, diamond nanothreads and graphene as well as carbon nanotubes) and hopefully a breakthrough will happen in at least one of them in the relatively near future.

Although no competitor was able to claim the NASA Centennial Strong Tether Challenge prize, the strength exhibited in competing tethers has continued to increase over the years as new and innovative methods are discovered for fabricating tethers with carbon nanotube technology. Indeed, research continues in material science technologies necessary to create long, very strong cables with an exceptionally high strength-to-weight ratio. Such tethers will enable advances in aerospace capabilities including reduction in rocket mass, habitable space structures, tether-based propulsion systems, solar sails, and even space elevators. Dramatically stronger and lighter materials are also revolutionizing the engineering of down-to-Earth structures such as aircraft bodies, sporting good equipment, and even structures of bridges and buildings. And just as important is the significant achievement of these Challenges has been the phenomenal involvement of competitors and the visibility given to space elevators through coverage of the Games (Swan, 2016).

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Chapter 8: Space Elevator Conferences and Sessions

8.1 Introduction

When the wider world took a greater interest in the concept of space elevators following the work done by Dr Brad Edwards and funded by the NASA Institute for Advanced Concepts (NIAC) in the early 2000s, the time was ripe for a conference which would bring together like-minded scientists and engineers to discuss ideas, further work and progress to try and make a space elevator happen. Although there had been the occasional space elevator or tether paper presented at diverse conferences, the first conference recognized as having the space elevator as the prime topic was organized by NASA's David Smitherman in 1999; this was followed by an international conference organized by Brad Edwards and held in Seattle in 2002. This turned into an annual conference which subsequently spawned an international event as well as numerous sessions held during the yearly International Astronautical Congresses in different parts of the world. This chapter provides an overview of the major conferences and congresses since 1999 that have had space elevators as a theme, either for the whole conference or for sessions within a broader congress. The focus is on conferences in the United States, Luxembourg, Japan and around the world at IAF Congresses. The chapter also briefly summarizes some of the depictions, technologies, applications and visions for the space elevators as covered by the various papers presented. It should be noted that the proceedings of many of these early conferences are not available - though some of the papers or abstracts presented can be found online.

8.2 Early Space Elevator Conferences

In 2000 David Smitherman compiled a report entitled *Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium* (Smitherman, 2000). This publication was based on the findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, managed by Smitherman, and held at NASA Marshall Space Flight Center, in Huntsville, Alabama, from 8-10 June 1999. Smitherman initiated the workshop primarily after reading an article on Fullerene nanotubes appearing in *American Scientist* in 1997, which noted Clarke's description in *Fountains of Paradise* and indicated that the materials for the space elevator [tether] might be possible in the near future. The workshop was attended by only some twenty participants, mostly from NASA, and included Joe Carroll, Bob Cassanova, Geoffrey Landis, Jerome Pearson, Paul Penzo and John Mankins. Arthur C. Clarke was invited to the workshop but had to decline because he was overwhelmed with projects and also wheelchair-bound. The topics covered at the conference related to the space elevator concept and basics; technology development paths in materials, tension structures, compression structures, electromagnetic propulsion; supporting infrastructure; and issues such as environmental and safety. The conference report provided key findings from the conference as well as the pros and cons of building space elevators, together with concerns and possible solutions, and also recommendations. The overall conclusion was that the space elevator was not a near-term project but a potential project for the latter part of the 21st century.

At a joint conference Space 2002 and Robotics 2002 (being the 8th International Conference and Exposition on Engineering, Construction, Operations, and Business in Space and the 5th International Conference and Exposition/Demonstration on Robotics for Challenging Situations and Environments) held in Albuquerque, New Mexico, 17-21 March 2002 (proceedings published by the

American Society for Civil Engineers and edited by Bryan Laubscher and others) there were a number of papers presented on space elevators and tethers. These included “Kinetically Supported Bridge Vehicle Lift to GEO” by James Cline; “The Space Elevator: Concept Overview” and “The NIAC Space Elevator Program” both by Bradley Edwards; “A High Payload Capacity Tether System” by Aaron Smith; “The Virtual Beanstalk Project for a Near Space Elevator “ by Allen Meece; and “The Economics of a Space Elevator” by Eric Westling.

Although also not a conference about the space elevator *per se*, at the 1st International ASI (Italian Space Agency) Workshop on Futuristic Space Technologies held in Trieste, Italy from 6-7 May 2002, and attended by Brad Edwards and David Raitt amongst others, Bob Cassanova from NIAC gave a very interesting presentation on visions of the future. In his talk he touched on various NIAC-funded studies including Edwards’ Phase II study on the space elevator (http://www.niac.usra.edu/files/library/meetings/misc/trieste_may02_mtg/Cassanova_Bob.pdf). He was followed by Brad Edwards who gave a more detailed presentation about the space elevator based on his studies for NIAC. And David Raitt also mentioned the space elevator in his presentation on Innovative Technologies from Science Fiction which had included the space elevator as one of the topics considered (see Chapter 3).

What is generally taken to be the first annual and international conference to focus on the space elevator was the one organized in Seattle on 12-13 August 2002, sponsored by HighLift Systems. The company was established by Brad Edwards who had teamed up with Michael Laine who ran the business side of things. The conference was attended by some 60 people - academics, scientists and engineers from industry and government labs, people working in the field of space transportation systems, materials, physics and the like. Among them were Jerome Pearson, Bryan Laubscher, Bob Cassanova, Anders Jorgensen, Eric Westling, Margaret Roylance and others, including Li Feng from China who spoke on the status of carbon nanotubes. There was also a representative (Dr David Raitt) from the European Space Agency who agreed to be the ESA contact and recruit and orchestrate European efforts that could assist the program.

If there were any proceedings of the conference then possibly one of the original attendees still has them, but to all intents and purposes they are unavailable and unfortunately there is not much in the public domain that discusses what was covered by this first conference or who was present. However, in his NIAC Phase II Final Report, Brad Edwards makes some mention of the conference and does provide the conference schedule, pointing out that it covered all technical and non-technical aspects of the program. Against all the topics noted (such as CNT composite status, ribbon design, anchor station, tall towers, meteors, budget, finance and so on) the name and affiliation of the presenter was given. The technical aspects of the program were discussed thoroughly during the conference, but other equally critical areas arose and marked the beginning of a new set of efforts. Legal and funding issues were at the top of the list and it was noted that fuller investigation of these would be covered elsewhere in the report (Edwards, 2003).

There are a few snippets though from the press at the time and they are worth just mentioning here to help document this important event. The *Seattle Times* ran a piece about Brad Edwards’ dreams for a space elevator stretching 100,000km in its issue for 8 July 2002 and announced the conference which was organized by Confcon (https://www.ocf.berkeley.edu/~temina/ekarmon/seattle/seattle19.html). The World Edition of BBC News briefly reported on the conference on 12 August 2002 in an item headed ‘Space elevator takes off’ and noted that HighLift Systems was looking into the idea of a space elevator backed by a $570,000 grant from NASA. The BBC noted that representatives from the European Space Agency, NASA and investment companies attended the two-day conference (http://news.bbc.co.uk/2/hi/technology/2188107.stm). On 14 August 2002, Dan Rowe of the *National Post*, also commented on the conference under the heading ‘Going Up? Space elevator wins support - U.S. company builds on Russian idea' (http://www.freerepublic.com/focus/news/732741/posts). A few days later, on 19 August 2002,

Leonard David (who also attended the event) writing in Space.com also mentioned the conference though the thrust of his article entitled 'Going up? Private group begins work on space elevator' was more about comments on the necessary developments by attendees such as Edwards, Roylance, Laine and Cassanova (http://lakdiva.org/clarke/going_up__private_group_begins_work_on_space_elevator.html). There were also a couple of brief news items elsewhere, but they are just based on the above texts.

However, this initial conference stimulated a greater interest and awareness in the concept and the participants agreed that it would be useful to continue the dialogue and research. As a consequence, the 2nd Annual Space Elevator Conference took place in Santa Fe, New Mexico from 12-15 September 2003. The event was hosted by Bryan Laubscher through the Los Alamos National Laboratory. We are fortunate to have notes taken by Blaise Gassend for the first two days of the event (http://gassend.net/spaceelevator/conference-notes/index.html) which opened with an introductory talk by Sir Arthur C. Clarke in Sri Lanka via a live video link connection. Clarke discussed the coverage the space elevator was currently getting in the press, addressed the topic of space debris, and gave his opinion on various technical aspects. All who were present agreed with Sir Arthur that it was time to get serious. Other introductory remarks were made by Brad Edwards and host Bryan Laubscher. Thereafter followed technical sessions with various papers being presented, questions asked and discussions ensuing on carbon nanotubes (Andrews; Zhu), tether technology (Gassend; Canning; West), tether environment and hazards (Rogers; Jorgensen), power beaming (Edwards), systems engineering (Pullum; Swan), climber technology (Laubscher), anchor location Gardner; Ragan), deployment issues (Smith; Butler), health and safety concerns (Morgan; Yancey), political issues (Darrah; Edwards), and cost issues (Edwards; Westling). Michael Laine showed a video of a high school ribbon climbing competition, there was a presentation on NIAC (Russel), and mention was made by Bruce Mackenzie of the effort to set up a Space Elevator Institute to coordinate volunteer effort on the space elevator. It was also noted that the annual International Astronautical Congress (IAC) starting in 2004 would have regular sessions on the space elevator which would be organized and chaired by David Raitt and Peter Swan.

The 3rd Annual Space Elevator Conference was held from 27-30 June 2004 in Washington, DC., organized by Brad Edwards through his then-current company the Institute for Scientific Research. Again we have notes made by Blaise Gassend who commented that still the big hurdle for the space elevator was the material as there had been no major breakthrough (http://gassend.net/spaceelevator/3rd-conference-notes/index.html). Many people who were at the 2nd conference were also at the 3rd. Edwards and Laubscher again made introductory remarks and were followed by the keynote speaker John Mankins who discussed what NASA's plans and budget were in relation to President Bush's new space vision. As before, the papers and presentations covered many topics, among them a review of carbon nanotube polymer composites (Andrews); a material analysis of the space elevator ribbon at selected altitudes (West); and a direct process for spinning fibers from carbon nanotubes (Kinloch). Laubscher and Bennett discussed powering the elevator, with the former concentrating on space solar power. Laubscher also gave a presentation of the defense of the space elevator. Gassend covered exponential tethers for accelerated elevator deployment; while Steven Patamia presented an analytic model of single cable dynamics. Ben Shelef talked about the power system for the climbers, as well as ribbon architecture and LEO deployment. There were papers on threats to the ribbon from satellites and debris and how to mitigate them (Gardner; Dzierski; Jorgensen); and the political and legislative landscape were covered by Chase. Edwards and Bartosek discussed climber design; Swan gave an architectural view of the space elevator; and a couple of speakers discussed health effects of carbon nanotubes (Yancey; Morgan). There was also mention of the NASA Centennial Challenges (Davidian).

After these first three early annual space elevator conferences, the landscape changed with these conferences becoming biennial and part of a larger conference and then later morphing into the International Space Elevator Conferences organized by the International Space Elevator Consortium (ISEC). At the same time, however, there were other conferences on the space elevator being organized in Europe (see below), and sessions on the space elevator being incorporated within the International Astronautical Congresses (see below).

There was no annual space elevator conference in 2005; however, in that year the Space Engineering and Science Institute (SESI) created Space Exploration 2005 - the 1st International Conference and Exposition on Science, Engineering, and Habitation in Space - held 3-6 April 2005 in Albuquerque, New Mexico. An important component of the conference was the 1st Biennial Space Elevator Workshop. Among the papers presented were three by James Cline - one on the characteristics of space escalator carousels versus space elevators, another on the space carousel's unique potentials, and one on carousel spacecraft electrical lift around the Earth up to GEO. Larry Bartoszek looked at the space elevator ribbon and climber from a machine design perspective, while Blaise Gassend discussed the fate of a broken space elevator. Brad Edwards talked about the operating costs of a space elevator as well as current activities, business developments and ongoing efforts. Other presentations were on CNTs and tether dynamics (http://gassend.net/spaceelevator/SEC2005/index.html).

SESI issued a call for papers for the 2nd International Conference and Exposition on Science, Engineering and Habitation in Space and the 2nd Biennial Space Elevator Workshop to be held 25-28 March 2007 again in Albuquerque, New Mexico. This conference was recommended for anyone who wanted to participate in making a space elevator a reality. Bryan Laubscher brought the audience (most of whom were not there for the Space Elevator portion of the conference) up to speed on the current concept (Brad Edwards' version) of the space elevator. Ted Semon addressed who would build the first, Earth-based space elevator, and Haym Benaroya, from Rutgers University, gave a couple of presentations on lunar aspects. Tom Nugent of LiftPort gave a talk on the rationale behind LiftPort's Beta Roadmap, while Bryan Laubscher ran through space elevator and rocket cost comparisons, and later the role of a space elevator in mitigating threats to Earth. Brad Edwards gave a presentation on a new organization - the European Spaceward Association - created to help foster interest in Europe towards developing a space elevator (see Chapter 6.4.4 and below). Fred Cowan of Raytheon also gave a presentation which looked at a different space elevator approach. There were, in addition, a number of other equally stimulating and interesting presentations. A robotic climber competition was held during the conference.

In 2008 the Space Elevator Conference was held from 18-20 July at the Microsoft Conference Center in Redmond, Washington at the suggestion of Bryan Laubscher who became conference chair. This was the fourth such international gathering of engineers, scientists, entrepreneurs and enthusiasts devoted to exploring the means of developing and utilizing a space elevator. Brad Edwards was the keynote speaker and he gave an overview of the space elevator. The first session focused on why the space elevator; the next session asked how close were we to creating the elevator. Two sessions followed looking at what kind of world would be created if we had a space elevator. A fifth session examined legal issues; another covered economics; while others were devoted to technical considerations.

The 5th International Space Elevator Conference sponsored by Microsoft and JPL Foundation was held from 13-16 August 2009 in Redmond again under the chairmanship of Bryan Laubscher, with some 280 delegates from Japan, Armenia and other far-off locations, as well as the USA. The conference brought together a wide cross section of experts and members of the lay public to learn and exchange ideas and a strong NASA presence attesting to the growing influence of the concept. Seeking innovative solutions to NASA's technical challenges through open prize competitions the space agency's two Challenge Competitions on Power Beaming and Strong Tethers were described by Ben Shelef. The conference was notable for a demonstration (in fact, the 2009 NASA-Spaceward Strong Tether competition), which unfortunately failed. Yoku Inoue and his team from Japan brought a 2.2m long loop of carbon nanotube material and presented an impressive briefing of their entire system for manufacturing CNT ribbons. In the test rig, however, the sample failed at well below its expected strength. Discussion followed about the kind of tether required (stationary or moving) as well as presentations about its oscillations. The abstracts of presentations can be found at http://www.isec.org/images/Store/0092010ConferenceInformation.pdf. Notes on the conference were made by Charles Radley (http://hplusmagazine.com/2009/08/31/notes-space-elevator-conference-august-13-16-2009/). There are also various videos on the various space elevator games on YouTube, for example https://www.youtube.com/watch?v=zO1EV6A76ZE.

The Space Elevator Conference for 2010 was held once more at Microsoft Headquarters in Redmond, Washington from 13-15 August. A free public lecture by Bryan Laubscher kicked the event off and the conference, focusing on all aspects of space elevator development, engaged an international audience of scientists, engineers, educators, managers, entrepreneurs, enthusiasts, and students. The focus of the 2010 conference was space debris mitigation, but it also featured topical discussions in all of the four pillars of space elevator development, namely: Science/Technical; Political/Social; Legal; and Economic. Papers were presented on the optimal design of tethers; updated reviews of nanotechnologies for the space elevator; space elevator construction issues; space elevators and Mars; and who could establish a space elevator. The NASA Strong Tether challenge was also held, though again no-one won. However, what was especially noteworthy was that the conference was attended by two of the leading pioneers in the field - Yuri Artsutanov and Jerome Pearson. In fact the conference was held on the 50 year anniversary of the publishing of Artsutanov's original article. Abstracts of papers presented at the 2010 conference can be found (after the 2009 conference papers) at http://www.isec.org/images/Store/20092010ConferenceInformation.pdf.

The Space Engineering and Science Institute issued its annual call for papers for the 2011 Space Elevator Conference at the Microsoft Convention Center in Redmond, Washington between 12-14 August. The Conference was sponsored by Microsoft, the Leeward Space Foundation and the International Space Elevator Consortium. For the fifth year, the NASA Strong Tether competition was a feature of the event again. In the Tether Session: '30 MegaYuris or Bust', there were presentations on making and breaking graphitic nanocarbon; limits of carbon bonds; contrasting carbon fiber and carbon nanotube development; recent progress in CNT materials; and limitations in macroscale CNT materials. Other science and technical session covered the space elevator operations concept; dynamics of space elevator systems; legal issues relating to space debris; and the IAA Cosmic Study on space elevator feasibility. Abstracts of presentations can be found at http://www.isec.org/images/Store/2011ConferenceInformation.pdf.

8.3 International Space Elevator Conferences

From 2012 onwards, the International Space Elevator Conferences have been sponsored by Microsoft, the Seattle Museum of Flight, Space Elevator Blog, the Leeward Space Foundation, and the International Space Elevator Consortium which organizes them. In fact, the yearly conference has gained momentum since the initial event and has taken on its own character. The ISEC Conferences are now run by David Horn who keeps enhancing the value of the dedicated conference.

In 2012, the annual Space Elevator Conference was held for the first time at the Museum of Flight in Seattle from 25-27 August. The theme was operating and maintaining a space elevator and papers covered this aspect as well as carbon nanotube research and strong tethers. Penny introduced the space elevator operations concept (CONOPS); Laubscher gave an overview of a nanotube detangler; Knapman spoke about high stage one; while Kai discussed the relationship of the space elevator to the law of the sea and sky. The Business and Operations session focused on operations for space elevator research (Lades); space elevator justification (Graham); and demand pull for space elevators (Swan). There were, of course, many other technical papers, plus an Outreach session. Abstracts of presentations made at the conference are to be found at http://www.isec.org/images/Store/2012ConferenceInformation.pdf

The theme of the 2013 annual Space Elevator Conference, held once again at the Museum of Flight in Seattle from 23-25 August 2012, was tether climbers. Sessions and papers covered tether materials, such as carbon nanotubes; the Strong Tether Challenge; space elevator feasibility; and the space elevator impact. Jerome Pearson was the keynote speaker and talked about his relationship with Arthur C. Clarke (https://vimeo.com/114408967). Martin Lades presented on climber-tether interfaces; while Larry Bartoszek spoke about the difficulty of getting the mass of the first construction climber to under 900kg. Bryan Laubscher gave a presentation on the various methods that might be used to power space elevator climbers. He also talked about creating strong CNT tethers. Other papers covered electric currents on the elevator; and space elevator operations concepts. During the conference, several mini-workshops were held, delving more deeply, with audience participation, into specific space elevator related topics. One was on Space Elevator Tether Climbers run by Pete Swan and Skip Penny; and another was on lunar elevators run by Michael Laine.

From 22-24 August 2014, the Space Elevator Conference, organized by ISEC, took place once again at the Seattle Museum of Flight. The theme was Architectures and Roadmaps, with a focus on comparing the major space elevator architectures proposed to date. Science author Leonard David gave the keynote address. The preliminary meeting of the ISEC Marine Node team was conducted as a mini-workshop at this conference. Led by Pete Swan, there was a good discussion on the development of the Marine Node, specifically identifying and exploring multiple topics that were essential for making progress on this key element of a space elevator system. Two further mini-workshops were held - one on concepts and issues in space elevator research covering tether materials, dynamics analysis and electrodynamics modeling, and global cooperation. The second was on the space elevator roadmap, the purpose of which was to introduce ISEC's definition of the the five discrete segments of its space elevator architecture, namely: Climber Segment, Tether Segment, Marine Node Segment, HQ/POC Segment and the Tether Tenants Segment. The workshop also sought to seek advice from the attendees regarding the kind of demonstrations they would like to see to prove the viability of the functions within the reviewed segments.

The 2015 conference was held 21-23 August in the same place and had two themes: CNT Tensile Strength Progress; and Marine Node Design. There was also a Youth Robotics Competition - Robo Climb 2015.

The 2016 space elevator conference was held from 19-21 August at the Museum of Flight with the theme Apex Anchor, Geo Node, and Communication Architecture. Papers were presented on these topics and there was also mini-workshops including one on design considerations for space elevator modeling and simulation. There was also the popular Shotgun Science Session competition, as well as the Youth Robotics competition Robo Climb 2016. The proceedings will be available from the ISEC store in Spring 2017.

8.4 International Astronautical Congresses

The International Astronautical Congress (IAC) has been organized annually in different parts of the world since 1950 under the auspices of the International Astronautical Federation, together with the International Academy of Astronautics (IAA) and the International Institute of Space Law (IISL) (http://www.iafastro.org/events/iac/).

8.4.1 Early Days Presentations

There were some papers on the space elevator presented at early congresses and some of the highlights are included below for historical interest.

One of the first was Jerome Pearson who gave a presentation at the 27th IAF Congress held in Anaheim, California from 10-16 October 1976. The title of his paper was "Using the Orbital Tower to Launch Earth Escape Payloads Daily" (paper IAAA 76-123) and was a precursor to his later work on the topic (see Chapter 2).

At the 30th IAC in Munich, Germany on 20 September 1979, the audience was addressed by Arthur C. Clarke, then Chancellor at the University of Moratuwa, Sri Lanka, on the topic "The Space Elevator: 'Thought Experiment", or Key to the Universe?" His paper was essentially a semi-technical survey of the rapidly expanding literature of the subject, with some speculations about ultimate developments. Whether or not the space elevator could be actually built, it was, nevertheless, of great interest as the only known device which could replace the rocket as a means of escaping from the Earth. If it was ever developed, it could make mass space travel no more expensive than any other mode of transportation. Clarke said what he wanted to talk about was a space transportation system so outrageous that many of the audience might consider it not even science fiction, but pure fantasy. Perhaps it was; only the future would tell. Yet even if it was regarded as no more than a 'thought-experiment', it was one of the most fascinating and stimulating ideas in the history of astronautics.

Clarke went on to consider the problem of nomenclature - what should the space elevator be called, and then the history, starting with Tsiolkovsky, and including others who we do not normally consider part of the space elevator vanguard but who were considering extremely long cables for other applications such as deep sea oceanography. He discussed the problem of materials and gave examples of substances that might possibly be used, before moving on to the deployment of the cable and the mass anchor. In his wide-ranging address he also covered possible catastrophes, dynamic systems, power and propulsion, subsidiary problems, and the linking of geostationary satellites around the world to prevent them from colliding. The same idea was promulgated almost simultaneously by the Russian G. Polyakov. But they were both anticipated by Buckminster Fuller who, in 1951, designed a free floating tensegrity ring-bridge to be installed out from and around the Earth's equator. Within this halo bridge, the Earth could continue its spinning while the circular bridge would revolve at its own rate. Fuller foresaw Earthian traffic vertically ascending to the bridge, revolving and descending at preferred Earth loci. Clarke concluded that all Fuller's vision needed to make it reality was the space elevator. And it was in this speech that, when asked when it was likely to happen, he stated "The Space Elevator will be built about 50 years after everyone stops laughing" (Clarke, 1981).

Tsuotomu Iwata of the National Space Development Agency of Japan had applied on 8 March 1979 to present a paper at the 30th IAC entitled "Space Escalator: a Quasi Permanent Engine in Space'. He succeeded in presenting it at the 31st Congress of the IAF held 22-27 September 1980 in Tokyo, Japan with the slightly modified title of "Space Escalator: Semi Perpetual Motion in Space" (Iwata, 1980).

At the 46th International Astronautical Congress held from 2-6 October 1995 in Oslo, Norway, Geoffrey Landis and Craig Cafarelli presented a paper which took another look at Tsiolkovsky's tower (see Chapter 2). Their conclusion was that building a compression structure from the ground up was unrealistic since there was no material in existence with enough compressive strength to support its own weight under such conditions (Landis and Cafarelli, 1995).

At the 48th IAC in Turin, Italy, held 6-10 October 1997, Jerome Pearson gave a paper entitled "Konstantin Tsiolkovski and the Origin of the Space Elevator". In it Pearson reviewed the relevant writings of Tsiolkovsky which revealed he was seeking to nullify the force of gravity that binds us to the Earth and then went on to describe the Russian's 'thought experiments'. Pearson examined these and the manner in which they were carried out and then compared Tsiolkovsky's writings with Artsutanov's and his own space elevators, as well as other concepts for space tethers. Pearson concluded that while Tsiolkovsky anticipated applications of space tether launched payloads, the invention of the space elevator cannot be attributed to him (Pearson, 1997). See also Chapter 2.

8.4.2 Regular Sessions

Starting with the 55th IAC Congress held in Vancouver, Canada from 4-8 October 2004, there have been regular annual sessions on the space elevator ever since organized by Dr Pete Swan and Dr David Raitt under the auspices of the IAA. The idea of organizing them was to bring the concept of the space elevator to a much wider worldwide audience than was possible with the yearly Space Elevator Conferences which were held only in the United States. Each of the IAC sessions was regularly attended by some 50-60 people and the papers give a good overview of the way that current thinking on the design, technology and deployment, particularly of the tether has progressed over the years. Interestingly, few papers were presented on the materials aspects - the carbon nanotubes; and eventually the discussion of climbers dropped out of the research effort - possibly because there were no new designs forthcoming. The abstracts of all the papers submitted to the Space Elevator sessions at the IAC, together with their full titles, authors and affiliations, can be found at https://iafastro.directory/iac/archive/.

The first sessions specifically devoted to the space elevator at the IAC in Vancouver in 2004 were included as part of the IAA Symposium on the Far Future: Renewed Visions. There were three sessions devoted to: Space Elevator Ribbons and Tethers in Space; Space Elevators: Systems

Architecture and Technology Development; and a Poster Session on Space Elevators and Advanced Tethers. There were ten papers presented in each of the first two sessions and seven in the poster session. The first presentation was an overview of the space elevator program at ISR (Institute for Scientific Research) given by Brad Edwards. Other papers in the first session were on tether deployment ground tests (Lansdorp); tethers as far mission descent-return tools; space elevator radiation hazards and how to mitigate them (Jorgensen); partial beanstalks for Mars exploration (Parkinson); and space elevator base leg architecture. The second session included presentations on the space elevator and NASA's new space initiative; space elevator's architectural view (Swan; Pullum); space elevator economics and applications (Raitt); lunar transportation scenarios utilizing the space elevator; space elevator systems engineering analysis (Laubscher); and the lunar space elevator (Pearson).

At the 56th IAC in Fukuoka, Japan from 16-21 October 2005, there were again three sessions on the space elevator again held as part of the IAA Symposium on the Far Future: Renewed Visions. These sessions were: Space Elevator System and its Environment (7 papers); Space Elevators and Advanced Tethers: Applications and Impacts (10 papers); and a Poster Session on The Far Future: Renewed Visions (3 papers). The papers discussed such topics (among others) as the motivation for a space elevator (Swan); private investment and space elevator development activities (Edwards); payload dynamics (McInnes); results from the first annual space elevator climber competition (Edwards); evaluation and testing of tethers; hazards; systems engineering for the space elevator (Pullum); and the place of the space elevator in history, literature and art (Raitt). David Smitherman gave an overview of the critical technologies for the development of future space elevator systems, and Bryan Laubscher discussed the space elevator and planetary defense.

The 57th IAC was held from 2-6 October 2006 in Valencia, Spain again within the IAA Symposium on the Far Future: Renewed Visions and there were two sessions: Space Elevator Systems: Engineering and Science (9 papers); and Space Elevators and Advanced Tethers: Programs and Applications (9 papers). The presentations covered such aspects as a vision of the space elevator as an enabler (Swan); the real history of the space elevator (Pearson); Earth-based space elevator R&D (Smitherman); space elevator stability and dynamics (Benaroya; Perek; Knapman); radiation shielding (Jorgensen); debris mitigation (Rugescu); and a climber developed as an answer to NASA's power beaming challenge (Lloro Boada *et al*).

There was only one session on the space elevator, once again as part of the IAA Symposium on the Far Future: Renewed Visions, held during the 58th IAC in Hyderabad, Andhra Pradesh, India from 24-28 September 2007. Entitled Space Elevator System and its Applications, the session contained a total of 7 papers relating to disposal of space debris by means of tethers (Chobotov and Melamed); dynamics method for soft landing and anchoring planning (Rugescu); multi-body modeling of tethered space elevators (Williams); effects of climber transit on space elevator dynamics (Cohen and Misra); mechanics of the space elevator (Evensberget); lasers and the space elevator (Bou); and the role of a space elevator systems architect (Swan).

In 2008, there were two space elevator sessions at the 59th IAC in Glasgow, Scotland from 29 September-3 October, again as part of the IAA Symposium on the Far Future: Renewed Visions. The first session: Space Elevator Systems Infrastructures contained 9 papers featuring presentations on NASA's power beaming and tether challenges (Klettner, Edwards and Shelef); cost effective disposal of geosynchronous satellites by means of tethers (Chobotov and Melamed); space solar power as enabled by space elevators (Swan); elevator transportation between Mars and its moons (Tala *et al*); and space debris removal (Penny and Swan). The second session: Space Elevators and Advanced Concepts had 10 papers discussing such aspects as momentum transfer tethers (Lenard);

tethers as sustainable space transportation (Kruijff, Ockels and van der Heide); improving stability of the space cable (Knapman); partial space beanstalks (Matloff); space blast pipes (Quantius *et al*); and the space elevators application to SETI (Prabhakaran and Prassad).

As part of the IAA Symposium on the Far Future there was a single session entitled Space Elevators and Tethers at the 60th IAC held in Daejeon, South Korea from 12-16 October 2009. Besides the regular presentations on debris mitigation (Penny and Swan) and tether stability (Yasaka; Rugescu) among the 10 papers, there were others on topics as diverse as the inevitability of the space elevator (Laubscher); Mars transfer trajectories (Engel); the Japanese space train concept (Tsuchida); and one by Swan on the creation of the International Space Elevator Consortium.

The 61st IAC was held in Prague, Czech Republic from 27 September-1 October 2010 and saw two sessions within the IAA Symposium on Visions and Strategies for Far Futures. The first session Access to Space in the Far Future focused more on tether systems and technologies. Among the 8 papers was one on a breakthrough in the structural design concept of a CNT mega-cable applied to a space elevator (Klettner and Pugno); another on tether technology for space solar power satellites and space elevators (Fujii); and one by Knapman on diverse configurations of the space cable. The second session Space Elevators and Tethers had a more diverse range of 10 papers covering such topics as systems requirements for the space toilet on the space train (Tsuchida *et al*); spinning carbon nanotubes (Okada *et al*); the physiological challenges of comfortableness in space elevators (Iwase); the space elevator road map 2010 (Tsuchida and Allison); and whether the first space elevator would be on the Moon, Mars or Earth (Swan).

In the 9th Symposium on Visions and Strategies for Far Futures within the 62nd IAC in Cape Town, South Africa held 3-7 October 2011, there was a single session entitled Space Elevators and Tethers. The 9 papers covered the space elevator road map 2011 (Tsuchida and Allison); deployment dynamics of the space elevator ribbon (Mazzoleni and Mantri); the space elevator stage 1 (Knapman); sling on a ring transport to space (Meulenberg); and quick look operations for a space elevator (Swan and Penny).

There was also one session within the same symposium at the 63rd IAC held in Naples, Italy from 1-5 October 2012. This session entitled Space Elevator Feasibility and Technology contained 13 papers by speakers from the USA, Japan, Iran, UK, Russian Federation, Germany and Malaysia (later withdrawn) - illustrating the global interest. Swan gave an overview of the IAA Cosmic Study on the space elevator feasibility; the space elevator roadmap 2012 was again provided by Tsuchida; Kao discussed how the law of the sea, sky and space pertained to the space elevator; Aslanov showed the motion of the elevator after ribbon rupture; Knapman spoke on the benefits and development of a high stage one for the space elevator; other papers looked at space elevator design aspects for the environment (Swan and Swan); deployment of a sub-satellite; producing a tether using a NEO (Hein); the interaction of a conducting space elevator with magnetic and electric fields in the near-Earth space plasma (Jorgensen); and the space elevator concept of operations (Penny and Swan).

In 2013, the 64th IAC was held in Beijing, China from 23-27 September. In the same symposium there was a session called Space Elevator Design and Impact which also contained 13 papers by representatives from India, Canada, Iran, Japan, USA, China, Argentina, though the papers from Italy and Malaysia were withdrawn. Topics covered included space colonization by means of a space elevator (Ganapathy *et al*); energy considerations in a partial space elevator (Woo and Misra); the effect of magnetic storms on an elevator (Jorgensen and Patamia); and the dynamics of space elevators in response to disturbances (Fujii). The paper on the ‘Babel Tower: a super-tall structure with a sub-orbital elevator’ was not presented. One notable paper was that by Yoji Ishikawa which discussed the space elevator construction concept of Obayashi Corporation. This is further explored in Chapter 9.

After ten years, the IAC and the space elevator returned to Canada. The 65th IAC took place in Toronto, Canada from 29 September-3 October 2014. Again there was one session as part of the 12th IAA Symposium on Visions and Strategies for the Future. With the title Global Strategy for Space Elevators the session had initially 13 papers (though several were later withdrawn) mostly from the United States. Interestingly, after several years with a dearth of papers on space elevator climbers, this year saw four: Penny spoke on climber operations; Swan also revisited tether climbers; Cohen discussed static deformation of the tether by climbers; and Yokochi studied the effect of a climbing rider on lateral deviation of the elevator. Knapman presented papers on space elevator research and the space elevator in the atmosphere; Takahashi summarized a space elevator concept comparison; and Guerman assessed the dynamics of a Moon elevator. In one of the other sessions in this Symposium, there was a paper on a mid-Earth orbiting tether for nuclear waste disposal.

Jerusalem, Israel was the venue for the 66th IAC held from 12-16 October 2015. Under the 13th IAA Symposium on Visions and Strategies for the Future there was a single session on Space Elevator Tether and Space Mineral Resources. There were 14 papers listed for the session mostly concerned with asteroid capture by tethers. Only two, however, specifically mentioned the space elevator: 'Dynamics of space elevator on asteroid' by Alexander Burov, Russia; and 'Space elevator: alternative design solutions' by Vadym Pasko, Ukraine.

The 67th IAC was held in Guadalajara, Mexico from 26-30 September 2016. Again as part of the 14th IAA Symposium on Visions and Strategies for the Future there was a single session on Space Elevator Tether and Space Mineral Resources. No fewer than 15 papers were listed in the final programme mainly from the USA and Japan and a good half this time dealing with the space elevator rather than tethers for asteroids. For example, Takahashi gave a status report on critical technologies for the space elevator resulting from the 2nd (ongoing) IAA study; Penny reviewed the concept for a space elevator Earth port; Knapman talked about the space elevator tower; Inoue discussed the dynamic behavior and mechanism of the driving roller for climbers in the space elevator; Jorgensen addressed the question of how do realistic magnetospheric fields affect space elevators; and Swan followed up with the space elevator development sequence. A couple of other Japanese papers (by Tao and Yamagiwa) also covered the space elevator proper.

Adelaide, Australia will host the 68th IAC from 25-29 September 2017, and the 15th IAA Symposium on Visions and Strategies for the Future will have a session entitled Conceptualizing Space Elevators and Tethered Satellites. The Call for Papers notes that the development of a system concept for space elevators requires systems engineering and architecture approaches. The new IAA study entitled 'Road to Space Elevator Era' is pulling together initial steps for a new look at space elevators. This study will show how to approach mega-projects with engineering discipline leading to the initial phase of a program - Concept Development. The study team is focusing on the early engineering and operational steps towards an operational capability, such as defining the missions and laying out the top-level requirements. This session will suggest strategies to illustrate the space elevator development leading to a phenomenal low cost to space infrastructure. In addition, the session can accept the strategies to leverage space tethers as a viable tool for space systems.

8.5 Other Major Conferences

Besides the annual Space Elevator Conferences, organized by ISEC, as well as those taking place within the framework of the IAC, there have been a number of other conferences or workshops devoted to the space elevator, especially in the early years.

The space elevator was featured at the Annual International Space Development Conference in May 2006 in Los Angeles with 15 talks and two panels. Speakers included Brad Edwards, Ben Shelef, Tom Nugent, Geoff Landis, Blaise Gassend and many more. There was also a space elevator mockup by the Spaceward Foundation and an update on the Space Elevator Games. The conference was hosted by the National Space Society and the Planetary Society.

8.5.1 EuroSpaceward Conferences

The European Spaceward Association (EuroSpaceward) was established in 2007 by Dr Brad Edwards and Markus Klettner prior to a space elevator conference in Luxembourg that same year. EuroSpaceward went on to organize a series of conferences on the topic. The 1st European Workshop on Space Elevator Climber and Tether Design was held in the city of Luxembourg on 10-11 November 2007. The first day was devoted to a presentation by Brad Edwards on the architecture of the space elevator; and another by Michel Benoit on solutions for the energy problems of an elevator. The second day discussed issues relating to carbon nanotubes (including their qualification), and on the rigidity and deployment of ribbon.

The 2nd International Conference on Space Elevator Climber and Tether Design was held in Luxembourg on 6-7 December 2008. It was organized by the European Spaceward Association in cooperation with the National Research Fund of Luxembourg, the Spaceward Foundation, the Japan Space Elevator Association, and various universities. Besides Brad Edwards, the conference scientific committee included David Raitt, Michel Benoit and Akira Tsuchida. The conference brought together high level researchers and engineers on space elevator systems and carbon nanotube fiber production, as well as experts from private elevator, laser, nanotechnology and space industries. Presentations were made by Bryan Laubscher, Markus Klettner, Brad Edwards and Akira Tsuchida amongst others. The aim was to advance the technology development by discussing the latest work in climbing systems and super strong CNT tethers and showcasing progress from the 4th NASA Beam Power and Tether Challenges in the autumn of that year. One focus was to attract young university researchers to stimulate European team building and networking in the NASA Challenges (eurospaceward.org/2008/2nd_International_SE_Workshop_in_Luxembourg_V28-06-08.pdf). The abstracts for the conference Day 1 and for Day 2 respectively can be found at http://eurospaceward.org/PDF/SE_conference2008_collected_abstracts_Sat_6Dec08_Final_Version.pdf and http://www.spaceelevatorblog.com/media/2008EuroSpacewardConference/Day2.pdf.

There was a breakthrough during the 3rd International Conference organized by EuroSpaceward with the theme Space Elevator, Carbon Nanotube Tether Design and Lunar Industrialization Challenges and held in Luxembourg from 5-6 December 2009 with Markus Klettner as conference chair. Experts on the space elevator system, CNT fiber research and lunar industrialization discussed latest results of their research work. Consensus was reached among the experts that a space elevator could be built only if it was based on the flaw tolerant design proposed by speaker Professor N. Pugno, published in 2006, abandoning earlier unrealistic proposals, which ignored the role of defects and assumed a mega cable strength even larger than 100GPa (Pugno and Klettner, 2009). At least a 10GPa strong mega cable was practically needed in order to be able to tackle a first prototype. It was also noted that space elevators needed to be powered by ground-based visible light lasers combined with adaptive optics. Existing technologies seemed to be mature enough to become usable for space elevator power beaming within 10 years as well.

EuroSpaceward also hosted the 4th International conference on Carbon Nanotechnology and Space Elevator Systems in Luxembourg on 4-5 December 2010. The first day was dedicated to space elevator systems while the second day was dedicated to carbon nanotechnology. The focus of the first sessions were on the scientific and technical aspects of space elevator systems as well as legal issues, international policy, ongoing research, economics and engineering contests. The carbon nanotechnology sessions focused on the status of ongoing research including carbon nanotube growth technologies relevant to space elevator systems, power transmission, energy conversion and the economics and environmental impacts.

8.5.2 Japan Space Elevator Association Conferences

There is a yearly meeting of the Japan Space Elevator Association (JSEA) with lectures, discussions and presentations relating to space elevators. The Association was created in 2007 and the first conference was held in 2008 and the latest one was in May 2016 at Nihon University, Tokyo, where the majority of the conference have been held. The meetings consist of an exchange of the latest information, ideas, views and activities. The topics are usually on latest developments in the space elevator field, with various technical papers on all aspects, as well as workshops. In most years there has also been an art competition for renditions of a space elevator. Each conference appears to be named a Space Elevator Society Conference (JpSEC). Since the meetings are in Japanese, they are not really accessible to most people - although they do sometimes have international content.

It is also worth pointing out that a major activity for JSEA is its space elevator challenge climber competitions (SPEC) - held in conjunction with its meetings. Japan leads the world in the execution of tethered balloon systems and climbers competing up a tether (see Chapter 7.7). The JSEA website can be found at jsea.jp and there are links to both JpSEC and SPEC - pages are in Japanese, but the automatic translation provided by web browsers are enough to get the gist of JSEA activities.

8.6 Conclusion

Starting with what can be considered the first conference of its kind in 1999, this chapter has tried to provide an overview of the major conferences and congresses held around the world since then that have had the space elevator as a theme, either for the whole conference or for sessions within a broader congress. Those events ongoing today in English and thus accessible to most space elevator enthusiasts include, in particular, the sessions at the annual International Astronautical Congresses around the world organized under the auspices of the International Academy of Astronautics; and the yearly conferences in Seattle organized by the International Space Elevator Consortium. The chapter has also looked at dedicated space elevator conferences in Europe and Japan and briefly summarized some of the depictions, technologies, applications and visions for the space elevator as covered by the various papers presented at all these diverse events.

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Chapter 9: Space Elevator Studies

9.1 Introduction

One of the activities that has brought space elevator enthusiasts and experts together has been consolidating concepts and data from random studies into organized academic approaches. There have been four major bodies funding or supporting studies from the earliest days of this century:

- Following on from the 1999 NASA workshop on space elevators, funding from the NASA Institute for Advanced Concepts (NIAC) enabled the start of the development of modern day space elevator concepts. There were two initial studies by Dr Bradley Edwards on the basic space elevator with later follow-on studies by Jerome Pearson and Robert Hoyt on lunar elevators. These have been extensively discussed in Chapters 4 and 5 and are not revisited here.

- The next is a series of one-year studies undertaken by members of the International Space Elevator Consortium (ISEC) focusing on individual topics (one topic per year) with the purpose of expanding the Body of Knowledge regarding space elevators.

- During the first five years of the second decade of this century, a study conducted for the International Academy of Astronautics (IAA) and culminating in 2013 brought together a truly global set of experts attacking the whole question of whether the space elevator concept was feasible. A second, follow-on, study for the IAA has been initiated to provide more systems engineering information addressing how to proceed in developing a space elevator.

- Also, during the early part of the second decade of this century, there has been an independent look at space elevator development by the Obayashi Corporation. Their task was to show how a space elevator could be accomplished to support the needs of Japan.

These last three studies are further discussed below.

9.2 International Space Elevator Consortium

As the first decade of the present century came to a close, there was a focused effort inside the International Space Elevator Consortium to address individual topics relating to space elevators in year-long studies. With only a small number of experts volunteering to participate, ISEC did not have the manpower to address too many issues concurrently. Thus the aim was to conduct a study into only one topic each year and produce a report on the research and results which would be accessible via the ISEC website at www.isec.org. An overview of the study topics is given below.

2010-2011 - Space Elevator Survivability, Space Debris Mitigation.

The Space Elevator community has always been concerned about the numbers and densities of space debris because of its dramatic growth over the last two decades. During this first study (Swan *et al*, 2010), the team addressed many issues including:

- The probabilities of collision in Low Earth Orbit (LEO), in Geosynchronous Earth Orbit (GEO), and in Medium Earth Orbit (MEO).
- The growth rate as it threatens an operational space elevator.
- A reasonable approach for space elevator developers to ensure infrastructure safety.
- Approaches to interrupt sources of debris.
- Mitigation of risk for the space elevator community through design, operations, policies, and lowering the threat.

The overall conclusion from the study was that the analyses showed that the threat from space debris can be reduced to manageable levels with relatively modest design and operational fixes.

2012-2013 - Space Elevator Concept of Operations.

This study (Penny *et al*, 2012) addressed the concept of operations for a future space elevator infrastructure. The findings and conclusion from the authors and participants in the study were:

Finding 1: While the development of space elevator tethers and climbers is a daunting task, their operation will leverage 50 years of satellite operations experience. Climbers, Apex Anchor and GEO node are essentially satellites just like the thousands that have been launched to date. Space elevator operations will be an easy extension of today's practices and operations centers will look very much like today's satellite operations centers.

Finding 2: The Marine Node, comprised of the Floating Operations Platform and Ocean Going Vehicles, will leverage over one hundred years of deep-ocean off-shore drilling operations. The Headquarters and Primary Operations Center will be the principle location to ensure robust operations across multiple centers are synchronized. These include: the Climber Ops Center, Tether Ops Center, Floating Ops Center, GEO Node Ops Center, and the Enterprise Operations Center.

Finding 3: Operational costs for a pair of space elevators seems to be reasonable for a business of its projected magnitude.

2013-2014 - Design Considerations for Space Elevator Tether Climbers.

Space elevator tether climber design has always been challenging and intriguing to developers. Climbers can be built with today's technology; however, there will be a myriad of designs leveraging new and future spacecraft technologies. One strength is that there are over 60 years of heritage in spacecraft design. The study (Swan *et al*, 2013) used a constant-power model as a baseline, rather than constant speed or acceleration, because the constant-power model simplifies design requirements and reduces the mass of the tether climber. Some of the conclusions reached in the report from this study were:

- A mass of 6 metric tons (MT) for a climber and 14MT for customer payloads seems feasible. With an estimated travel time of one week to Geosynchronous Earth Orbit (GEO), seven tether climbers can be on a 31MT tether simultaneously.
- The communication architecture should be integrated into the space elevator infrastructure and nodal layout. This would enable the tether climber to be in constant contact with operators and customers.
- It appears possible to operate the tether system exclusively on solar power, eliminating the need for ground-level power sources. Exclusive use of ground-based laser power

transmission also seems practical. A hybrid of solar power and laser power transmission is also an option.

2014-2015 - Space Elevator Architectures and Roadmaps.

Here the study team took on the challenge of explaining a path to develop the major revolution in space transportation occasioned by a space elevator. The report (Fitzgerald *et al*, 2014) notes there are currently three 'validated' architectures addressing space elevators. Validated in this context means publication of a full space elevator architecture that addresses all major elements, discussions at major venues and conferences, defense of major approaches and refinement of concept during the process. These three validated architectures are:

- Dr Edwards' NIAC studies, with refinements in his 2003 book.
- International Academy of Astronautics Study Report, 2013.
- Obayashi Corporation concept.

Each of these approaches has strengths and weaknesses, proponents and detractors and - most importantly - great potential. During the exploration period of this study, it was determined that the space elevator architecture would be composed of five delineated segments. These delineations helped the study team to agree on what was included in the architecture, and what was not. The team determined that the architecture would be a growing entity - so, the destination was the space elevator architecture when its initial operational capability was achieved. In other words, the team envisioned the architecture when it would be 'open for business'. This was termed the 'IOC Architecture'. The five segments of the architecture are the Marine Node segment; the Tether segment; the Climber segment; the Apex Anchor segment; and the Headquarters/Primary Operations Center - all of which are more completely defined in the latter portions of the report.

2015-2016 - Design Considerations for Space Elevator Earth Port.

The Earth terminus of the space elevator has been discussed in general terms since the beginning of the concept. This study provided ISEC's view of the Earth Port (formerly known as the Marine Node) of a space elevator system (Hall *et al*, 2015). Essentially, the Earth Port would:

- Serve as a mechanical and dynamical termination of the space elevator tether, providing reel-in/reel-out capability and position management in order to deal with tension, wind, current and debris avoidance.
- Serve as a port for receiving and sending Ocean-going Vessels (OGVs); the OGVs will move tether climbers, payloads, supplies and personnel.
- Provide landing pads for helicopters from the OGVs.
- Serve as a facility for attaching and detaching payloads to and from tether climbers and attaching and detaching climbers to and from the tether.
- Provide tether climber power for the 40km above the Floating Operations Platform (FOP).
- Provide food and accommodation for crew members as well as power, desalinization, waste management and other such support.

In fact, the design and construction of the Earth Port would be a straightforward extension of today's practices.

2016-2017 - Design Considerations for GEO Node, Apex Anchor and Communications Architecture.

The 2016 ISEC study, which is still on-going, is intended to help define the upper reaches of a space elevator infrastructure. The two physical nodes will be defined while the overall communications system for a space elevator will be presented. The baseline for the discussions started with a description of an Apex Anchor and GEO node and the development of a Communications System Architecture (Penny *et al*, 2017). The latest thinking is that the Apex Anchor will evolve from being considered only as a counterweight and instead be involved in system operations to include communications node, deployment scenarios, and damping of ribbon dynamics. The primary role for the GEO node will be the drop off (and pick up) of GEO satellites. It is expected that a new generation of satellites, in significantly greater numbers, will arise taking advantage of the lower cost and simpler design. The interconnectivity of all the space elevator components are being analyzed in the study to determine the major communication functional needs. The focus will be to define what and how much data must be delivered and/or received by each component, how much, and how communications needs will be fulfilled.

9.3 International Academy of Astronautics

The International Academy of Astronautics, within its Commission structure and its Scientific Activities Committee, establishes studies to be conducted over three to four years with space expertise contributed from within its 1,000 elected members. Studies usually have 15-50 members from around the globe with all types of expertise and experience. The following two studies reflect activities inside the Academy pertaining to the space elevator.

2011-2014 - Space Elevator: An Assessment of the Technological Feasibility and the Way Forward.

This study was first proposed in 2009 by Dr Peter Swan and Dr David Raitt and when accepted they became the joint chairs and established a suitable team of international experts to work on the study. The extensive research and subsequent comments from peer reviews were gathered into a lengthy study report (Swan, Raitt *et al*, 2013). Basically, the report addresses simple and complex issues that have been identified through the development of space elevator concepts over the last decade. The report begins with a summary of those ideas as put forward by Edwards and Westling in their book *The Space Elevator: a Revolutionary Earth-to-Space Transportation System* (2003). Out of these beginnings has arisen a worldwide group of individuals who have focused their areas of expertise on and are applying it to space elevator development and operational infrastructure. The report answers some basic questions about the feasibility of a space elevator infrastructure, namely what is a space elevator?; why should it be developed?; and can it be done?

The authors recognized that the whole project, especially the projected price per kilogram, was dependent upon a strong, lightweight material that would enable a 100,000km space elevator tether. The principal issue is material produceability at the strength, length and perfection needed to achieve this. Almost all other issues surrounding each of the major segments have either been resolved in space before or are close to being space-ready today. Only the tether material is at a high technological risk at this time. The Conclusions from the study fell into four distinct categories:

- Legal: The space elevator can be accomplished within today's arena.
- Technology: The space elevator "Seems Feasible."

- Business: This mega-project will be successful for investors with a positive return on investment within 10 years after completion.
- Cultural: This project will drive a renaissance on the surface of the Earth with its solutions to key problems, and stimulation of travel throughout the solar system, with inexpensive and routine access to GEO and beyond.

2014-2018 - Road to Space Elevator Era.

After several modifications to its mandate, this follow-on IAA study, chaired by Akira Tsuchida and co-chaired by Dr Peter Swan and Dr David Raitt, kicked off its activities in 2014 with the aim of accomplishing the development of the unique space transportation system of the future, by means of more international cooperation stretching across the science and systems development community. To accomplish these desires, projects are being identified that can be accomplished in the near future leading to risk reduction and engineering enhancements. These include on-orbit verification projects such as utilization of the International Space Station characteristics, promotion of space technology spin-out into industrial application, and execution of precursor mission, levering current technologies to demonstrate space elevator prototypes.

It is the intention of the IAA Study Group on the Road to Space Elevator Era to support any activities in connection with the topic; and, to bring within the reach of every country the opportunity to understand the potential, design approach, and benefits/issues with a developmental program. The exploitation of space elevators to initiate space-based solar power is an initial focus that will demonstrate the possibilities available to humanity. As has been opined many times, the deployment of a space elevator transportation infrastructure will change the space arena and significantly improve the human condition through expansion into space. The study team has already made much progress with defining mission objectives and requirements and is on track to complete the report on schedule.

9.4 The Obayashi Corporation

In 2011, the Obayashi Corporation in Japan gathered a project team together with seven engineers to develop an innovative approach to space elevators. The expertise of the construction corporation was combined with the guidance of Professor Yoshio Aoki of Nihon University in Tokyo and, taking as a starting point Brad Edwards' design, they refined the concept from that initial set of assumptions and produced a Construction Concept in 2012. The first presentation outside Japan was at the 2013 International Astronautical Congress in Beijing (Ishikawa, 2013). In 2013, the effort was reinforced with more time to conduct research and development on the topic while working with governments, academia and other industrial teams. There were many joint research projects with multiple universities as the concept was developed. One of the significant points was to focus upon the cable dynamics and tether-climber interaction. The project was broken into three components to help direct the design efforts: designing the total space elevator architecture; analyzing the cable dynamics and its impact on strength requirements; and understanding how to accomplish the construction of a total system of systems (Ishikawa, 2016). These are discussed briefly below.

Regarding the design of the total space elevator architecture, the design of the concept includes resolving all necessary components including cable, stations and climbers. The cable, made of carbon nanotubes, has a length of 96,000km with multiple locations along the tether. The length was chosen based on three criteria; first, the cable should not resonate with periods of tidal forces from the Sun and Moon; second, it had to be long enough to send spacecraft to as many planets as possible in the solar system; and third, the overall length of the cable should be a multiple of the interval of periodically ascending climbers. In their concept, Obayashi assumed the tensile strength of the cable to be 150GPa with a safety factor of two. The climber, which was not designed in detail in the study, was assumed to weigh 100 metric tons.

The basic design of the tether started with the Edwards number of 150GPa tensile strength requirement. This included a slight taper ratio and defined two tethers per cable. This dual cable arrangement was to provide a larger safety factor as Obayashi identified human transportation as a priority. The Obayashi concept was designed based on the numerical results of the dynamics of the cable. The equation of motion was formulated by treating the cable as a multibody system composed of many point masses. The various forces, such as Earth's gravitation, centrifugal, Coriolis, elastic and air resistance were all taken into consideration. Continued research into the cable dynamics focused mainly on the cable's behavior during its initial deployment and with the climbers' ascent and descent.

For the construction process, as noted, Obayashi basically followed Brad Edwards, but modified the details. The process mainly comprised the construction of the Earth Port, the cable and the stations along the way. The construction of the cable includes the launch of an initial cable to GEO, the deployment of the cable from GEO to Earth, and the reinforcement of the cable with ascending climbers. Their analysis concluded that the reinforcement or thickening of the cable required 510 climbers and would take 18 years!

There was much design consideration during the development of the Earth Port concept. The floating structure would be a hollow concrete box with two types of support - pontoon or semi-submersible. There would be mooring lines and hulls made to withstand the large ocean forces, while being mobile by design. The self-propelled climber is estimated to be roughly 100 metric tons with a payload mass of 70 metric tons. The size of each climber car is 18m long and 7.2m in diameter and there would be six cars (for a total capacity of 30 people) - the total length then being 144m including the driving mechanisms. The energy would be supplied from ground-based or GEO-based laser beam stations.

The GEO Station has been designed to support 50 people in a gravity free zone - thus it would be roughly ten times the size of the current International Space Station. As with all large space structures (as well as elsewhere) modularity is important as a basic design principle. This modularity will enable several missions to be combined and cross purposes supported by simple designs and assembly. Repair and improvements will be easy and growth should follow naturally. A long, vertical structure was adopted for the GEO station because it is more stable in terms of the gravity gradient and is also suitable as a platform for housing the six-car climbers.

In short, the construction approach and timeline matches the Edwards layout, and there is also a very good parallel with the development of the IAA study architecture. However, the development of the extra strong cable and double tether arrangement require a longer development cycle and construction time. The estimate is that operations will begin somewhere around 2050 with placement of the initial single string tether in the 2030 time period. The development time between those dates reflects the complexity of building up the tether cable design from the initially deployed cable. Indeed, the Obayashi Corporation agrees that the essential research area is tether material development with additional studies dealing with all the other components of this system of systems.

9.5 Conclusion

The refinement of studying the space elevator infrastructure development has matured over the years since the NIAC studies from 2000-2003 and especially since 2009 when a proposal was prepared by Pete Swan and David Raitt for presentation to the International Academy of Astronautics. A second proposal for a follow-on study was submitted by them to the IAA in 2013. There have been a series of one-year studies from the International Space Elevator Consortium focusing upon significant problems, and new studies are planned. And there have been studies conducted by other organizations - Obayashi Corporation being predominant. It was NASA that started much of the modern day space elevator discussions inside their innovative research organization, which then blossomed into a phenomenon around the world. The initial studies were global in nature and reached a wide audience. As the second decade matured, the studies took on more directed topics and produced reports that answered specific questions in greater detail. As such the understanding of the complexity of space elevator development - enhanced by space elevator competitions in America, Europe and Japan which have contributed greatly to knowledge - has grown to a level where initiation of the project should be able to begin in the near future.

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Chapter 10: Beyond the Earth and a Look to the Future

10.1 Preamble

Despite others before him, it is probably Jerome Pearson to whom credit can be allocated for bringing the space elevator onto the world stage (see Chapter 2). Following his work published in 1975, the space elevator, as discussed in Chapter 3, soon worked its way into numerous science fiction novels such as Sir Arthur C. Clarke's *The Fountains of Paradise*. Released in 1979, this seminal novel is often regarded to be the vanguard in bringing the space elevator to the attention of the wider public readership. Coincidentally, in the same year, Charles Sheffield also published his science fiction novel *The Web Between the Worlds*, which also featured the elevator as the central theme of its story. Interestingly, as with Artsutanov and Pearson, Clarke and Sheffield were entirely unaware of each other's work at the time. And while the space elevator remains far from deployment, the scientific work that has been done on it in the years following Pearson's paper has only become more extensive as numerous individuals, groups, and organizations strive to see it realized. Between the International Space Elevator Consortium, the Japanese Space Elevator Association, and companies like LiftPort in the USA, whose goal is to have an elevator on the Moon by the end of 2020, and Obayashi Corporation in Japan who expects to see an operational Earth elevator by 2050, the space elevator is not without its burgeoning growth of supporters as a glance at the papers presented yearly at the various dedicated sessions and conferences held around the world shows (see Chapter 8). Indeed, one such organization, the International Academy of Astronautics (Swan, Raitt *et al*, 2013), concluded, as had others, after a four-year study that space elevators do seem to be feasible!

10.2 Non-Earth Elevators

Although the bulk of writings - both scientific and literary - have focused on a space elevator emanating from Earth, there have been other depictions and descriptions of space elevators elsewhere in the solar system. And it would be remiss not to mention them somewhere in this history since, in some cases, they predate Pearson and Clarke.

10.2.1 Lunar Elevators

In 1972, an individual named James Cline wrote to NASA with a proposal for a Moon cable which he believed would be a profitable space transportation system and a good follow-on project after Apollo. In his document he briefly presented the fundamental transportation project together with a set of engineering concepts which might be used to implement the siphon-like system (Cline, 1972). A cable, or other tension structure, of length less than the distance between Earth and Moon, would be attached to the Moon's surface and extended up out of the Moon's gravity pit toward Earth far enough so that part of it hung down part way into the Earth's gravity pit. It would stay there in place without external energy applied, if the weight of the part of the cable in the Earth's pit was at least as great as the weight in the Moon's pit.

The cable he proposed was to be made out of silica fiberglass, grown from a seed filament, and manufactured from the plentiful silica on the Moon's surface. He believed this to be the ideal cable material, though he also considered using foamed steel as a building material because of its outstanding usefulness. In the event, NASA declined to take up the conceptual idea partly because of unsubstantiated assertions and partly because their funding priorities lay elsewhere (see http://www.kestsgeo.com/1techconcepts/documents/lunarspaceelevator1972/lunarspaceelevator1972.html).

A few years later, some selected papers of Soviet space pioneer Fridrikh Arturovich Tsander were posthumously published (in Russian) in 1977 in Riga revealing that he conceived of a lunar space tower with a tapered tether deployed near L1 as early as 1910 (Tsander, 1977). He was acquainted with the work of Tsiolkovsky with whom his own ground-breaking ideas compared favorably. Tsander, designer of the first Russian liquid-propellant rocket in the 1930s, was also the first to study gravity assist, solar sailing and aerobraking. As a result of his trajectory calculations he developed a fascination for Mars, though it is not known whether he drew up a concept for a Mars elevator as he did for a lunar one.

Following on from work first carried out in 1977, Hans Moravec noted in early 1978, that on the Moon, in particular, a tapered kevlar skyhook had enormous advantages over rockets for the supply and crew rotation missions envisioned or space industrialization efforts (Moravec, 1978). He took his ideas even further in his other 1978 article on cable cars in the sky where he mentions the Tower of Babel, as well as the work of Tsiolkovsky, Artsutanov and Pearson (Moravec, 1979). He wrote that at first glance a lunar skyhook seemed even more absurd than a terrestrial one and that a Moon skyhook apparently had to be much bigger that an Earth model. He discussed skyhooks not only anchored to the lunar surface, but also on Mars (see below).

Also in 1978, Jerome Pearson extended his theories to the Moon and was one of the first to describe a lunar elevator. His ideas on a lunar anchored satellite test were first shared in a paper presented at the 1978 Astrodynamics Conference. His article 'Anchored Lunar Satellites for Cislunar Transportation and Communication' examined the concept of satellites balanced about the collinear libration points L1 and L2 of the Earth-Moon system and attached to the lunar surface (Pearson, 1979). He was subsequently given a grant by the NASA Institute for Advanced Concepts to explore the concept further and his Phase I Final Report on the subject was published in 2005 - see Chapter 4.4 for a discussion of this work. The concept of the space elevator applied to the Moon was also put forward by Yuri Artsutanov (1979). Like Pearson, he took advantage of the fact that the rotation of the Moon is gravitationally stabilized by the Earth and the Moon has a weaker gravitational field compared to the Earth. This allows a longer tether to be attached to the surface of the Moon and stretch beyond either of the Lagrangian libration points.

A number of years later at the 2011 Annual Meeting of the Lunar Exploration Analysis Group, T. M. Eubanks and Michael Laine of LiftPort gave an overview of LADDER - the development of a prototype lunar space elevator. LADDER was a mission to deploy an operational prototype lunar space elevator using currently available technology. The idea was to erect a 264,000km elevator from the lunar surface, past the L1 Lagrange point, to a counterweight deep in cislunar space (Eubanks and Laine, 2011). At the 2014 ISEC Space Elevator conference in Seattle, Laine subsequently announced that his company, LiftPort, was pursuing the deployment of a lunar space elevator by 2020 and he saw this as a precursor to an Earth-based elevator.

10.2.2 Martian Elevators

Space elevator concepts for Mars have also been presented in science fiction, as briefly discussed in Chapter 3. But there has been scholarly work, as well. The concept of a Mars space elevator has been mentioned in at least two NIAC studies - see Chapter 4.5. But much earlier, in 1977, Hans Moravec gave a presentation at the 23rd IAAA Meeting which outlined the concept and configuration of a non-synchronous orbital skyhook. He explained that a satellite in low circular equatorial orbit had two long tapered cables extending in opposite directions. The satellite rotated in the orbital plane, and the cables touched an elongated planet on each rotation, with the rotational velocity canceling the orbital velocity. The system acted like two spokes of a giant wheel rolling on the equator. When considering cables for the Moon and Mars he gave the parameters of a number of materials including kevlar, steel, fiberglass, silica and graphite (Moravec, 1977).

Moravec expanded his ideas shortly afterwards (Moravec, 1978) and came to the view that the combination of a new material, kevlar, together with a new, less expensive, satellite skyhook configuration, would now make skyhook transportation feasible on bodies as large as Mars (see also above). In another article written in 1978, but published slightly later (Moravec, 1979), he opined that foremost among the planets, Mars seems to have been designed with a synchronous skyhook in mind. It had a gravity well just deep enough to make a conventional matter skyhook interesting, a simple gravitational environment, and a high rotation to keep the hook short. He thought that kevlar was almost strong enough for the job. A martian kevlar skyhook would have a taper of 15,000 and a mass ratio of a million, though a material twice as strong would give a taper of 100 and a more reasonable mass ratio of 6,000. He concluded that some graphite composites occasionally achieved that. He went on to say that Arthur C. Clarke had suggested that Deimos, 3,000km above synchronous orbit, was in exactly the right place to provide a mass anchor for a truncated martian skyhook and using it would permit a skyhook with one third the mass of an equivalent full length cable.

At 'The Case for Mars II' conference, held in 1984 at the University of Colorado, Paul Penzo (1984) presented a paper entitled "Tethers for Mars Space Operations". The classic space elevator approach for Mars would involve a satellite in a stationary orbit with a cable attached to the surface of Mars. Deimos is a bit outside the synchronous altitude for Mars, so one idea was to move it to where it could serve as the counterweight for the martian space elevator. A shortcoming of this approach was that Phobos is at a much lower altitude, representing a serious hazard to the cable. Active control of cable oscillations, as noted above for the Moon, could provide a solution. The approach would be to let the cable swing in a harmonic of the Phobos orbital period, thus always missing it at times of closest approach. However, Penzo took a different approach, using Phobos as a hub, and tethers to snatch items from the martian surface or low Mars orbit and transfer momentum to lift them up to rendezvous with Phobos. Another tether could send items from Phobos on to Deimos, and yet another tether could send items on an escape trajectory out of Mars orbit.

Some twenty years later, Leonard Weinstein (2003) came up with the novel approach of creating an industrial civilization beyond Earth by taking into account the unique configuration of Mars and its moon Phobos to make a low-cost transportation system capable of raising mass from the surface of Mars to space. Mars would be used as the primary location for support personnel and infrastructure, while Phobos would be used as a source of raw materials for space-based activity, and as an anchor for tethered carbon-nanotube-based space elevators. Weinstein believed that this approach would lead to colonization of Mars.

10.2.3 Tethers and Asteroids

The space elevator ribbon is also known as a cable as well as a tether. And while possibly not a true space elevator in the style of the terrestrial, lunar and martian concepts, there are several papers which describe the use of tethers with regard to asteroids. Indeed, at the NASA workshop on the space elevator in 1999 it was postulated to harness an asteroid with a tether; and a number of papers presented at the last couple of International Astronautical Congresses (see Chapter 8.4) in the space elevator and tether sessions have been on topics such as redirecting asteroids with tethers, rotation of spacecraft tethered to asteroids, and the dynamics of a space elevator on an asteroid.

However, in another 1984 paper, Paul Penzo (see above) presented ideas for using a rotating tether to attach spacecraft to asteroids. The spacecraft orbit is changed in this way without rocket propulsion, analogous to a gravitational assist. Jerome Pearson (1980) and Guy Pignolet (1979), in separate publications released at nearly the same time, presented an idea of using a rotating tube around an asteroid to throw off material into space, providing rocket thrust to propel the asteroid to another location for retrieval. A spinning motorized tether (Artsutanov-Moravec tether) is another possibility, capable of catching suborbital payloads and throwing them out of orbit. The surface launch to suborbital flight might be accomplished by electromagnetic "mass launchers" rather than rockets.

Despite others thinking that a lunar elevator could be constructed first, Peter Swan, in his paper "First Space Elevator: on the Moon, Mars or the Earth?", agreed with the points that the martian and lunar elevators could be build today. However, he reminded everyone that the most critical factor in opening up the solar system is cheap access to space - beating Earth's gravity. Therefore, his opinion was that the first space elevator should be located on the Earth (Swan, 2010).

10.3 Consolidation of Efforts

One of the key insights during this century's growth of space elevator concepts was that there were numerous topics that were not being addressed in a systematic approach (see Chapter 6). There were many individual and group efforts to address separate issues (such as dynamics, materials, lunar) as each developed their own concepts towards space elevator goals. However, there were few coordinated efforts around the world on space elevator topics. It has to be said, though, that these individuals and groups did move the development of the space elevator forward with their contributions. With his work, Brad Edwards created a monumental effort focused on developing a doable space elevator and his efforts provided the impetus for further, more coordinated, research and study. He enlisted many willing volunteers to help him focus on how to do a space elevator from scratch.

Not least of these individuals was Ben Shelef of the Spaceward Foundation who provided the impetus for NASA sponsored space elevator competitions (see Chapter 7). Indeed, the NASA Centennial Challenges pushed technologies towards the space elevator developmental needs. As shown by the fact that neither challenge prize funds for power beaming and tether climbers were fully awarded during the years of the Challenges, there is clearly still a long way to go in both tether material and the ability to power space elevator tether climbers. However, the significant achievement of the Space Elevator Games, as they were called, was the phenomenal involvement from competitors and the visibility given to space elevators through their coverage. And, of course, they were the forerunners of other similar events around the world, in Europe, but particularly in Japan. The involvement of engineering teams and scientists as well as all the support infrastructure ensured that the lessons learned (and not only by the 'old-timers' but also an upcoming generation of enthusiasts) would be passed on to the various aspects of space elevator development.

During the last fifteen years, as the chapters in this book reveal, many people worked on the concept of the space elevator and how to improve its implementation. There were significant baseline architectures developed during these decades that advanced Brad Edwards' early modern day design.

Each increased the Body of Knowledge in the area of space elevators significantly with new concepts and enhancements. Common understanding of the current baseline includes three architectures: Edwards' initial modern day design; the International Academy of Astronautics enhancements leading to a concept defining the Initial Operational Capability (IOC); and the Obayashi Corporation's refinement towards a Full Operational Capability (FOC).

Brad Edwards and his team provided the baseline for the modern day space elevator and reduced the significant issues he addressed inside the NASA community to developed achievable solutions. His two studies funded by NIAC and resulting book described a systems level concept and showed how the dream of low-cost access to space through a permanent infrastructure could come about. His work leveraged a large number of interested people to come together around the world to try and bring the project to fruition. The major study on the space elevator undertaken under the auspices of the International Academy of Astronautics further consolidated many ideas from around the world into a lengthy report by 41 authors and five editors (Swan, Raitt *et al*, 2013). Using Edwards' baseline, the whole concept was advanced and taken a step further resulting in an architecture for an Initial Operations Capability.

Then, again building on Edwards' concept, the Obayashi Corporation in Japan initiated a study on how to develop a fully operational space elevator (Ishikawa, 2016). Their plan responded to the needs of Japan and included new requirements beyond those of Edwards and the IAA. These have now become the current baseline concepts for the future of space elevators and have been discussed at length in chapters throughout this book (notably, 4, 5 and 9). No doubt there will be further tweaks as new research is conducted and made available for development.

10.4 New Research Activities

Such R&D will certainly include: carbon nanotube development; dynamics research; multi-stage elevators; definition of a Pathfinder Mission; tether climber power; tether design; and a lunar space elevator. The feasibility study published by the IAA in 2013 presented the state-of-the-art in many areas. Since then, as John Knapman has noted, progress has been made in several areas including the reduction of the power requirements of tether climbers, dealing with the atmosphere and the design of the Earth station. There remains the shortfall in material strength for the tether (see Chapter 5) as long lengths of high strength are required. Knapman's solution to this is to explore using alternative technologies that could augment or support a tether made with existing materials or materials of intermediate strength that may soon become available. He puts forward a new proposal for a multi-stage elevator using materials weaker than previously envisioned. He believes that this viable option would render the construction and operation of several space elevators so attractive that solutions to the other issues would be found relatively quickly (Knapman, 2016).

Already, there is exciting progress. As reported in numerous press pieces, diamonds in the sky might recall a popular Beatles song, but researchers from Penn State University in Pennsylvania think that is exactly where these diamonds belong. They discovered a way to produce ultra-thin diamond nanothreads that could be ideal for lifting a space elevator from Earth to the Moon. The team, led by chemistry professor John Badding, applied alternating cycles of pressure to isolated, liquid-state benzene molecules and were amazed to find that rings of carbon atoms assembled into orderly chains, thus creating a neat thread 20,000 times smaller than a strand of human hair but perhaps the strongest material ever made. The researchers had a hunch that these diamond nanothreads, which are remarkably light and strong at the same time, could prove to be an ideal material for a space elevator (in their view, a long cable anchored on Earth and reaching into space to attach to a satellite in orbit.) Following up on this, a team from Queensland University of Technology in Australia modeled the diamond nanothreads using large-scale molecular dynamics simulations and concluded that the material is far more versatile than previously thought and has great promise for aerospace properties (http://www.space.com/31180-diamond-nanothreads-support-space-elevator.html).

Another interesting development is afforded by a U.S. patent approval for an ambitious space elevator design granted to Ontario-based Thoth Technology Inc. in July 2015. The idea is for a free-standing elevator column which would reach some 20km into the sky, topped with a launch pad for shuttle jets to take cargo and astronauts into low Earth orbit. The tower will consist of sections of kevlar airbags stacked upon themselves and filled with a lighter-than-air gas like helium or hydrogen inflated to a pressure of about 100 times that of Earth's atmosphere. To keep from tipping over the column will have an active guidance system to help counteract buffeting by winds and maintain its centre of gravity. The company is looking for partners and investors to build an initial prototype tower of 1.5km high at an estimated cost of $1.5bn within five years and move to the 20km tower within 8-10 years. Thoth believes that such towers would revolutionize access to space, generate renewable wind energy and communicate over a wide footprint. The company was granted a second U.S. patent in August 2016 for its innovative new space elevator car mounting method. The spiral elevator mechanism allows bi-directional travel up and down the space tower and it is thought there will be huge benefits for space tourism with a ticket price of some $2000 to ascend the full elevator.

And here is as good a place as any to mention the way in which different groups have seized inspiration from the space elevator. There is a young rock band from London who call themselves Space Elevator! The group of four released their debut album in 2014 and released a second in 2016, the cover of which features a space elevator, as does the group's website at http://spaceelevatorband.com. What is even more interesting though, is that Thoth Technology, Inc. have teamed up with the group to promote their idea of a space elevator (read about this at http://spaceelevatorband.com/wp-content/uploads/2016/03/SpaceElevatorThothPressRelease.jpg). Thoth has procured the exclusive rights to the Space Elevator band's Elevator track, which they are using in their demonstration video for the ThothX tower (see it at http://thothx.com/news-2/ or https://www.youtube.com/watch?v=FVsUyPEN1eY).

In another interesting recent development a small group of computer professionals have dedicated themselves (at their own expense) to developing a collaborative high quality feature rich computer modeling software platform for the space elevator, named Usque. Although there are several tools to model different facets of the space elevator they usually focus on one discipline at a time. Usque, by contrast, can be used to simulate more than one discipline at the same time. As it is collaborative by design, more than one organization can be the source of the mathematical model and more than one model per discipline is allowed. The software can model how a space elevator can be built and deployed, it can model the tether's material, taper ratio, shape, force, harmonics and more, the models can be run together for numerical results which can then be put through a rendering engine for visual effect, modeling how the space elevator will deploy climbers is possible, and the costs of building and operating a space elevator can also be modeled. Find out more at http://www.usque.software.

10.5 Future Thrusts

As this book has shown, since the original studies by Brad Edwards, the space elevator community is primarily focusing upon studies, conferences and competitions - though there are many articles appearing in magazines and journals and especially online on the web that offer fresh perspectives and news. The hope is that there will be a breakthrough in funding to allow more focused and enhanced research on the topic of space elevator feasibility. Risk reduction activity is essential to the development of a real space elevator infrastructure. The current activities are (Swan, 2016):

Studies: One of the principle activities that has brought together space elevator enthusiasts and experts has focused upon academic studies of varying duration and participants. These studies have advanced progress and established the current Body of Knowledge. ISEC is set to continue to produce yearly study reports and another major study is currently being undertaken for the IAA. Companies and other entities are also looking into the lower cost access to space provided by a space elevator to enable the growth of our solar system activities. (See Chapter 9).

Conferences: A very effective way to bring together enthusiasts and experts is to hold symposia, conferences and other gatherings focused on space elevators where participants can meet, present and discuss their latest research interests. Indeed, the IAA sessions on the space elevator since 2004 at the annual International Astronautical Congress are set to continue as are the ISEC yearly Space Elevator Conferences. The Japan Space Elevator Association also holds regular annual meetings on specific topics they wish to investigate. (See Chapter 8).

Tether Climber Competitions: As Chapter 7 has revealed there have been a number of Space Elevator Games/Challenges/Competitions since 2005 in America, Europe and Japan. Initially concentrating on both power beaming and tethers and climbers, they now mainly concentrate on the tether and the climbers. The Japan Space Elevator Association and the Technical University of Munich with its EuSPEC competition are the chief organizers of these events which act as a stimulus to young researchers and a point of interest to the public.

10.6 Benefits and Applications of Space Elevators

As noted above there are currently multiple areas of activity that are applicable to future space elevator developments. However, one aspect that has not really been covered to any great extent in reports and conference papers and the like - which have mainly focused on the technical and material issues - is that of the use and benefits of a space elevator. It has often been overlooked that, as much as anything else, these will be major drivers for any space elevator operational system. James Cline did, however, at the outset of a paper presented in 2002 suggest that the Earth-encircling carousel form of space elevator could have a major impact on civilization and provide new solutions to major issues upcoming for mankind. The intention would be to solve crises in energy, greenhouse gas, recycling of toxic and high entropy materials, sustain space access, and generate room to grow (Cline, 2002).

Besides facilitating interplanetary space exploration by providing a helping hand through reducing the amount of rocket fuel needed to escape gravity, and also the potential of more convenient asteroid mining, the benefits for humanity on Earth could be enormous. The ability to inexpensively deliver large and even small payloads to orbit cheaply will spur capabilities that can stimulate an Earth revival. For example, the facility to provide power to any location on the Earth's surface (by means of space solar power satellites) will enable development across the globe. With finite oil resources dwindling, less reliance would need to be placed on them, while certain countries would not need to burn so much polluting coal or clear forests. In addition, the increase in the number of communications and Earth resource satellites would enhance and expand the emergency disaster warning systems already in place, as well as allow Africa to leapfrog ahead in its development. The problem of space debris could perhaps be ameliorated by cheap, easy-to-launch vacuum cleaners via the space elevator. Using the space elevator to haul up and store water in orbit for subsequent manned missions might be another possibility. And some intractable problems on the Earth's surface would also have solutions, such as the safe and secure delivery - and thus disposal - of nuclear waste to solar orbit. Another might be to somehow sequester large amounts of carbon dioxide to move off-planet with an elevator. The space science community might be able to employ space elevators as giant flypapers to catch cosmic dust for analysis. In this vein, too, elevators might be able to help forecast space weather by sensing and monitoring coronal mass ejections, thus providing an early-warning system for vulnerable electronic equipment and telecommunication lines on Earth. Such possibilities as these would give an impetus to a whole new range of industries around them being created (Raitt, 2016).

Of course, it must be cautioned that while some of these proposed solutions are putatively doable, they may be niche applications. The amount of power we use on Earth is so vast, that delivery of power via solar satellites may only dent the market. Although getting rid of radioactive waste is currently a huge problem with high costs, the number of nuclear power stations is diminishing as more are decommissioned - though their waste will still be hazardous for thousands of years. However, even a little is better than nothing and the situation will likely improve in time. On the other hand, what is putatively more possible is the colonization of the Moon, Mars and asteroids by means of space elevators. This could be equated with the benefit wrought in the United States by Conestoga wagons and the trans-continental railroad!

History, of course, is a continuing process and is still being written!

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Appendix A: Contributor Biographies

Brief details on the contributors to this book are given below in alphabetical order.

Mark Dodrill works in the high-tech field and became acquainted with the space elevator concept about five years ago. He assisted with the ISEC Space Elevator History Committee interviews process, and has recently transitioned to being the ISEC Webmaster.

Nicholas Martin is a member of the ISEC History team and the inspiration behind this book. He has a Bachelor's degree from the University of Denver with further studies undertaken at the Minneapolis College of Art and Design. He is currently an Epic credentialed trainer at Centura Health in Englewood, Colorado where he provides training for medical staff in EMR systems and on-going support for use of the Epic EMR system. Prior to that he was with the Bridge Education Group teaching English as a second language. He produces and edits written content intended for publication in science and aerospace magazines and journals and has collaborated with others to record the history of the space elevator concept.

Dr David Raitt retired as Senior Technology Transfer Officer in the Technology Transfer Programme Office at the European Space Agency's R&D establishment, ESTEC, in Noordwijk, The Netherlands, at the end of 2009 after over forty years service at the Agency's offices in Paris, France and Frascati, Italy. He has been involved with the space elevator since 2002 when he met Brad Edwards in Trieste, Italy and at his invitation attended the very first international space elevator conference in Seattle that same year and agreed to be the ESA point of contact. Together with Pete Swan, he has organized and co-chaired space elevator sessions at the International Astronautical Congress around the world since 2004. He has also been the co-chair of two important studies relating to the space elevator conducted under the auspices of the International Academy of Astronautics. In addition he was Chairman of the Academy's Commission VI (Space and Society). He was also Chairman of the International Online Information Meeting for some 20 years as well as similar sister conferences around the world, and he was Editor of The Electronic Library, a journal he founded, for thirty years. He created and maintains a family history website. He has a doctorate in information science and has published nearly 200 articles, conference papers, chapters in monographs, reports, editorials and the like over the years.

Ted Semon, during his professional career spanning 33+ years, worked in all aspects of software development, including designing and writing software, systems development, software management and Professional Services. He has nearly ten years of international experience, including 8+ years in Saudi Arabia and the Middle East. He was an early employee and contributor to the success of Silicon-valley startup Portal Software (now owned by Oracle). Since he retired, he has devoted much of his time to charities, including child welfare (as an Advocate with C.A.S.A.) and animal welfare. He also enjoys the art of bonsai and following and supporting activities in the space elevator arena. He is a past president of the International Space Elevator Consortium and was the author of the Space Elevator Blog for nine years.

Evan Smith obtained a Master's degree in Space Sciences from Florida Tech in 1986 and then spent over 25 years at NASA-Goddard, studying spacecraft dynamics and x-ray astronomy. He served as chief science scheduler for the Rossi X-ray Timing Explorer. He is currently a professor at Eastern Florida State College in Melbourne teaching mathematics, statistics and astronomy. He became aware of the space elevator as an undergraduate at the University of Florida (1977-1982) and has maintained this interest within ISEC.

Dr Peter A. Swan graduated from the U.S. Military Academy in 1968 with a Bachelor of Science degree. Over his 20-year Air Force career, he held a variety of research and development positions in the space arena. He taught at the Air Force Academy and retired as a Lieutenant Colonel. Upon retirement in 1988, he joined Motorola on the Iridium satellite program. As a System Engineer, he initially provided space systems engineering leadership to the field office in Washington D.C. He then led the team responsible for the development of the Iridium spacecraft bus. In 1998, he developed his own company and taught space systems engineering for Teaching Science and Technology, Inc. His classes emphasize engineering know-how and management techniques to successfully develop space systems of national importance. Pete's final degree was a PhD from the University of California at Los Angeles in Mechanical Engineering with a specialty in space systems. His dissertation was on tethered satellites. This led to a natural extension to an interest in space elevators where he has participated for over fifteen years with great interest. He has published many papers and a few books - two of which are on preparing for scuba trips.

Appendix B: Chronology of Space Elevators

This chronology attempts to give the major events with dates that are important in the history and development of space elevators.

Date	Comments
c 500 BC	Tower of Babel
early 1400s	Jack and the Beanstalk fairy tale
1895	Konstantin Tsiolkovsky inspired by Eiffel Tower to consider building tower into space
1910	Fridrikh Arturovich Tsander conceives of lunar space elevator
1958	Arthur C. Clarke writes short story in which very strong cables are used to lift blocks of ice from planet surface to an orbiting spaceship. Not published until 1986.
1960	Yuri Artsutanov lays down all the basic concepts of a space elevator in Pravda article in Russian
1966	John Isaacs, Allyn Vine, Hugh Bradner and George Bachus discuss very long tapered cables in space and consider possible materials
1967	Vladimir Lvov brings Artsutanov's work to the world in English. Ideas already in circulation in USSR as a space elevator is depicted in a painting by Leonov & Sokolov
1969	Collar & Flower mention it would be possible for a cable to reach all the way down to Earth's surface
1972	James Cline proposes Mooncable to NASA who reject the idea
1975	Jerome Pearson (re)invents space elevator in his orbital tower article
1978	Hans Moravec described orbital Skyhooks for the Moon and Mars
1979	Sir Arthur Clarke and Charles Sheffield each wrote a novel featuring a space elevator
1979	Clarke reviews history, nomenclature and concept of space elevator at 30th IAC in Munich, Germany
1979	Pearson and Artsutanov both publish concept of a lunar space elevator
1980	Tsuotomu Iwata presents paper at 30th IAC in Tokyo entitled Space escalator: semi perpetual motion in space
1991	Carbon nanotubes discovered in Japan by Sumio Iijima (also about the same time in Russia). They show potential for a space elevator.
1992	Tekkaman Blade anime series features six space elevators
1992	First of Mars Trilogy books by Kim Stanley Robinson which feature space elevator operations on Mars and Earth

1997	Kido Elevator published in Japan by Ishihara Fujio Kaneko Ryuichi. Republished in 2009 as Space Elevator.
1997	Jerome Pearson gives paper at 48th IAC in Turin on Konstantin Tsiolkovski and the origin of the space elevator
1999	David Smitherman, of NASA, organizes Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether 'Space Elevator Concepts'
2000	David Smitherman publishes NASA study on space elevators based on Workshop
2000	Brad Edwards has NIAC grant to study concept of space elevator - Phase I
2001	Brad Edwards gets new NIAC grant for Phase II study of space elevator (2001-2003)
2002	Italian Space Agency hold 1st International Workshop on Futuristic Space Technologies in Trieste. NIAC's Bob Cassanova mentions space elevator. Attendees included Brad Edwards and David Raitt.
2002	1st International Space Elevator conference takes place in Seattle organized by Brad Edwards and Michael Laine. Attendees include Bryan Laubscher, Bob Cassanova, Jerome Pearson, Eric Westling, David Raitt and Anders Jorgensen among others.
2003	Brad Edwards and Eric Westling publish seminal book on the space elevator which provides the baseline architecture for future research
2003	Marc Boucher initiates a site called the Space Elevator Reference
2003	Michael Laine forms Liftport and pursues carbon nanotube production
2003	Ben and Meekk Shelef create the Spaceward Foundation dedicated to furthering space science and technology in education and in the public eye. They approach NASA with idea of funding a Space Elevator prize. NASA accepts and allocates $400,000 in prize money.
2004	David Raitt announces 2nd Clarke-Bradbury Science Fiction Competition with theme of space elevators. Book containing submitted stories and artwork published in 2006.
2004	Regular sessions, chaired by Pete Swan and David Raitt, on space elevators are inaugurated as part of yearly International Astronautics Congresses. The sessions have been at Vancouver 2004, Fukuoka 2005, Valencia 2006, Hyderabad 2007, Glasgow 2008, Daejeon 2009, Prague 2010, Cape Town 2011, Naples 2012, Beijing 2013, Toronto 2014, Jerusalem 2015, Guadalajara 2016, Adelaide 2017.
2004	Elevator:2010 project started by Spaceward Foundation - no established space elevator teams at this time
2005	First NASA Centennial Challenges for power beaming and tether strength take place organized by Spaceward Foundation
2006	Ted Semon creates Space Elevator Blog
2007	EuroSpaceward Association created to lead the space elevator activities in Europe and to organize the European Space Elevator Games (2007, 2008)

2008	International Space Elevator Consortium (ISEC) established and kicks off multiple activities to continue the momentum of space elevator conferences and challenges
2008	The Japanese Space Elevator Association is created and then hosts annual competitions and conferences
2008	Bryan Laubschur initiated a series of space elevator conferences in Seattle co-sponsored by Microsoft Corporation. During the 2010 conference, both Jerome Pearson and Yuri Arsutanov attended and traded stories of the early days.
2009	First space elevator competition held in Japan
2010	ISEC conducts a year long study each year with a focus upon a topic of importance to advance the Space Elevator Development. The reports covering these topics are: 2010, Space Elevator Survivability, Space Debris Mitigation; 2012, Space Elevator Concept of Operations; 2013, Tether Climber Design; 2014, Architecture and Roadmaps; 2015, Marine Node Design; and 2016, Design of GEO and Apex Anchor Nodes.
2011	ISEC commences publication of CLIMB - a peer reviewed journal covering topics of interest to the development of space elevators
2011	LiftPort refocuses efforts to developing a lunar elevator built with current technology as a precursor to and Earth elevator
2012	ISEC takes over organization of the space elevator conferences at the Seattle Museum of Flight
2013	The International Academy of Astronautics (IAA) invited 41 global experts to participate in a major four year study to assess the feasibility of space elevators as future launch infrastructures. The study report (published in 2013) concluded that "The Space Elevator Seems Feasible." A further IAA study on the space elevator is underway and due for completion in 2018.
2014	The Obayashi Corporation in Japan was hired to study the concept of space elevators. Their study showed how the space elevator could be accomplished with carbon nanotubes as the baseline and with humans using it by 2050.
2015	ISEC commences publication of Via Ad Astra
2016	London Space Elevator is theme for young architect's Master's degree thesis project
2017	John Knapman and Peter Robinson give space elevator history milestones over next 50 years

Appendix C: Selected Oral Interview Transcript Summaries

The ISEC History Committee believed it would be useful to capture the memories and recollections of especially those involved in the origin and development of the space elevator from the early beginnings. Accordingly, a list of potential individuals was drawn up who were approached to see if they would be amenable to being interviewed. A number were, but other important pioneers are still missing from the list such as Jerome Pearson, Michael Laine, David Smitherman and others. It is hoped that they will consent to being interviewed in the near future. (There is an early interview with Michael Laine in October 2004 which gives an interesting historical perspective of his views and aims at http://www.nanotech-now.com/Michael-Laine-Oct2004.htm).

The oral interviews, based on a set of questions (see below) sent to the interviewees in advance, were recorded mainly by Mark Dodrill, and from these recordings a transcript was made by Mark, Mike Hall and others. These transcripts are gradually being summarized (many by Mike Hall). The transcripts, summaries, and their audio files, are available on the ISEC website (www.isec.org). However, seven transcript summaries from people who were involved to a greater or lesser extent from the start are given below. The individuals included here are: Yuri Artsutanov; Bradley Edwards; Yoji Ishikawa; Bryan Laubscher; David Raitt; Ben Shelef; and Peter Swan. The summaries have only been lightly edited so as to retain the flavor of what was said and how by the interviewees.

The complete set of interview questions prepared by Mark Dodrill in July 2014 is as follows:

ISEC Space Elevator History Committee

Categorized Interview Questions

Personal Information

- Full Name
- Current Professional Position and Company (or retired)
- Past Professional Position(s), related to the Space Elevator concept

SE Background

- When and how did you first hear about the Space Elevator? Book, professional paper, presentation/conference, other
- What interests you most about the concept of a Space Elevator?
- Have you done any research on a specific area related to the Space Elevator? If so, describe specifically what you have worked on.
- Who do you believe are the most influential people in this field in the past and today?
- Have you participated in any specific Boards related to the Space Elevator?
- Have you written any papers on topics related to the Space Elevator?
- What keeps you interested/involved in the Space Elevator?
- Do you consider yourself to be a proponent or a critic of the Space Elevator? (May not need this one, seems like everyone we would interview would be a proponent)

SE Feasibility

- Do you think that humankind will be able to build a Space Elevator in the next 50 years? 30 years? 20 years?
- If not, what do you think the major stumbling blocks are?
- Who do you think will be the ones to build the first Space Elevator? Government, corporations, private sector/individuals, consortium, all the above?
- How do you explain the concept of a Space Elevator to someone who isn't familiar with it?
- What do you think the cost would be to build the first space elevator, in USD?

SE Opportunities

- What are the Space Elevator's top 3 benefits for humankind ?
- What are the next 3 major steps that need to be taken to make the Space Elevator a reality?
- What new industries do you think would be created by a 100x reduction in the cost to get into space?
- How can the average citizen get involved?

SE Challenges

- What do you see as the top 3 challenges/hurdles in building a Space Elevator? (e.g. construction/deployment, technologies, money, etc).
- How would you respond to critics of the Space Elevator related to these topics:
    - Cost
    - Lack of technologies for all necessary components
    - Other human problems should take priority (poverty, hunger, disease, etc.)
    - Possible terrorism target

Specific Detailed Questions (probably secondary, specific to the interviewee)

- Where do you think the optimal ground location is for the Space Elevator? Why?
- What do you think is the best solution for powering the climbers? Why?
- Do you think Space Tourism would be a feasible way to help build a Space Elevator?
- Would you volunteer to ride in a climber up to the top?
- Do you think that the Moon should be used to help construct an Earth Space Elevator? Or used as a prototype?

Thank you.

Mark Dodrill

Yuri Artsutanov

An oral interview with Yuri Artsutanov was not done, however he did respond to the questions that were sent to him. This summary is based on his answers.

1) After high school, I entered the Leningrad Institute of Technology and graduated as an engineer for fuel processing. In this capacity, I worked for three years in the Scientific-Research Institute of the Petrochemical Industry (Petrochem), and then enrolled in the post-graduate school of the Institute of Technology in the Department of Colloid Chemistry. I finished it in three years, and after that taught there for a few years. Then I worked as a researcher at the first All-Union Scientific Research Institute of Synthetic Rubber, and then at the All-Union Scientific Research Institute for Abrasives and Grinding. I worked in the latter until my retirement.

During all this time I had no thoughts of a space elevator but one day one of my friends told me that the Americans had made a strong rope, capable (as a measure of its strength) of holding 400km of its body weight. And then I had an idea what you might do with a rope of infinite length.

The higher you go above Earth the less the force of gravity becomes. This is what I wrote in an article that was published in the paper "Komsomolskaya Pravda" in 1960. In it, I wrote that if you can create a very durable material, then it will be possible to make a rope long enough to climb into space without the use of rockets. The fact is that when a rocket is used to escape Earth's gravity with high kinetic speed and with great thermal energy it emits tons of incandescent gas, which is practically lost.

How to travel into space without the use of rockets? It is necessary to construct a very long and very strong rope, which will not fall to Earth as the Earth's centrifugal force will prevent it from doing so. And the longer the rope, the less the force of Earth's gravity and the greater the centrifugal force. And if it is long enough, it will remain taut and with it you can travel into space much cheaper and easier than with rockets. That was my idea and I wrote about it in that article.

2) The greatest interest to me is precisely that rope or tether. How long can it be made, i.e. the higher above the Earth, the greater the centrifugal force, and less gravitational pull by the Earth. And so it will remain upright and taut.

3) The biggest challenge is the strength of the rope, so it does not break with the centrifugal force acting on it. It has to have the strength of diamond fiber - this is important. These materials already exist, at least are very close to existing, but as the rope needed must be tens of thousands kilometers long, the amount of material required will be millions of tons, which is very, very expensive. So far, that cost is greater than the cost of the energy that is lost using rockets.

The fiber with the structure of graphite (i.e. the way the atoms are linked in graphite) - it is merely a nanotube, i.e. material which now exists only in minimal amounts. So the biggest problem - a durable material which is at present very, very expensive.

Another problem is that of meteorites in space, which can destroy the tether in a collision. However, current experience with satellites shows that there is a possible solution.

The source of energy used for the initial start-up could be nuclear.

4) Travel into space using an elevator will be much cheaper than rocket-propelled flights. The tether/elevator will operate for a long time and will be able to transport people and goods. Therefore, if and when the Earth can no longer sustain the huge number of people, or if it becomes known that a certain planet will collide with Earth at some future time, or that the Earth will become uninhabitable for some reason in the foreseeable future, a single lift will be able to transport all the people from Earth to a new planet in two to three years with using a single elevator.

5) I do not know when and who is going to build an elevator into space. I only know that no-one is specifically engaged on it in Russia. But in the rest of the world (America, Japan), there are certain groups of enthusiasts who are interested in this issue and are working on it. Most likely it will happen in America, but there is not yet any designated group actively constructing it.

6) What is a space elevator? I explain it to those interested that the idea is very simple i.e. if you lift a rope high above earth and then let go it will fall back to Earth. But if it is made very long then on the one hand Earth's gravity will become less and less, and on the other hand the centrifugal force of the Earth's rotation will be more and more. If the rope is very long, i.e. tens of thousands of kilometers, the centrifugal force at such a height becomes greater than the force of gravity of the Earth and the rope will remain upright. Therefore, based on this fact, any device equipped with the necessary power source, can lift the load to the end of the rope, and then, when the Earth points in the appropriate direction, this cargo at the end of the rope can be released and it will fly in the desired direction, depending on the Earth's angle of rotation. It will get beyond Earth's gravity and will be free of it. All the energy required to travel along the rope will be applied to leave Earth.

This applies to the load on the sling: the sling is propelled through its own inertia depending only on its speed. Similarly the load on the rope, at an altitude of more than 60,000km its speed will be equal or greater than 'escape velocity', and it will fly of its own inertia, in the direction depending on the angle of rotation of the Earth. A jet engine, if necessary, may change the direction or operate as a brake, but not as an accelerator.

7) It can be used to search for minerals on other planets, for the tourist industry as well as resettlement from Earth, as it is quite possible that the Earth will become over-populated.

8). We have to encourage industry to produce that material for the rope and thus make the rope a reality.

9). The space elevator should be the goal and advice for all mankind, and not merely individuals or certain organizations. Everybody should be educated to be altruistic, i.e. not merely to think of themselves and their business, but also about other people. That is to love others as yourself!

A three-part interview with Yuri Artsutanov conducted by phone in March 2010 by Natalie Sherman and Eugene Schlusser can be found on the Space Elevator Blog. Part 1 is available at: http://www.spaceelevatorblog.com/?p=1406; Part 2 is available at: http://www.spaceelevatorblog.com/?p=1407; and Part 3 is available at: http://www.spaceelevatorblog.com/?p=1408. It was republished in Via Ad Astra, Vol. 1, No. 1, 2015, pp. 1-12

Bradley Edwards

This oral interview with Dr Brad Edwards was conducted in 2015 by Mark Dodrill and Chris Wimer, transcribed by Matthew Farrell and summarized by Peter Swan.

Bradley Edwards says that he's talked to the Japanese a few times about the space elevator and their interest in building it. He's got a company right now that makes carbon nanotubes, which is basically the thing required to get the space elevator moving. That's sort of the technological challenge that people point to and say well we don't have the material, we don't have the carbon nanotubes. By saying that, that sort of slows them down actually from doing much more on the elevator. But as I was just saying there's been a couple of papers - I forget where they're out of - I think they're actually out of China. There's one where they've made carbon nanotubes at about 190 or 200GPa which is over three times what you need for the space elevator. There are people who are growing them 55cm in length. We grow them only to a few millimeters - up to 6mm. And they're high strength carbon nanotubes. In reality all you need is to get to about 20mm. Then you'd be able to spin all the threads you want for an elevator. You know if somebody actually wanted to do the space elevator they could put in, and it wouldn't even be a large chunk of money, but they would put in a chunk of money and get to where they needed to in carbon nanotubes. So it's more a matter of will and interest than it is of any actual technological hurdle. If we had the investment, our carbon nanotubes are going into composites and other things. If we had the investment to make the long ones for spinning, we'd probably redirect our resources to do that. I'm not sure how long it would take, but it wouldn't be very long. In our current system we may even be able to do it in a year's time simply by running the system longer. We may be able to get there. We haven't tried it yet, because our system isn't optimized for that. It'd be sort of a pain to do it but we could. Right now we don't have a real need to do it.

Mark commented that Brad was angling in a different direction than directly to a space elevator. To which Brad replied that was correct, they have customers they actually have to ship things to. But if we got them ¾ of an inch we could send them off to Don Rush off in North Carolina, a guy we've worked with. He had spun some carbon nanotubes for us prior when we worked in Cincinnati. Spun a mixture of polyester and carbon nanotubes. With just a very small percentage of carbon nanotubes, I forget what it was, doubled the strength of fiber or whatever it was. He said they're very easy to spin. So it's not a problem. So once we get them to ¾ of an inch or an inch he's waiting with baited breath over in North Carolina anxious to get his hands on some so he can spin. You can get at 90% of the strength of the individual fibers into a spun thread - which is what they do with cotton and whatever else. If you've got carbon nanotubes that are twice the strength, not even three times, but twice the strength of what's needed, and you go to spin them you now have something that's almost twice the strength of what you need. It's very conceivable with what we've got. It could be done very soon if we wanted to. There's all kinds of politics and everything else that run around that have more issues than technological.

Mark asked if Brad could give a little more background on kind of what got him going down this road in the first place? Brad replied he was at Los Alamos - he'd been there since 1990 - working on advanced technology and was one of the co-leads on the spacecraft down there. We were developing advanced technology like superconducting tunnel junctions. We built the world's first optical cryocooler which is a big thick piece of glass. You hit it with a high-powered laser and it cools down. I built that one in a lab and tested it. People had been trying to build it since 1928. Every decade someone had tried to build it and had failed. Technology kept coming closer and closer. Then we were able to do it mid-nineties, ninety-five or something, and we published it in *Nature*. Turns out Eric Cornell, who got the Nobel Prize up in Colorado, was working on it at exactly the same time we were. But he went a different route. Right after we published it in *Nature* we got a nice letter from him saying basically "you beat me."

Brad agrees that he's always been kind of interested in technology and pushing the boundaries and learning new things. He continues - that was sort of what I was doing, I was always sort of developing stuff. It came around into the nineties. I saw a book that I think was out of NASA, out of Marshall, possibly out of the report that Dave Smitherman did saying that it would be 300 years to never before we built the space elevator. David Smitherman had headed up a group who did a report on it. But they had based their effort on stuff like Arthur C. Clarke's work. Basically elevators that had been discussed to date at that time. Those were all huge elevators ten meters in diameter. They talked about capturing asteroids, mining them and extruding it down. And that's when I said we're not building this anytime soon. When I saw that, I sort of thought…, well, I knew about carbon nanotubes at that time. You know, about a 30 second calculation in your brain tells you that a ten meter diameter carbon nanotube cable would be able to lift the top ten feet of Washington State and all the buildings on it. It's like there's no way you need that. So what do you actually need to make something that's viable? I started looking into it. It's like well, let's say you want to launch twenty tons, which is what the shuttle does. You need a thread, you need a string. You don't need a huge cable. If you got a string and you could actually use it, how heavy would it be? What would it take to launch it? Then how do you use the string? How do you climb it? That's where I started. When I started looking at it just briefly, well, all of this sounds like there should be a way to get around each of these hurdles. So I started looking into it. I just kept looking, and I sort of worked through each of the details each of the issues as they popped up.

I wrote a brief paper for *Acta Astronautica* in the nineties which basically had an outline for this. Obviously not in all the details, because the paper was only eight pages long or whatever. But that was sort of where it started. I had a lot of the details of the individual components. The ribbon, the climbers, how you power, various things like that. That one I basically rewrote into a proposal and sent it to NIAC. That was 1999 or some such thing. As Gentry Lee tells it, he was on the committee that was looking at the NIAC proposals and he said somebody basically picked up my proposal and said space elevator, and like this, throws it straight for the garbage. And Gentry says whoa, whoa, whoa and he sort of grabs it halfway to the garbage can. I don't know if physically that was the actual situation or if it was just that they were all reading and said wait we need to look at it. He said they started looking at it, and decided, hey there's actually real details in here. No this isn't a massive cable that we can't build, this is actually something we may do. That's when they gave me the Phase One Award for the NIAC. I started working on that when I was down in Los Alamos. It was actually very interesting. It was right about that time that a fire had gone through Los Alamos and burned a third of the town including the quad where I was living. I happened to be out of the country at the time that it burned so...I had an overnight bag in the truck. The overnight bag is what I carried to...wherever I was. And the truck had been parked at the airport. But everything else was gone. But when I got back, basically everything else was rented or gone at that point, so I ended up in a three or four hundred square foot studio or some such thing. Half a bedroom kind of place. Basically, that's where I did the Phase 1. I was working at Los Alamos at the time, and after that I was just calling whoever I needed - Boeing for their lasers, or various other people for their various components - and talked to them. So I was working at Los Alamos and then doing another job on the side doing this. I had free time and whatever else and so that's what I did for the six months down there. And then on May 9, I had turned it in, and I gave my final presentation around then.

In response to a question from Mark about their reaction, Brad said it was very interesting. Bob Casanova said, "Well, we need you to come out and give a presentation on your work." And it was like, okay, how long do you want me to present? He's like, "Well, present it all." He said all of it, yeah. However long it takes. I was like okay, if you really want that. So I went out and started the presentation in the morning. And then we broke for lunch after a couple of hours, and I continued to present through the afternoon. So it was basically an all-day talk.

At the end of the day, people were very happy. And very impressed. They thought it was an incredible job. They were extremely skeptical when I first showed them my proposal. But after this, they were very happy with it. And the space elevator, before they canceled NIAC, the space elevator was always on their front sheet when they went to present to people about that. It was like a sort of poster child saying, "This is what our funding has done." You've heard about this. And so it was always showing up. I would see them present and my elevator would be on the front page. So it was good. And they were very happy. I went to a couple of their conferences, and presented various things. And then after that, I basically wanted to do something different, and I met my current wife. So we left Los Alamos and basically headed down to the Caribbean to live with her for a few months. But literally as I was walking out the door, the day before I left Los Alamos, I got a notification that I had gotten Phase Two. And so of course some people at Los Alamos weren't too excited to see me walk out the door with the $500,000. Then that started the Phase Two. So I did that for a few months down in the Caribbean. We came back up, and we spent a month in Russia, where my wife is actually from, then we spent a couple months in Wisconsin where my family is from, and we were looking around at where we wanted to live. And then we ended up here in Seattle. And during that time I was working on the Phase Two. And doing additional work and additional details. So the Phase One, the real bulk of the material, and then Phase Two was going into the time-consuming details of various aspects of it. The clean up, clean up this part, clean up that part, that sort of thing. And so I started doing that here in Seattle. And that was also when Eric Westling contacted me about turning the Phase One study into a book. And then, so Eric and I were going back and forth on re-writing that. That's how it got published. I wasn't really thinking too much about making it into a book, but he called me up and I said, Yeah, that sounds like a good idea. I didn't know Eric. He called me out of the blue. He said, I read your report. It's great. It really is good. It needs to be re-written, and it'd be great for a book. I'm like, Great! Excellent! I don't have the time to do that. He's like, I do. So it's like, OK! [The book in question is *The space elevator: a revolutionary Earth- to space transportation system,* by B. C. Edwards and E. A. Westling, and published in 2003 by B. C. Edwards.]

The space elevator, all that work on the Phase One and the Phase Two, you can see all the people that did the various components in the book. And there's lots of people I called and would ask, How do you do this and this? What is the best motor for this? How would you spin these? How would you get the laser to do this? I was calling all over the place. There's a long list in there and I doubt that I got everybody, but I was calling all over the place. And that's what most of it was. I didn't meet any of those people that I worked with in person until afterwards. I didn't even meet Eric until after the book was published. I never met him until the conference later, or something. And that was the first time I even met him. So it was all done in this virtual, telecommuting type thing.

Mark commented that's probably typical now, with Brad communicating with so many people. He agreed - anything like this, it sort of has to be. In companies like ours, I'm working with people directly, hands-on kind of thing. And that's sort of the way it has to be in that. But when you're developing a concept and doing the designs, and stuff like this, unless you've got the entire team right there...I spent my time picking the best people on the planet that I could find to answer questions. There was no point in me talking to some guy two blocks down just because he was two blocks down. It was much better for me to call the world's expert in...English, or something, and pick his brain. And I had no problem, you know, every single person I called, they were more than happy to just spill everything, you know? Freely. Explaining the work and how it's going, what we're doing, stuff like that. I'm sure I got more than my fair share of intellectual property sort of spilled out onto me.

Brad believes that the space elevator is very conceivable, and China they could go ahead and build the space elevator if they wanted to. They could be working on it right now for all we know. And that would allow them to go to the Moon, to Mars, to build stuff in space and start sort of a whole new space economy. However, he thinks that the Japanese are probably the most likely, more so than China who are a sort of unknown quantity. His impression of China is they've got money, they can redirect resources in directions that they choose, they want to prove that they are a real power kind of thing, and keep proving it - there's a political drive. And those kinds of things can combine to start a space program. And if they see the U.S. and Russia's space programs sort of backing down, they may see that as an opportunity. Saying, look, U.S., Russia, they did their space programs and now they're failing, or whatever story they'll spin. And come back to it and say now we're doing it, but we're doing it in a real way, and we're gonna go take over the Moon, take over Mars, we don't care about any international treaties that might say it's a shared resource or whatever. We're just gonna go. We have an elevator and you guys don't, you can't stop us.

Mark queried whether Brad thought that's possible, that one country or nation or organization could do it alone, or because of the nature of the project, would they have to do it with others? Brad noted that one could do it alone. China could do it alone. Japan could do it alone. The issues that come up are those of political pressure, because the U.S. would probably push to be a participant in a Japanese program, or there may be external politics that slow them down. But as far as budget, and ability goes, it could be done.

Actually, it might be of interest to learn that there is a rather old historical interview by Keith Curtis which took place during a chance meeting with Brad Edwards in Seattle on 14 October 2005. The interview, which elicited 85 comments can be found at http://keithcu.com/wordpress/?p=17.

Yoji Ishikawa

The oral interview with Yoji Ishikawa was conducted by Mark Dodrill on 23 August 2015. This summary was prepared by Mike Hall.

Yoji is a Senior Engineer with the Obayashi Corporation (OC), the engineering and construction group and Lead Engineer of their space elevator research team, which he has led for four years. He first heard about the concept of the space elevator as a student studying aeronautics and space engineering, possibly through reading ‘Fountains of Paradise’. The aspect of space elevator that most interests him is the possibility of making space travel easier and less expensive. He has spoken many times at space elevator conferences in Japan, mostly about Obayashi Corporation’s concept of the elevator. If the elevator existed he sees many benefits; mostly the expansion of business. He would definitely like to make the elevator rise into the skies.

The Obayashi Corporation is interested in the space elevator not just for the concept itself but for the industry world-wide it could generate. Yoji says the main reason they are doing these activities is because the space elevator cannot be built by one company, not even by OC who have experience in material, mechanical and aerospace engineering. If other industries get money for the elevator then it would eventually come back to OC in the form of construction business. For example, they may get the business if a CNT-producing factory is required. If other business increases then the economy increases and all will benefit; all the citizens in Japan and maybe even the U.S.

When Yoji speaks to other people who have never heard about the space elevator, he describes to them that it will make space travel less expensive - possibly costs two orders of magnitude lower than conventional methods. Everyone would be able to go to space at a reasonable cost; people understand this, especially kids.

Yoji thinks the main obstacle is that the technology is not ready - “if we need a hundred, maybe we just have one or two”. There are so many things to be done which is the tough part. The cost to build the elevator is not so high once people get convinced that it will not be a problem. He says you have to push other industries hard. It will be a lot of hard work. OC do not make carbon nanotubes so they have to ask someone else to make them, which is the tough part. Making the ‘port car’, for example, could be too difficult.

He then discussed with Mark, the vulnerability of the space elevator. Someone with objections could sabotage and destroy the whole thing by cutting the cable. The ideal thing is to have a very peaceful world. “There should be no enemy”. When he talks about this ideal, lots of people say that this would be the most difficult problem to solve.

Yoji doesn’t think one country could build the elevator. If one country, for example Japan, builds the space elevator then other countries may say no. This means that we have to one entity involving all the countries of the world. That’s a very difficult thing to do. All countries should be involved, Yoji emphasises.

Bryan Laubscher

The oral interview with Dr Bryan Laubscher was conducted by Mark Dodrill on 22 August 2015. The transcript was summarized by Mike Hall.

Dr Bryan Laubscher is the President of Odysseus Technologies, and General Chair of the Space Elevator Conference. He first heard of the concept of the space elevator when he was a child but didn't have a really good understanding of how it worked until around 1999-2000 when he was at the Los Alamos National Laboratory. He attended a presentation by one of his colleagues, Brad Edwards, who had been inspired by a news report of a NASA workshop held in 1999 in which they predicted the space elevator would be built in 300 years! Brad's curiosity regarding that kind of prediction led him to further research and he was reporting on his first results for the NIAC. The presentation and Brad's description of the space elevator concept was a revelation to Bryan and he was hooked. As an astrophysicist he had always been interested in science, technology and space travel. He remembers watching the Apollo astronauts walking on the Moon.

Considering a particular aspect of the space elevator that most interests him, Bryan relates the "long journey" to his involvement with space elevator projects. Initially, it was an informal association with Brad Edwards who left the laboratory a year or so later and gave a conference, in Seattle, in 2002, which Bryan attended. They had an interesting conceptual design; Bryan gave a high level presentation but became aware that there were so many different routes to take from this conceptual design; so many different options and ways to approach the concept from a systems engineering sense. Following on from this, Bryan put on a conference in Santa Fe, New Mexico in 2003. In 2004 he helped Brad with a conference in Washington, D.C., funded by the Institute of Scientific Research. At this point, Bryan wanted to try something different and went on entrepreneurial leave from the laboratory in December 2005. He joined Brad, who then had a small company in Seattle, and worked with him for a year. It was a high strength materials company and Brad was trying to get things happening, get investors and so on.

At the conference, there were people that had invested in Michael Laine's investment fund based on eventually building space elevators. Bryan cautioned them that it would be a long time before any money could be made from elevators there but they could make money in high strength materials. Unfortunately, Bryan was proven right, the whole thing fell apart, and a lot of people lost their money.

As an aside, Bryan describes how, at the Santa Fe conference, they set up satellite link to Sri Lanka and together with a telephone link were able to talk to Arthur C. Clarke who answered some of their questions.

In 2006 Bryan came to Seattle, worked for a year, worked with Brad Edwards, learned a lot about entrepreneurship and met his future wife. He went back to the laboratory for a year and then returned to Seattle; eight months later, Brad, the company and his involvement with it all imploded. There are significant differences of views of what happened to the company between Brad, Ben Shelef and those of Bryan. By this time Bryan had started his own material sciences company. At the beginning they had very small ideas using simple approaches to make the strongest nanotube thread. They competed in the NASA Centennial Challenge, but no one came close to winning. In 2007 Bryan gave a talk at the Microsoft conference. Two people came to talk to him after his presentation, one of whom, Maurice Franklin, became a friend. They offered help and Bryan suggested that together they should put on a conference; they obtained Microsoft backing and these modest conferences, which started in 2008, continue to this day. Microsoft has world class facilities which they let them use at a low price. Bryan thinks that someday there will be changes, especially if there are advances in materials.

In 2010, Maurice started the family involvement approach and robotics competitions. The Museum of Flight approached them and, following Microsoft advice, the events were transferred there. At this time Maurice was becoming less involved and David Horn was taking over the running of the conferences. Bryan was also becoming less involved with the organization of the conferences and now just shows up to give presentations. The conferences continue to be successful.

In July 2009 Bryan joined NASA at the Johnson Space Center, working in the space radiation analysis group. Unfortunately, as a result of the Constellation program being cancelled in 2010, Bryan became one of 7,000 people that NASA laid off. He returned to Seattle and continued to compete in the Space Elevator Games. When they had the conference in Washington D.C. in 2004, Ben Shelef came with Meekk Shelef and some others. They wrote a proposal to NASA for the Centennial Challenge - Bryan's group encouraged them - NASA provided the funding and the competitions continue. Bryan entered the high strength materials competition many times and there were also climber competitions which Bryan thought were interesting technological test-beds. The competitions involved teams from universities and elsewhere and produced some eccentric solutions. In the 2005 event, only one team managed to raise their climber two feet using the supplied light source. As the years went by, others used various light sources to drive their climber, including microwave. One high school team had a very slow but successful climber which did not win any prizes but won on reliability. Another team, trying to use microwaves, was noted by an electrical engineer to have the wiring completely wrong. In 2006, the team from Saskatchewan University, regular participants in the competitions, was the first team to bring their own light source, a 2.1kW laser! They were very well organized. In 2007 they used an RV to house their 9kW laser and optical train. At the same competition, Bryan recalls his concern that the LaserMotive team, mainly scientists, had a more laissez faire approach to safety with their 8kW laser. During a night run of the Saskatchewan laser they had to switch off the beam when a curious aircraft came close and flew around the testing area!

Eventually, Ben Shelef got the competition moved to NASA Dryden at Edwards Air Force Base and Dryden took on a lot of the organization. Most teams used GPS as a part of their control systems. LaserMotive instead used a joystick which turned out to be a good solution since GPS did not work at Dryden! The systems approach adopted by LaserMotive, eventually won them a $900,000 prize. Saskatchewan come close to winning many times in the earlier competitions and managed to raise around an impressive $350,000 each year in order to participate. Bryan was so impressed by the Saskatchewan teams that he says if he had had a daughter he would have encouraged her to pick one!

In 2010, after these challenges, Bryan decided he needed to plough his own furrow and start up a company. He had become convinced that current approaches at the time were going in the wrong direction. Growing nanotubes long and strong was impossible. Techniques such as chemical vapor deposition (CVD) could not do it; a whole new technology was needed. He saw that a key technology for the space elevator project was high strength materials development. He attended a conference in 2011 at the University of Cincinnati and bought some of their nanotubes for experimentation purposes. He saw a demonstration of a micro-medical device for diagnosing problems. The technique used to coat the sensor with re-agents using a uncoil-coil mechanism impressed Bryan and led him towards conceiving the Nanotube Detangler and started development work in his garage.

He built and installed equipment, for example, a 'glove box' ventilation system. His detangling system would increase strength eight-fold plus or minus four so he needed more accurate mass measuring equipment. One of the investors in the company, an alumnus from Washington State University (WSU), was instrumental in providing an introduction to the WSU materials engineering group. Bryan started volunteering, supporting undergraduate student salaries and instructing students in carbon nanotube experiments with equipment he provided himself. With some of the university's better diagnostic equipment, more accurate experiments were performed. The new instrument showed that the strength had increased by a factor of 14. He could put in an untwisted carbon filament and strengthen it up to the same strength as a twisted filament! Inspection after the tests revealed that amorphous carbon was being removed and it was increasing in density.

The following year at the same conference Benji Maruyama, of the Air Force Laboratory, revealed that the Air Force Research Lab. had been studying for ten years trying to understand why CVD growth of carbon nanotubes stops. Bryan also talked about this in his presentation. First, the hot carbon-bearing gas allows not just carbon atoms to crack on the surface of the metal catalyst and then move in or on the surface to become a carbon nanotube. It can also become amorphous carbon. It forms amorphous carbon and chokes off the path for the other. Secondly, of course in this heat the catalyst particle dissolves down into the substrate and the catalyst particle becomes too small to grow a carbon nanotube. Thirdly, of course, is that the Ostwald ripening system makes the smaller catalyst particles lose mass to the larger ones and they both become the wrong size to grow a carbon nanotube. Bryan decided he had to do something, to invent a new way to grow carbon nanotubes because they are always going to get short, damaged tubes. The final problem with CVD growth is that the already grown nanotube is sitting there cooking in this hot carbon gas, carbon-bearing gas environment, like acetylene or whatever they're using, and reactions occur on the surface to damage the carbon nanotube. He concluded that in order to get long strong pristine tubes, CVD growth was not the answer. Of course the chemists who were working on CVD never agreed with him and a year later he had another six ideas but each one of them had a problem.

He talked with a German physicist from First Nano, a CVD equipment company. He quickly found the exact same problems and agreed with Bryan that he needed another approach. A year later he had a seventh idea. He showed it to Maruyama who agreed it might work and from then on Bryan started raising money; mostly from himself, his family and friends.

Having raised a small amount of money with his investors Bryan set about performing proof-of-principle experiments. Much of the equipment was self-built or self-modified systems based on his thirty years experience in research and development; for example, modifying an old vacuum system and drilling his own masks. Bryan has a belief that products of pure carbon nanotubes rather than carbon nanotubes used in a composite matrix material will impact society most profoundly Thus being able to start with pristine strong tubes is very important. Secondly, being able to work with them and to achieve growth processes that eliminate impurities like amorphous carbon. Then we could start producing super strong filaments that are untwisted. Twisting creates problems in the form of 'forces that come back to bite you'. Other uses for these materials could be batteries and possibly armour. When this reliable construction thread is achieved he believes it can be used for carbon-based space structures. He further believes that carbon nanotubes will feed into other industries and the by-products of space elevator development will be a carbon-based revolution in the way cheap steel and aluminum did. He says it is not a question of whether we build the space elevator but once the carbon nanotube revolution has improved life on Earth, people will demand that we build the elevator. He notes that the discovery-to-widespread commercial use timescale for carbon fiber was about fifty years.

Bryan does not have a specific goal for the length of that carbon nanotubes he is trying to grow because at this stage he is doing proof-of-principle experiments based on his experience at Los Alamos. When he worked at the Los Alamos National Laboratory, his work involved conceiving of ideas, studying them from a theoretical point of view, then carrying out proof-of-principle experiments, and sometimes building a prototype.

He is looking for partners and/or eventually a buyer for the company, who could progress the work that he has been doing. He recalls being frustrated working in the government laboratory that some good ideas and proven solutions were not pursued. In particular, the work they did on rendering improvised explosive devices (IEDs) ineffective, which could have saved a lot of lives and injuries.

Bryan thinks the biggest benefits if we had space elevator now, are firstly to build an infrastructure of solar-powered satellites leading to clean energy. With this you don't have to worry about the day/night cycle, the weather or the angle of the Sun across the sky. That would change the world in the way that the 1928 U.S. government program to get electricity to the rural areas did. So the first phase would be solar power. We would then be living in a different world where space is 'close'. Schools and industry would have cheap and easy access to space for their experiments or products. A lot of the cost in current space access is the 'space hardening' and 'packaging' to get into orbit; for example, the James Webb Telescope. With the space elevator you just load it or suspend it beneath the climber. Bryan relates the compromises that the Hubble Space Telescope people had to make to fit the scope into the rocket fairing which had fixed dimensions. The small fairing issue and the throw-away rocket are big problems and the space elevator will change all that with a possible cost reduction from $20,000 to $60 for a 20lb load!

Mark's final questions for Bryan are what does he think is the best way to power climbers? For the first climber Bryan thinks laser power beamed from the ground. Secondly, where does he think the first elevator would be located, for which he doesn't have an exact answer but recalls Brad Edwards' study which favored a location west of the Galapagos Islands. Thirdly, if he had the chance would he ride the Space Elevator and the answer was an unequivocal "I would".

David Raitt

The oral interview with Dr David Raitt was done on 15 July 2014 by Mark Dodrill. David was the first person to be interviewed as part of this project. This summary was prepared by David himself from the transcript.

At the time of this interview I had been retired from the European Space Agency for some years (after over 40 years service in France, Italy and Holland) and for the last 10 or 12 years, I was the Senior Technology Transfer Officer working at ESA's main R&D establishment at ESTEC at Noordwijk in the Netherlands. The earliest recollection I have where anything was actually happening with a space elevator was when I went to an international workshop on futuristic space technologies in May 2002 in Trieste, Italy. There I met Bob Cassanova from NIAC who spoke about Brad Edward's study on the space elevator. Brad was also at that conference and made a presentation on the topic. We had dinner a couple of times and he told me more about his ideas on the space elevator, and particularly the reports for NIAC. After that we kept in touch and he subsequently invited me to the first space elevator conference, which took place in Seattle in August 2002. There I met other interested parties. I agreed to be the ESA contact and recruit and try to orchestrate European efforts to assist the program.

The things that interested me most about the concept of the space elevator were the very uniqueness and imagination of it. It appealed to me because I was always thinking outside the box and this led me to conduct a study in 2001 to look at innovative technologies from science fiction for space applications. The idea was to see whether it would it be possible to do those imaginative advanced things that they were talking about and describing in the sci-fi books and magazines of the 1940s and 1950s with today's technologies or with technologies we knew were just around the corner. The space elevator was one of the concepts that we considered in that study, subsequently leading me to organize an essay competition, involving Brad Edwards. Prizes were offered, provided by Brad, for the best papers on the space elevator, and all the papers were published in a book.

If I consider the most influential people in the concept of the space elevator, then Brad Edwards certainly has to be one right from the start. Another one has to be Michael Laine, who was very much in the early days with Brad, but then they split up with Michael setting up his own company. He has been influential in what he has done, and still is active today. Another one, of course, has to be David Smitherman who also did quite a big study of the space elevator for NASA in the early days, and that study was followed by another by Jerome Pearson on a lunar space elevator. Jerome is still very active today, as is Bryan Laubscher who worked with Brad for a while and who was responsible for organizing quite a few of the space elevator conferences. Then there is Pete Swan who is one of the most influential people today - not only a prolific author in the field, but also the driving force behind trying to get the space elevator up and running in some form or another. Together we introduced the topic at the International Astronautical Conferences and there has been at least one, usually two or three, sessions devoted to the space elevator at every IAC since 2004. Two others from the more distant past who have to be the precursors of the ideas are Konstantin Tsiolkovsky and Yuri Artsutanov. Of course, I didn't know them as I knew the others mentioned here. They wrote the original papers that led Brad Edwards, David Smitherman and Jerome Pearson to write more about the concept.

I do participate in a number of "boards" relating to the space elevator. I'm a member of the ISEC History Committee, of course. I was chairman along with Pete Swan of the space elevator sessions on the IACs since 2004. I co-chaired with Pete the IAA Study Group on the space elevator and am also co-chair on the follow-up study. And actually I was a director and on the board of the European Spaceward Association for a few years when it was active.

Besides the science fiction study and the competition and resulting book on the space elevator, I have also contributed several other papers, though not really technical stuff, to the field. I wrote an illustrated paper on the space elevator in history, art, and literature. I did a paper on space elevator economics and applications - comparing the scale and costs of a space elevator with other mega construction projects like bridges, maglevs, tunnels. I was involved in another paper on the textile aspects of tethers. I was also the co-chair, along with Pete Swan, of the study conducted under the auspices of the International Academy of Astronautics entitled "Space Elevators: An Assessment of the Technological Feasibility and the Way Forward." This study culminated in a book of the same name published in 2013 and I was an editor for this publication. I have also written a couple of chapters and papers on the whole history of the space elevator and its place in conferences.

Although technology is moving forward in leaps and bounds, it will be at least 20 years or so until a space elevator is built - possibly by the private sector, or the Japanese, or even the Chinese (though we don't know much about their plans). Besides funding, major stumbling blocks at this time are carbon nanotubes, made in proper lengths, joined together somehow, and fashioned into a giant ribbon. Also the skepticism of governments or space agencies and other priorities in conflict with space elevators need to be addressed. But there would be some major benefits of a space elevator for mankind. Getting rid of nuclear waste safely and efficiently would be one. Space-based solar power would be another. Using the space elevator to haul up and store water in orbit for subsequent manned missions might be another. Yet another might be to somehow sequester large amounts of carbon dioxide to move off-planet. We have to convince the major players and possible private investors on the value and benefits of the space elevator project so that they will invest and make it happen. More funds are needed for research and development and on aspects like ribbon production. But in fact a host of new industries would be created by the building of a space elevator, and others - I mean we could think of the nuclear waste disposal industry, asteroid mining projects or space tourism, the space science community could use the elevator to catch cosmic dust for analysis - we would have a wealth of new opportunities and business.

I have explained many times and in many different contexts what the concept of a space elevator is. I relate it to the "Jack and the Beanstalk" story. The beanstalk reaches up into the heavens, to the sky. This story goes back to the 1600's or even 1400's. There is also a Chinese story of people going up to a mountain and then ascending into heaven. Instead of a beanstalk, I tell them the space elevator is a ribbon one meter wide, and as thin as a sheet of paper, and extends 100,000 kilometers into space. Most people understand the concept then even if they are not sure how it works!

As for responding to critics of the space elevator; well the projected cost generally doesn't come up too much, but you can relate it to the costs of launching anything into space. If I recall, Brad Edwards' initial figure was $6bn, and some 10-15 years ago we were saying it would cost about $10bn - well costs have likely increased, but technology has also made some things cheaper. But people need to compare the costs of current mega projects - Boston BigDig, the Øresund Bridge, the Channel Tunnel, and the like. As noted earlier a French bank was fined $9 billion for violation of U.S. laws related to supporting sending USD to prohibited countries. Fines for Swiss banks and others are in the billions also. Fines that BP had to pay for the Gulf of Mexico oil spill, also have run into the tens of billions. Also, companies spend billions on research for new drugs and the oil companies' research expenditures are huge. Daimler is saying it will spend $10bn on R&D for ten battery-powered cars. Even if it's now $15bn, the cost of building a space elevator is fairly small relative to these!

Another objection is related to not having all the technologies necessary, but these are being worked on and being improved all the time. Most are already there with the exception of the ribbon. Still another objection is that we should spend the money on other human problems (poverty, hunger, health etc.). The money from the huge bank fines could be used for these purposes, but it isn't. Human problems should not always take priority because the space elevator could help solve some of these problems (directly or indirectly). Private investors are investing their own money, and they can do what they want now, why would this be any different? People also object by saying it would be a terrorist target. I don't see why it would be any worse than any other national landmark or structure like a bridge or maglev. Why would they bother, what would be gained?

One final though - space tourism could greatly benefit from the space elevator. If the price is reduced and if it is safe, there could be a large market. Especially if you could get the price down to the cost of a couple of nights in a hotel. In a study I did for the IAA on Space Expectations, when people were asked, "Would you want to go into space?" a very high percentage of participants from all over the world responded they would jump at the chance to go into space - and many said they would even go on a one-way trip to Mars!

Ben Shelef

The oral interview with Ben Shelef was conducted by Mark Dodrill on 23 August 2014 at the ISEC Space Elevator conference in Seattle. This transcription summary is by Mike Hall.

Mark asked Ben about his background and how he became involved in the space elevator project. Ben related that he was a mechanical engineer and joined the space elevator project in about 2003 after a meeting with Brad Edwards. He did the Space Elevator Games and wrote a few papers; notably "Space Elevator Power System and Optimization" and "The Space Elevator Feasibility Condition".

Ben found the most interesting aspects of the space elevator were the engineering challenges and its unique solution. He thought the benefits from building the elevator would be the cheapest way into space if it worked as hoped. Asked how he explains the concept to people, who are not familiar with the space elevator, Ben replied that he gives presentations at various places. The reaction he gets is generally enthusiastic; at the first contact with the idea they can't really judge, they just like it!

Ben thought the major stumbling blocks to progress from where the project is now to a working elevator were primarily the development of the nanotube tether and power systems which are not easy. They are demanding and expensive.

Ben, currently, is not involved in the space elevator process; this conference was his first in four years. He came to the conference mainly to meet old friends. Mark asked Ben what the next steps should be in order to move forward with space elevator project. Ben replied that if there is no breakthrough with the nanotube tether it is a "No Go!".

Ben suggested that along with Brad Edwards, Yuri Artsutanov should be included in space elevator history report, if he was still available!

Mark asked about the 'Spaceward Foundation' which Ben created. Ben answered that they ran the Space Elevator Games from 2004 to 2009 as annual events; mainly relating to climbers and other things. There is a link to a good archive of the games via spaceward.org.

Peter Swan

The oral interview with Dr Peter Swan on 1 July 2016 was conducted by Paul Morrison and transcribed by Mike Hall, who also provided this summary.

Pete Swan is the President and a Director of the International Space Elevator Consortium and Paul first asked him to give some background of himself and his involvement with the space elevator program. Pete declared he is a natural teacher who has taught scuba diving and space systems orbits etc. He loves working with young people, particularly young up-and-coming professionals. After retiring from the Air Force he was Emeritus Professor of Teaching Science and Technology, Inc.. Whilst doing his PhD, "in the dim and distant past" and waiting for sign-offs, he was about to do another tour with the Air Force. He had a weekend spare and so he played about with a simulation, attaching a tether to the Moon just to see what it would do. This led to all sorts of discussions on the space elevator in about 1984. He confessed he was by no means the first to think about this; Jerome Pearson and others had worked on this before him but it did open up his thinking and suggested the concept of a stable tether as an elevator. His great break when it came to elevators was the recognition in 2002 that Brad Edwards had held a space elevator conference and he had missed it! He has met everyone since then plus a few others and so he had become involved with space elevators big time around 2002/2003.

Paul asked Pete what, to him, was the most interesting part of the space elevator as a whole project - to which Pete replied that he loved the whole concept. He said it was a huge challenge and would change the way humanity lives. The realization that space elevators are delivering people and payloads to space in a daily routine manner will enable colonization of the Solar System. The reality is that space elevators will open up cislunar space and trips to Mars by enabling a very low cost connection to space. He believes the space elevator has huge potential as a major project similar to digging the Panama Canal or putting up the Golden Gate Bridge. It would be a project in the order of more than a billion dollars, and lasting more than ten years. He has always enjoyed working with the big picture items, the initial concept development of a big project and has always loved to be in the group that created the big picture - "where are we going, what are we doing, how are we doing it?"

The answer then, to Paul's question of what is his favorite part of the space elevator project, is the architecture and how it is going to be done conceptually, where are we going, the vision engineering architecture; what are the problems? How do we develop solutions to the grey-skies picture?

Paul queried Pete on what he thought were the biggest challenges and the problems that have to be overcome? Pete responded that he thought the biggest problem was material. Starting with a belief that the space elevator will happen, the biggest question is when will the material be ready? Materials long enough, strong enough and able to survive in the environments of Earth orbit and cislunar space. He stated that there are many people working on carbon nanotubes, boron nitride tubes, diamond strings, so there are three concepts of material today. There are projects published in the International Academy of Astronautics 2013 study, "The Feasibility of Space Elevators". In this study they were projecting lengths of hundreds of kilometers of carbon nanotubes being available in a 2022-2025 time frame. We are not talking about more than a decade; we are talking about material being ready by 2030! So the real base challenge is material availability, the rest is a systems level challenge.

There is a need to put this together; the climber is nothing more than a big spacecraft, the GEO node is no more than a big station and the tether anchor is no more than an Earth port holding an oil bearing platform on steroids! He doesn't believe there are any showstoppers. He believes the materials will get there, but that is a belief not reality. So he thinks we will have a space elevator - it might not be in the time frame we are looking at though, but it will come about.

Paul recalled an earlier statement of the project costing one billion dollars and asked who did Pete think will foot that bill and build the whole space elevator complex; will it be government or private enterprise. Pete said his answer is two-fold - first the estimate will be more than a billion dollars. In their initial estimates on space elevators, Brad Edwards gave a figure of $6bn, but in the 2013 IAA study, the figure was $15bn for the first three space elevators. The first will be more expensive than the second two. The Obayashi Corporation, talking about their operationally capable system of delivering people up to GEO, estimated $100bn. The range of costs are still to be agreed.

Pete admits that question of who is going to build it and who is going to fund it, is a big question. His personal opinion, given in something he wrote earlier, was based on a study of a commercial development of a space elevator similar to building the Golden Gate Bridge. Then the backers charged a toll for every car that crossed. So he believes that this is a way to make millions of dollars with an initial outlay of some $10bn to build it.

This is not a great deal of money, Pete thinks, and there are many places that spend $10bn for something. It can be afforded in a commercial world; the product will provide access to space at a phenomenally low price. He also thinks there is a huge market for this; firstly the known market - synchronous satellites and tourist trips and similar things, and also the unknown market for a huge set of businesses that no-one has yet thought of! He can see a commercial arrangement that takes a tank and refuels and repairs satellites. It would get fuel from the Moon and asteroids and it is much cheaper to bring fuel from these places than it is to send it up by rocket. So they could sell their fuel at an exorbitant amount of money and people who brought their satellites and rockets up to orbit could buy their fuel cheaper than at lift off. So the businesses he sees are going to be phenomenal in the future. His interest is commercial, he adds.

Pete continues that there is also the aspect of strategic strength for a country to be the one providing access to space, so other countries could very easily jump in and build it. The U.S. could do it, Japan could do it and India could do it. Many people have talked about rich nations funding it and space nations building it. For example, the United Arab Emirates financing an Indian project is not out of the question. So it would be governments funding it and a commercial company building it and a third option is government funding and building it like any launch. Many countries launch satellites these days and they could be viable contenders; but Pete's vision is that it would be a commercial venture and this is what was put as the preferred option in the IAA study.

Asked how he explains what space elevators will do for mankind, Pete responds that the first thing is to define a space elevator. He has prepared a statement as President of ISEC, the International Space Elevator Consortium, that he can repeat very easily. It is intended for people who have not been introduced to the concept of space elevator so they can understand. It states that the space elevator will be two orders of cost less and two orders of magnitude greater in payload delivery compared to today's launch methods. It is done with a ribbon one meter wide and 100,000km long; comparable to swinging a rock around your head on a piece of string. It has climbers that have opposing wheels to press against the ribbon with the friction and electricity driving the wheels and the climbers just go up and down. It's a simple concept of wheels in a material with ridges and it is done to give the belief that it will provide solutions to Earth problems and will enhance the human condition by providing phenomenal access to space. Exploring the cislunar space first and then the solar system with robotic satellites and with humans and if you wonder about that now, there are two companies, 'Planetary Resources' and 'Deep Space One', that have robotic prospector satellites either launched or ready to be launched, looking for asteroids for water, ice and minerals to mine. They are actively pursuing asteroid mining; when they find these asteroid products they are going to have resources to sell.

Pete believes the first resource to sell will be water at the Lagrangian Point One (L1) which is most of the way to the Moon in a semi-stationary position. The products would be brought to that location, to a Space Port. At this Space Port there will be people who want to go to the Moon, who want to go to Mars, want to go asteroid mining or come back to Earth and they will need fuel. Water provides oxygen and hydrogen; oxygen for breathing, water to bathe in, water to drink. So water will be very valuable at the L1 Space Port. Why bring it from asteroids, not up from the ground? A kilogram of water at the L1 position is about $40,000, so if you bring water to the L1 Space Port you could sell it to these guys at $39,999 per kilo and make a killing. The second aspect is the people on the ground who are launching, who are taking the water up can take more hardware instead of water. They don't need to bring the fuel and water to go to Mars. They can bring the hardware and then fuel up at L1. So he believes the first business at the L1 Space Port will be selling water.

Paul then asked what is the next immediate step, the next thing that has to be done? Pete replied that there are multiple groups around the world working with the concept of the space elevator. The Obayashi Corporation has just completed a big study inside their company trying to provide money for a space elevator. The rational for the Japanese company is that their country has no natural resources for energy, so they need energy for their lifestyle and the geosynchronous solar-powered satellite has been proposed as an answer to their problems. They are investing and focusing on solar-powered satellites and one of the ways to get them up to space in efficient manner would be a space elevator. They have a design and timeline of 2070 for delivering masses and people up to the geosynchronous location. So the Japanese are pursuing it already as a very rational energy source for their country.

Pete continues by outlining the role of the International Space Elevator Consortium; it is an all-volunteer organization, pursuing the space elevator as a commercial venture and is a facilitating agency supporting anyone who is interested. What ISEC does is try to increase the body of knowledge for the space elevator by doing academic studies and research and working together. The next stage is to define a funding profile to reduce the technological risk part that is in the carbon nanotubes. There is already a trillion dollars going into carbon nanotubes so he doesn't think the space elevator community has much impact there!

He states that there is a need to let the carbon nanotech community know that there is a big requirement up there and ISEC needs do some work with that community. For example, a research program looking at the factors, like how do to develop the material for the ribbon? What type of weave is needed? What is the coefficient of friction the nanotubes? And so on.

A major requirement is to understand the dynamics of the space elevator tether; this requires good modeling and simulation capability. There is a lot of diverse activity; we need to come up with a gold standard vetted by the ISEC. We need to look at how we take care of the Earth Port. One present study to investigate a port with multiple stages that go up into altitude and cut down the length of the elevator required and skip the atmosphere. There are lots of problems: wind, lightning, rain water. If we could get through the atmosphere without getting our climber-tether exposed, that would solve a lot of engineering problems. Then there is an idea of having a platform at 40km to bring your satellites in a box, to the climber in a box and take it from there.

There are multiple ideas surfacing about how to do space elevators, we need to do more research, fund researchers and things like that; set up a research grant funding mechanism that starts with money. After we do the research, which would probably be a five or six year project, we may need to fly a pathfinder prototype into orbit. The prototype Pete would like to fly would be to 2,000km altitude, 1,000km long, that would be testing prototype tethers, climbers, prototype tether deployment and simulation etc. Pete believes a prototype climber is needed within eight years. The cost would be sizeable, up to $50m for research. He believes there would be a research phase, a prototype phase and in parallel to that the development of materials. During this phase of developing the space elevator, a Program Office and people working on the space elevator would arise.

Paul asked Pete if he had any final thoughts or advice for the space elevator community as a whole? Pete replied that he would just say “join ISEC”! He thinks the best thing is for people to become involved, do what they would want to, research, ISEC community studies and so on, and “Keep climbing”

In an historic meeting in St. Petersburg Russia in August 2006, the two inventors of the space elevator met for the first time, when Jerome Pearson visited Yuri Artsutanov and they talked, through an interpreter, outside the Hermitage Museum.

Space Elevators: A History

Under the editorship of David Raitt, this timely book brings together for the first time the record of people, places, developments and activities, in fiction and in fact, of the space elevator - a 100,000 km long, meter wide, ribbon reaching up from the Earth and into space along which robotic climbers will travel to bring payloads into orbit at a fraction of the price of rocket launches.

The chapters in this book cover the early pioneers who dreamt up the concept initially some 120 years ago; the work of modern day scientists and engineers who have developed the concept into doable plans; how the concept has been portrayed in novels, films and art; the conferences at which interested people could present and discuss their work and ideas; the global community that has grown up around space elevators and the competition challenges that have been held; and what the future may hold. The book provides an interesting, historical overview of the complete development to date of space elevators and as such is a valuable addition to the literature on the topic. Prepared under the auspices of the International Space Elevator Consortium History Committee.

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