AIRCENTRE

ATLANTIC INTERNATIONAL RESEARCH CENTRE

Atlantic Constellation Preliminary Definition

May 2020

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INTRODUCTION: AIR CENTRE

- International, distributed and collaborative network institution
- To foster **job creation** and **knowledge driven economic development** in Atlantic regions
- Based in **scientific excellence** and providing services to the scientific community
- To monitor and decisively contribute to reach the UN sustainable development goals, summarized in 3 main global challenges:
  - Climate Change
  - Digital transformation
  - Income inequalities and population dynamics

Main Thematic Missions

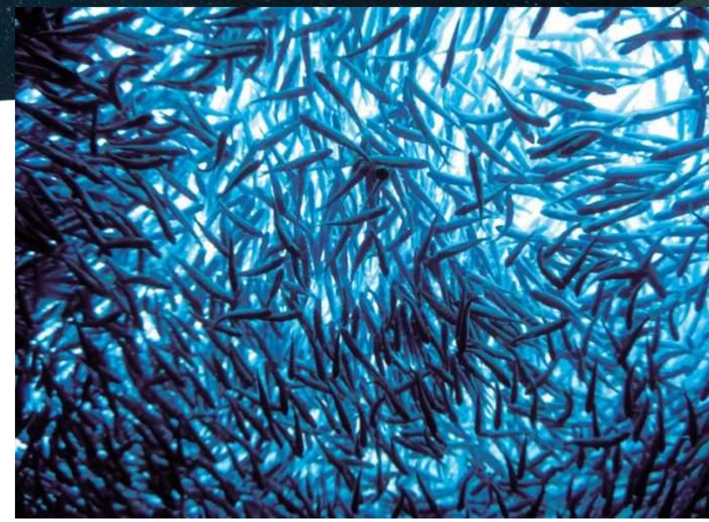
- Bay and stuarine areas
- Floods and natural disasters
- Sustainable food production (aquaculture and agriculture)
- Coastal ecosystems and processes
- Low cost sensors and information systems
- Islands

Basic Scientific Agenda:

- Marine resources and biodiversity
- Healthy and clean oceans
- System integration from deep see to space
- Mitigation and adaptation to climate change
- Sustainable energy systems
- Data Science
- Remote Sensing Sciences

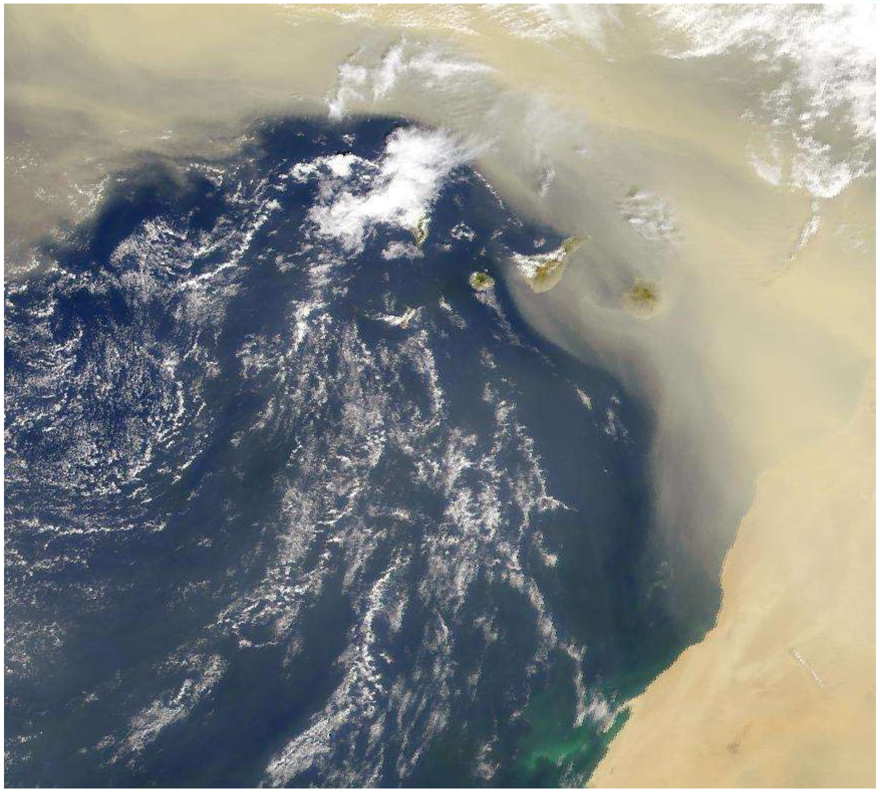
ATLANTIC USER NEEDS

- Coastal erosion, bay and stuarine area protection
- Fish stock management and protection of fisheries
- Optimization of aquaculture and algae bloom monitoring
- Detection of oil spills, plastics and ocean contamination
- Climate change monitoring and marine weather forecast
- Atmospheric and Air quality monitoring
- See surface temperature, ocean color, salinity, chlorophyll maps
- See ice monitoring and marine operations safety
- Ocean ship monitoring and air traffic service (**AIS** and **ADSB)**
- Precision agriculture and forest resources services
- **Internet of Things** (IoT) with sat constellation
- Disaster monitoring:
  - Floods risk and evolution
  - Tsunami alert
  - Fire risk and recovery
  - Earthquakes and volcanoes
- Deforestation and desertification
- Urban monitoring and interaction urban-rural
- Biodiversity assessment and animal migrations
- Water quality, resources and management
- Ports safety and energy, oil and gas services



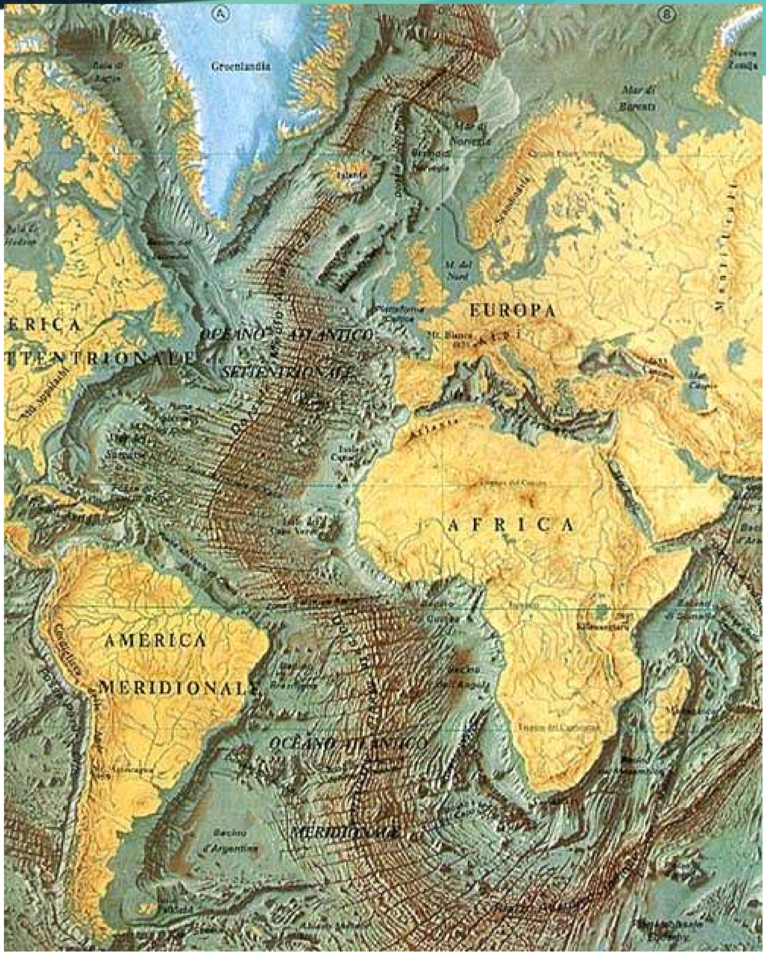
ATLANTIC POLE TO POLE OBSERVATION SYSTEM OF SYSTEMS (APPOSS)

- The complexity of the user needs requires a holistic approach encompassing different sciences (space, ocean, atmosphere, climate, data, energy, ...)
- At the same time, a **framework** that provides a complete understanding of the environment (ocean, land, atmosphere, space) is needed
- This **framework** can not be a single system, as it is impossible to observe all the complexity with a single type of sensors
- AIR Centre proposes this framework to be a "**system of systems**" for the observation of the Atlantic in its whole complexity
- The **Atlantic Pole to Pole Observation System of Systems (APPOSS)** is a holistic framework to provide the required measurements and to deliver the required services to cope with the identified user needs

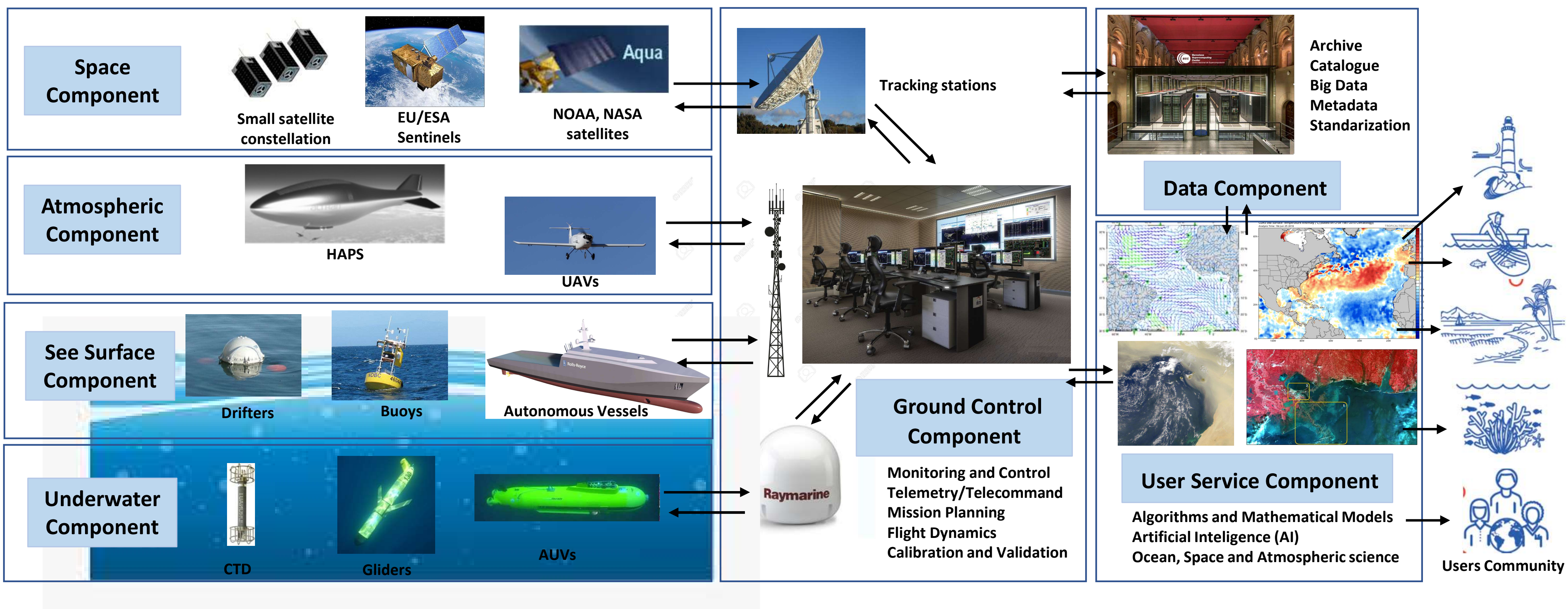


ATLANTIC POLE TO POLE OBSERVATION SYSTEM OF SYSTEMS (APPOSS)

- The principles for the development of the APPOSS framework are:
  - APPOSS is a **collaborative and distributed** framework, developed by industry, academia and research centers in different countries along the atlantic
  - There is no need to develop all components of APPOSS, an important part of the framework shall be the **integration of existing observing systems**
  - The APPOSS framework shall be developed in a **step by step** approach due to the extraordinary complexity of the final product
  - AIR Centre shall perform the task of **coordination** and **interface management** between the different components of APPOSS and the different stakeholders

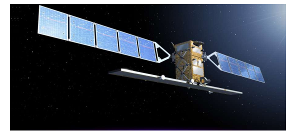


APPOSS ARCHITECTURE



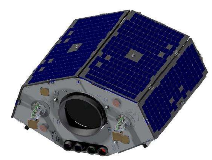
APPOSS SPACE COMPONENT

- The use os satellite is of paramount importance because it provides **synoptic measurements** due to its very large field of view
- An important part of the space component are existing satellites from Europe (Copernicus's Sentinels), USA (NOAA, USGS and NASA) and others AIR Centre members: Brazil (CBERS), Nigeria (NigeriaSat), Spain (Paz, Ingenio, Deimos 1, Deimos 2)
- Direct access to data from those satellites shall be developed at the **Ground Control Component**, the seed of this part is the **EO Lab**
- Appart from above existing satellites, a **new constellation of small satellites (Atlantic Constellation)** shall be developed to complement providing the required short revisit time and low latency
- This document provide a **preliminary definition** of this constellation

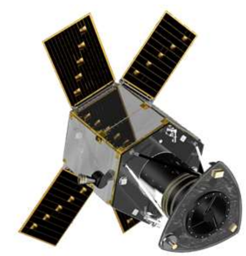










REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS

- The principles for the analysis of requirements and identification of potential payloads are:
  - Duplication of existing capacities should be avoided. In this frame, as the most comprehensive satellite system for Earth Observation is the Copernicus program of the European Union and the European Space Agency, with a policy of open and free data, this document shall focus in complementing the existing datasets. Therefore **identification of data gaps in the Sentinel satellites is an important part of this exercise.**
  - When analysing user needs, the corresponding measurements required and the associated payload that could provide this data, it must be noted that we are dealing with a constellation of small satellites (nano, micro-satellites) and there is an important limitation in size, volume, mass, power and data volume for those payloads. **Therefore payloads that are incompatible with above limitations must be discarded**.
  - The analysis is divided in two group of different services:
    - **Commercial services** with a product that can be delivered directly to final commercial customers and generate immediate revenues for the constellation
    - **Institutional services** that provide datasets to be used for the scientific community and for the value added industry to generate applications and solutions for a variety of final users

REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS: COMERCIAL SERVICES

The most important direct commercial user needs and associated payloads are the following:

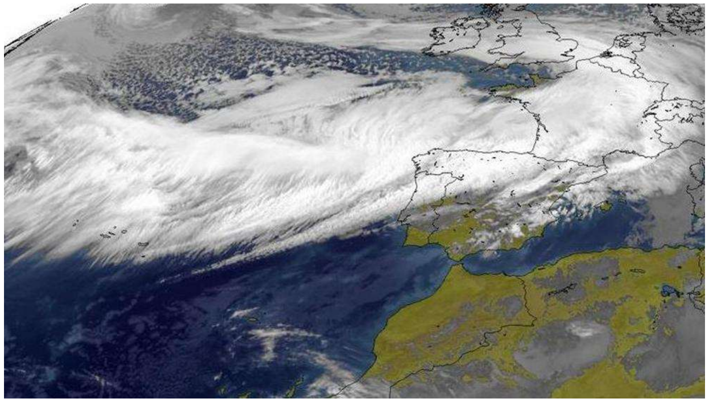
- **Maritime traffic data**: there is a need to monitor the maritime traffic and identify the vessels in order to provide traffic management, collision avoidance, search and rescue, illegal traffic detection, illegal fishing detection, illegal immigration and related type of services. The satellite payload that can provide this type of data is **AIS**, which has been already used by some space systems and can be miniaturized to fly in very small satellites.

- **Air traffic data**: there is a need to monitor the air traffic data over the Atlantic region for the different air traffic authorities. The control over the largest part of the North Atlantic region is done from the island of Santa Maria in the Azores by NAV, the official Portuguese Air Traffic Navigation Authority. The satellite payload that can provide this type of data is **ADSB**, which has been already used by some space systems and can be miniaturized to fly in very small satellites.

- **Communications**: there is a need to provide communications for fixed and mobile users (vessels). The payload compatible with a small satellite system is a **transponder for IoT** (Internet of Things) services. This system can provide communications to a large number of potential users, including M2M service, search and rescue, collection of scientific data from autonomous sensors (drones, autonomous vessels, ...).

REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS: INSTITUTIONAL SERVICES

- For the **institutional services** we first select the 12 most important **user needs**:
  - Coastal erosion and protection of bays, stuarine areas and mangroves
  - Natural disaster monitoring including flood, sea rise, tsunmais, fires, earthquake, volcanoes, ...
  - Marine weather forecast, alert for extreme severe weather
  - Fishing pressure and fish stock assessment, aquaculture and algae bloom monitoring
  - Water quality, water resources, ocean color maps
  - Marine operations safety, ship position mapping and ports monitoring
  - Land for infrastructure status assessment, and mapping (risk assessment),
  - Agriculture and forestry (hydric stress),
  - Atmosphere for weather forecast and air quality
  - Climate for ozone layer and UV and climate evolution
  - Sea ice monitoring (extent and thickness), iceberg monitoring
  - Natural habitat and protected species monitoring, biodiversity monitoring



REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS: INSTITUTIONAL SERVICES

- Above user needs can be served with different **measurements**, we shall pay attention to the measurement gaps of the Sentinels (ref. paper published in 2018 with the title: "*Gaps Analysis and Requirements Specification for the Evolution of Copernicus System for Polar Regions Monitoring: Addressing the Challenges in the Horizon 2020–2030*" by Lancheros, Camps, Park, Sicard, Mangin, Matevosyan and Lluch). The required measurements are:
  - **Sea Surface Temperature (SST)**, with a spatial resolution < 1km, revisit time < 3h and latency < 1h
  - **Ocean Chlorophyll Concentration**, with a spatial resolution < 1km, revisit time < 72h and latency < 1h
  - **Ocean hyperspectral imagery**, with a spatial resolution < 100m, revisit time < 3h and latency < 1h
  - **Ocean multispectral imagery** , with a spatial resolution < 10m, revisit time < 3h and latency < 1h
  - **Color dissolved organic matter**, with a spatial resolution < 1km, revisit time < 72h and latency < 1h
  - **Land multispectral imagery (visible and NIR)** , with a spatial resolution < 10m, revisit time < 3h and latency < 1h
  - **Land hyperspectral imagery**, with a spatial resolution < 100m, revisit time < 3h and latency < 1h
  - **Vessels monitoring (AIS)**, with a spatial resolution < 100m, revisit time < 3h and latency < 1h
  - **Soil moisture at surface**, with a spatial resolution < 10km, accuracy of 0,01 m3/m3, revisit time < 24h and latency < 1h

REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS: INSTITUTIONAL SERVICES

- Above user needs can be served with different **measurements**, we shall pay attention to the measurement gaps of the Sentinels (ref. paper published in 2018 with the title: "*Gaps Analysis and Requirements Specification for the Evolution of Copernicus System for Polar Regions Monitoring: Addressing the Challenges in the Horizon 2020–2030*" by Lancheros, Camps, Park, Sicard, Mangin, Matevosyan and Lluch). The required measurements are (continuation):
  - **Atmospheric pressure over see surface**, with a spatial resolution < 1-25km, revisit time < 3h and latency < 1h
  - **Ocean surface currents**, with a spatial resolution < 1-25 km, accuracy < 0.5 m/s, revisit time < 3h and latency < 1h
  - **Dominant wave direction**, with a spatial resolution < 1-15km, accuracy < 10º, revisit time < 3h and latency < 1h
  - **Significant wave height**, with a spatial resolution < 1-25 km, accuracy 0,1 m, revisit time < 3h and latency < 1h
  - **Wind speed over see surface**, with a spatial resolution < 1-10 km, accuracy 0,5m/s, revisit time < 3h and latency < 1h
  - **Ice measurements (type, cover, extent, thickness, tracking, drift)**, with a spatial resolution < 10 m, revisit time < 3h and latency < 1

The most important requirement of above measurements, that can not be provided by Sentinel satellites is the very small revisit time and latency (3h and 1 h respectively), the only way to provide those figures is by a constellation of satellites as the Atlantic Constellation defined in this document.

REQUIREMENTS ANALYSIS AND POTENTIAL PAYLOADS

- Once the **user needs** are prioritize and the **measurements** needed to solve above needs are identified, the next step is the **identification of instruments** (payloads) that can provide above measurements with the required accuracy and compatible with the limitations of a small satellite (e.g. we have discarded active sensors like SAR, LIDAR, radar scatterometer or radar altimeter). The final resulting list of potential payloads is the following:
  - **AIS** decoder for maritime traffic and vessel identification
  - **ADSB** sensor for air traffic
  - **IoT** communications transponder
  - **Multispectral** optical high resolution camera in visible, NIR and TIR bands for ocean and land imaging, see surface temperature, chlorophyll concentration, color dissolved organic matter, see ice cover, etc.
  - **Hyperspectral** optical medium resolution camera in visible, NIR, TIR and other bands for the same application as multispectral plus monitoring of alga bloom
  - **GNSS/R** sensor for wind speed over see surface, significant wave height, dominant wave direction, ocean surface currents, see ice cover and thickness, soil moisture, flooded areas, etc.
  - **Microwave atmospheric** sounder for atmospheric pressure over see surface
  - **IR sounder/spectrometer** for sea surface temperature and sea ice cover
  - **Microwave radiometer** (X, K, Ka, W or L bands) for sea ice cover and thickness and soil moisture

INSTRUMENTS BASELINE FOR CONSTELLATION PRELIMINARY DESIGN

- The final selection of instruments for the Atlantic Constellation is subject to a deeper analysis, however in order to perform the initial constellation design we need to select a baseline payload. Taking into account the priority of needs we select the following instruments as baseline:
  - An **AIS** decoder for vessel monitoring, covering a conical field of view under the satellite, limitted by the minimum elevation of the satellite from see surface that is set to 5º
  - A **Multispectral** optical high resolution camera in visible, NIR and TIR bands with a geometric resolution better than 5 m, a swath of 20 km and optical properties (MTF, Signal to Noise, etc.) to be defined at a later stage
  - A **Hyperspectral** optical medium resolution camera with a geometric resolution better than 50 m a swath of 100 km and spectral bands to be defined at a latter stage
  - A **GNSS/R** sensor able to track all GNSS constellations (GPS, Galileo, GLONASS and Beidu) reflected on the sea surface with angles up to 35º-40º

- The remaining instruments (ADSB, IoT transponder, Microwave atmospheric sunder, Microwave radiometer, IR sounder) are "**nice to have**" payloads, that shall be considered in a deeper analysis

CONSTELLATION PRELIMINARY DESIGN

- For the design of the constellation we shall consider two type of instruments:
  - **Optical instruments** (Multispectral and Hyperspectral cameras) that work in "**pushbroom**" mode with capability of **off-nadir pointing**, the most important parameter is the "**field of regard**" which is the area on the ground that can be potentially imaged by the camera (not to be confussed with the **swath**, which is the actual imaged area and is much smaller) and which depends on the maximum off-nadir angle of the system. We shall consider a nominal "maximum off-nadir angle" of +/- 30º, for extreme urgent cases of emergency we may use +/-45º off-nadir, but this is not used for the design. The constellation shall provide a global **mean averaged revisit time of 3 hours**, as required by the users, and a **latency of less than 1 hour**.
  - **Conical instruments** like the AIS, able to receive signals from the sea surface with a minimum elevation angle of 5º. For the constellation design we require a continuous coverage of the Earth surface with gaps under given limits, in the Atlantic Constellation we require a global mean visibility gap lower than 15 minutes, a worst case latitude mean visibility gap of 20 minutes and a global worldwide worst case gap of a maximum of 1 hour.
- Above set of requirements shall allow us to start the preliminary design of the constellation

CONSTELLATION DESIGN: ORBIT SELECTION

- The Atlantic Constellation shall be designed to provide valuable data along the whole ocean, from pole to pole, therefore a polar or quasi-polar orbit is mandatory. For the optical sensors, a **Sun-synchronous (SSO)** orbit is very interesting as it always give the same illumination angle for images of all satellites in the same orbital plane, making easy the comparison of different images taken at different epoch. SSO orbits are quasi polar (inclination around 98º). The inclination of SSO orbits is a well known direct function of the altitude.
- In addition to SSO, we select for the Atlantic Constellation "**frozen orbits**", those orbits are extensively used in Earth Observation as they provide always the same altitude at a given geographic latitude allowing also an easy comparison of images taken at different epoch. In addition they also provide a repetitive pattern in a cycle of a selected given number of days. In this way the planning of the constellation and the ground segment operations are much easier as once it is done for a few days (the repetition cycle) it can be repeated contituously.
- The repeat cycle of a given frozen orbit depends on the altitude. The SSO frozen orbit condition gives as degree of freedom the altitude, for each altitude we can get a repetition pattern and the mean semimajor axis, mean eccentricity, mean orbital inclination and mean argument of perigee.
- A list of frozen orbits has been generated to be taken as a catalogue as a function of the altitude, where we can choose the most suitable value, in the next page we show an example of frozen orbits at different altitudes with the corresponding repeat cycle, every line of the table is a different orbit with a different altitude.

CONSTELLATION DESIGN: ORBIT SELECTION

ORBIT MISSION ANALYSIS PROGRAM

MINIMUM REF. ALTITUDE (KM) : 650.
MAXIMUM REF. ALTITUDE (KM) : 700.

MAX. REPETITION CYCLE (DAYS) : 30
MEAN MEAN ANOM. AT INJ. (DEG): 177.78

BROUWER-LYDDANE MEAN ORBITAL ELEMENTS

NCO	I	D	PER(S)	SMA(KM)	HREF(KM)	ECC	INC(DEG)	SOM(DEG)
14	5	7	5871.84	7028.874	650.739	0.0000000	98.01374	162.5547
14	17	24	5874.22	7030.775	652.640	0.0000000	98.02136	265.3350
14	12	17	5875.20	7031.557	653.422	0.0000000	98.02450	298.2850
14	19	27	5876.07	7032.253	654.118	0.0000000	98.02729	193.1300
14	7	10	5877.55	7033.437	655.302	0.0000000	98.03205	229.2856
14	16	23	5879.29	7034.827	656.692	0.0000000	98.03763	110.1703
14	9	13	5880.63	7035.897	657.762	0.0000000	98.04193	234.3422
14	20	29	5881.69	7036.746	658.611	0.0000000	98.04534	29.1027
14	11	16	5882.55	7037.436	659.301	0.0000000	98.04811	205.5549
14	13	19	5883.87	7038.489	660.354	0.0000000	98.05235	47.1278
14	15	22	5884.83	7039.255	661.120	0.0000000	98.05543	180.1163
14	17	25	5885.56	7039.837	661.702	0.0000000	98.05777	311.0214
14	19	28	5886.13	7040.295	662.160	0.0000000	98.05961	333.8487
14	**2**	**3**	**5890.91**	**7044.112**	**665.977**	**0.0000000**	**98.07499**	**324.3870**
14	19	29	5895.53	7047.803	669.668	0.0000000	98.08987	271.8145
14	17	26	5896.06	7048.229	670.094	0.0000000	98.09159	88.6718
14	15	23	5896.74	7048.767	670.632	0.0000000	98.09376	287.8960
14	13	20	5897.61	7049.465	671.330	0.0000000	98.09658	141.7986
14	11	17	5898.80	7050.411	672.276	0.0000000	98.10040	125.6285
14	9	14	5900.49	7051.763	673.628	0.0000000	98.10586	172.2782
14	16	25	5901.64	7052.682	674.547	0.0000000	98.10958	210.0044
14	7	11	5903.11	7053.852	675.717	0.0000000	98.11431	296.4515
14	19	30	5904.33	7054.828	676.693	0.0000000	98.11826	151.4802
14	12	19	5905.04	7055.393	677.258	0.0000000	98.12055	81.6780
14	17	27	5905.82	7056.022	677.887	0.0000000	98.12309	166.3350
14	5	8	5907.69	7057.514	679.379	0.0000000	98.12913	245.8250
14	18	29	5909.43	7058.904	680.769	0.0000000	98.13476	254.0201
14	13	21	5910.10	7059.433	681.298	0.0000000	98.13691	270.6514
14	8	13	5911.58	7060.615	682.480	0.0000000	98.14170	89.9930
14	11	18	5913.31	7061.995	683.860	0.0000000	98.14730	236.6105
14	14	23	5914.29	7062.775	684.640	0.0000000	98.15046	185.5599
14	17	28	5914.91	7063.277	685.142	0.0000000	98.15250	14.6470
14	3	5	5917.81	7065.585	687.450	0.0000000	98.16187	339.8997
14	16	27	5920.81	7067.981	689.846	0.0000000	98.17161	79.5233
14	13	22	5921.50	7068.526	690.391	0.0000000	98.17382	182.8428
14	10	17	5922.58	7069.391	691.256	0.0000000	98.17734	209.8540
14	17	29	5923.40	7070.048	691.913	0.0000000	98.18001	326.4986
14	7	12	5924.57	7070.979	692.844	0.0000000	98.18380	219.3418
14	11	19	5926.35	7072.400	694.265	0.0000000	98.18959	273.3804

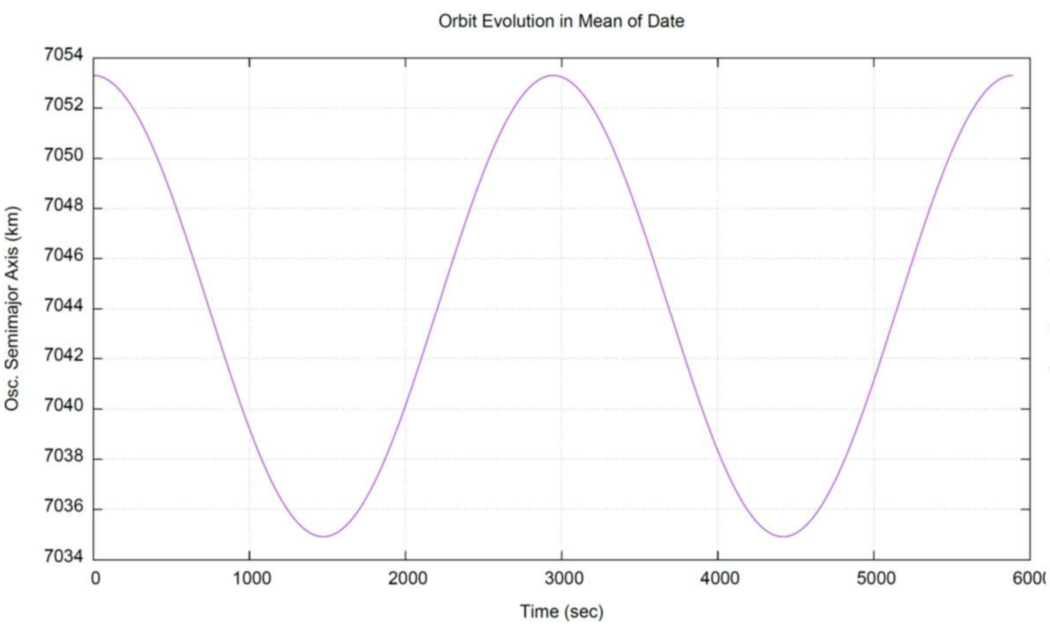
- This is the list of SSO frozen orbits between 650 and 700 km altitude with a maximum repetition cycle of 30 days (one line per orbit)
- For the selection of the repetition cycle it is important to clarify that this is for a constellation and not for a single satellite project
- A very low repetition cycle is very good because the same geometry is reproduced with high frequency and the planning and operation are simplified.
- However for a mission with a unique satellite a very short repetition cycle means that some points of the Earth are always seen with the same geometry, which in some cases implies always a large off-nadir viewing angle, with distortion and loss of resolution. For that reason short repetition cycles are normally not selected for single spacecrafts with off-nadir pointing capabilities.
- As we are dealing with a constellation, we can choose a very short repetition cycle as the large number of satellites ensures always a good viewing geometry and small worst case off-nadir angles.
- In this case we select the altitude that provides 14 2/3 revolutions per day, which is a repetition cycle of 3 days or 44 orbits.

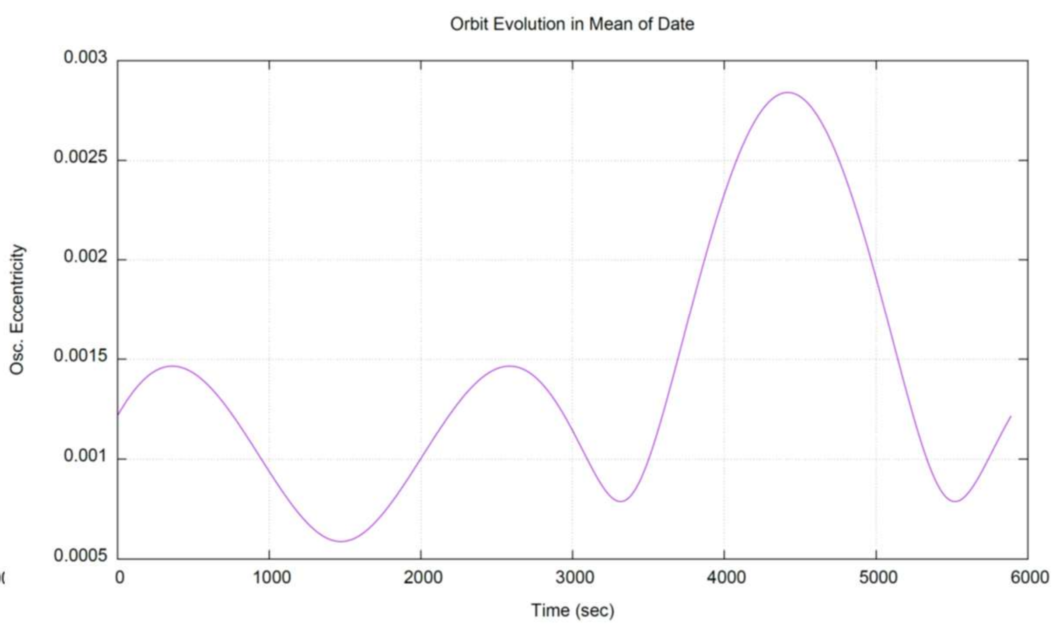
CONSTELLATION DESIGN: ORBIT SELECTION

- The mean orbital elements (averaged with the theory of Brouwer-Lyddane) for our selected **SSO frozen orbit** are as follows:
  - Mean **semimajor axis**: 7044.112 km (orbital period of 5890,91 seconds or 14 2/3 orbits per day, 3 days repeat cycle)
  - Mean **eccentricity**: 0.00000
  - Mean **inclination**: 98.07499º
  - Mean **argument of perigee**: 324.387º
- The right ascension of the ascending node can be freely selected, normally it is selected in order to provide a required Mean Local Solar Time at Ascending Node (MLST at AX) according to the user preferred solar illumination of the image
- The altitude range (between 650 and 700 km) where we have chosen the 3 day repetition cycle has been selected also as a trade off:
  - Lower altitudes improves the resolution of optical images and requires less energy at launch
  - Higher altitude improves the swath, the field of regard and therefore the revisit time and the visibility cone of AIS sensors and reduce the need of propellant as there are less drag forces
- The range 650 – 700 km is a compromise altitude, not too low and not too high. However operational issues during payload selection may force to change this altitude in further analysis.

CONSTELLATION DESIGN: ORBIT SELECTION

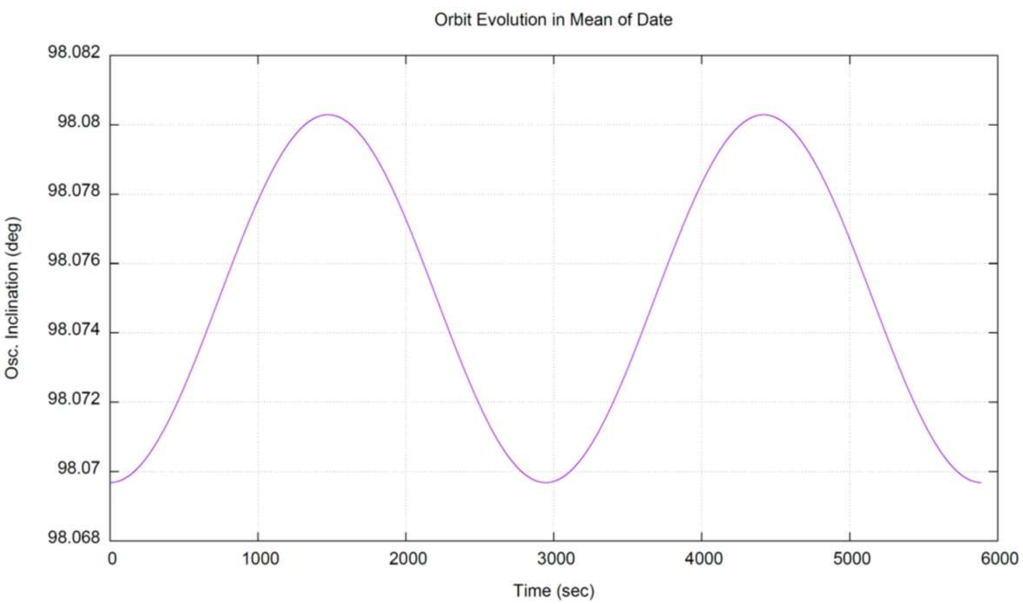
- Evolution of the selected orbit osculating semimajor axis and eccentricity in Mean Earth Equator of Date frame from ascending node to ascending node:

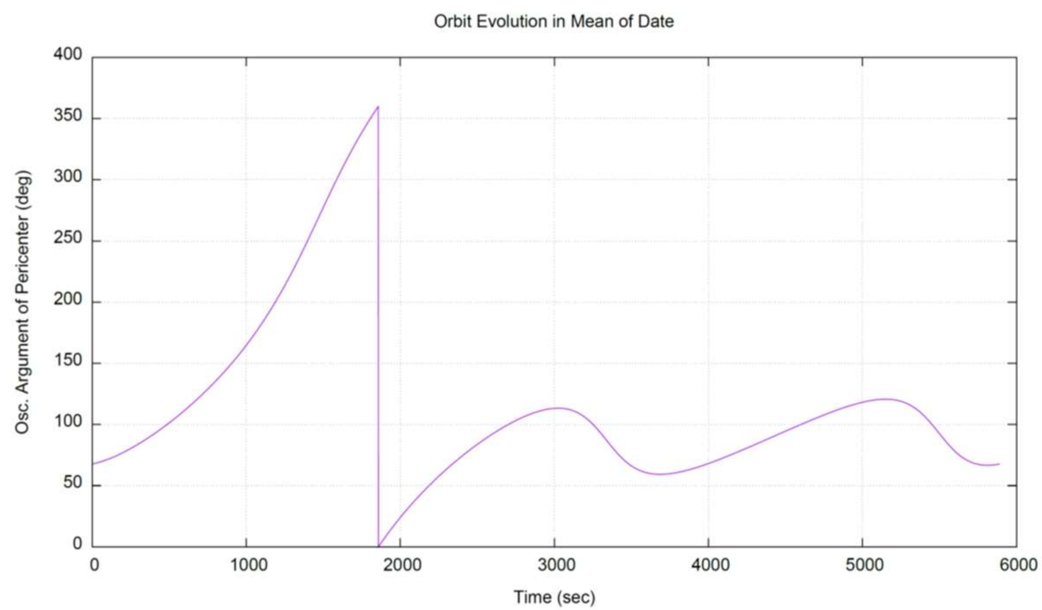




CONSTELLATION DESIGN: ORBIT SELECTION

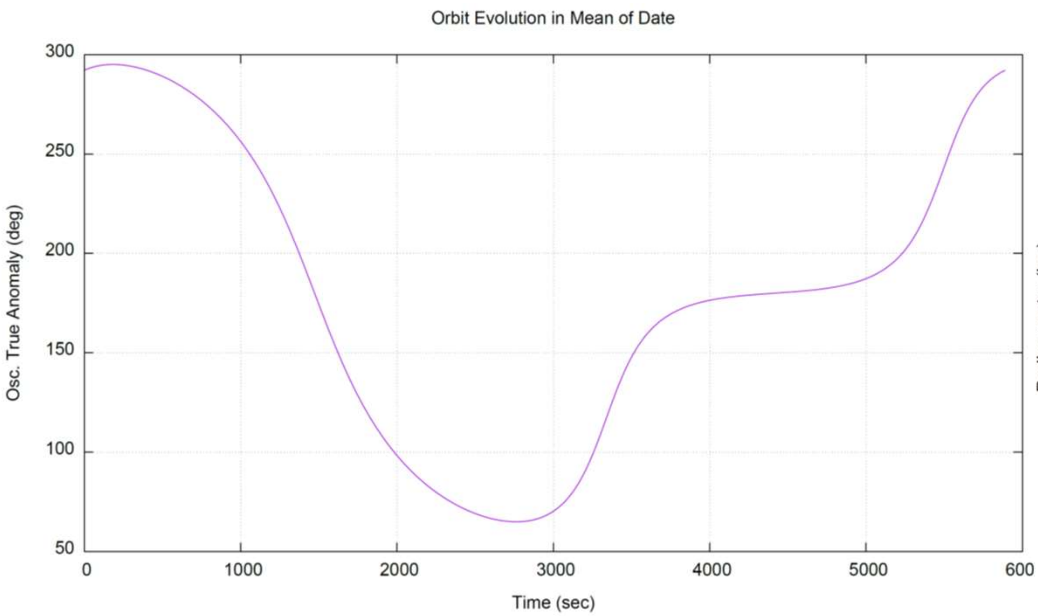
- Evolution of the selected orbit osculating inclination and argument of perigee in Mean Earth Equator of Date frame from ascending node to ascending node:

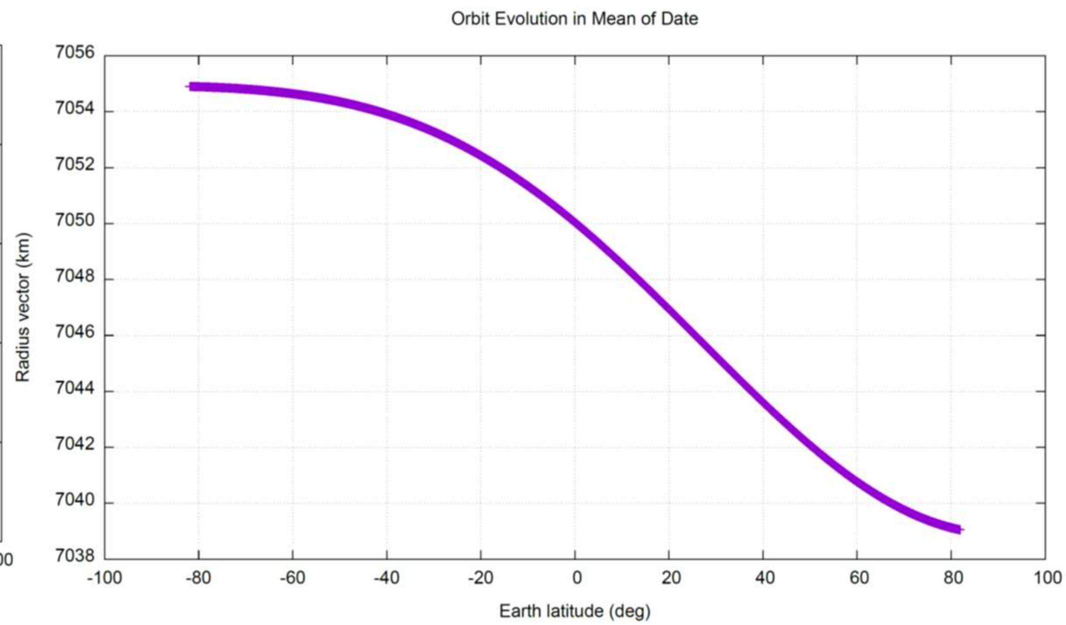




CONSTELLATION DESIGN: ORBIT SELECTION

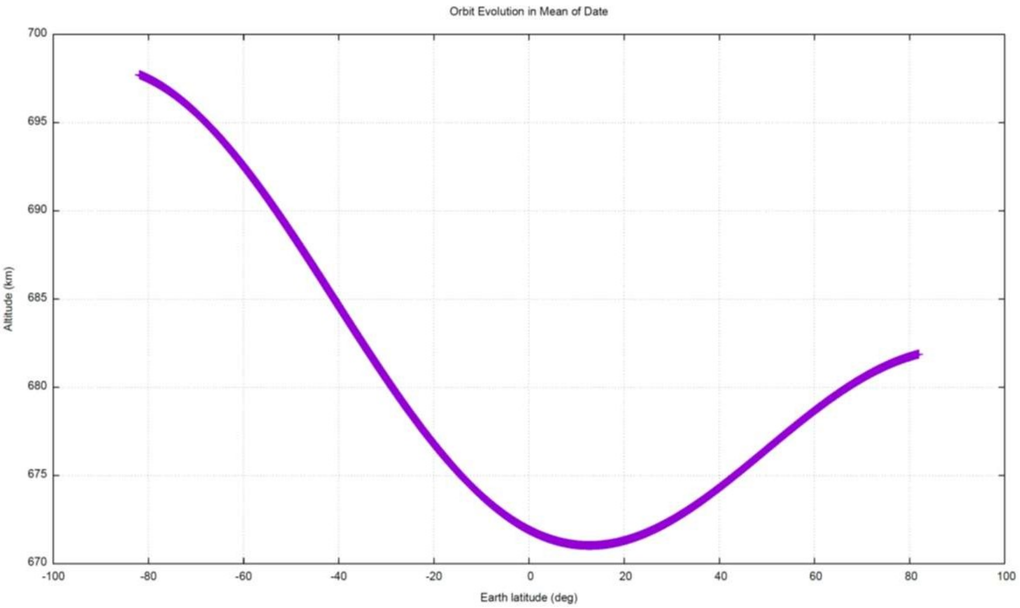
- Evolution of the selected orbit osculating true anomaly in Mean Earth Equator of Date frame from ascending node to ascending node and the satellite radius vector as a function of the geographic latitude.

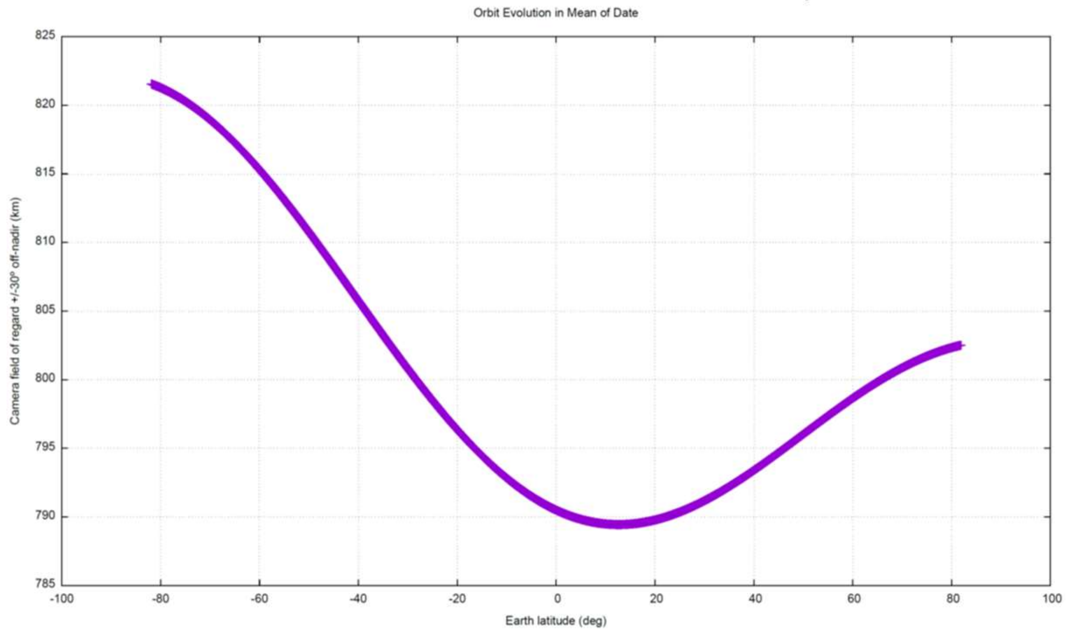




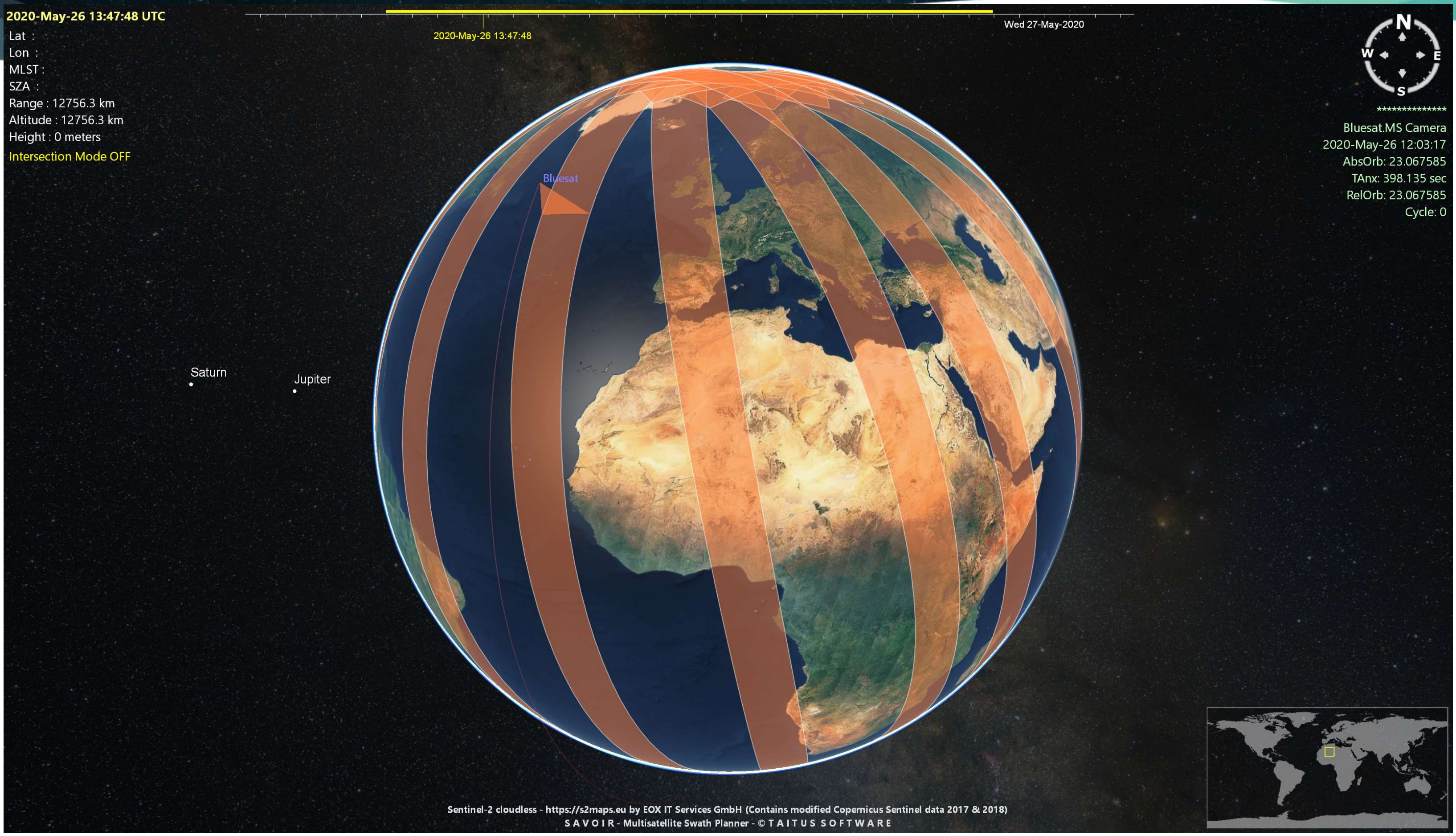
CONSTELLATION DESIGN: ORBIT SELECTION

- Evolution of the satellite altitude and camera field of regard (for +/- 30º off-nadir angle) as a function of the geographic latitude. It must be noted that there is a large variation of the satellite altitude as a function of the geographic latitude, it moves between 671 km and 698 km, this should be taken into account for payload design. The corresponding field of regard of the camera ranges between 789 km and 822 km width as the satellite overflies a region of the Earth. As we selected a frozen orbit, the altitude profile versus latitude is constant for all satellites and all orbits in the cycle.





CONSTELLATION DESIGN: ORBIT SELECTION



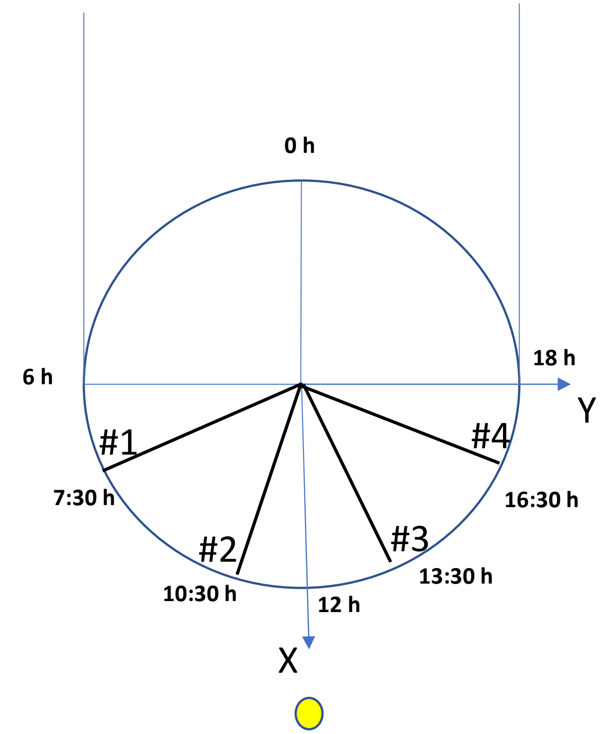
- 3D representation of the finally selected orbit with the field of regard over the Earth of a single satellite in one day of operations

CONSTELLATION DESIGN: SELECTION OF ORBITAL PLANES

- The following step in the constellation design is the selection of the total numer of orbital planes
- A large number of orbital planes improves the revisit parameter but increases drastically the cost of constellation deployment. A manoeuvre to change the orbital plane of a satellite is unfeasible due to the large energy required, therefore every orbital plane requires normally a dedicated launch, and the launch cost is one of the most expensive items in a space project. The conclusion is that we should select the minimum number of planes that satisfies our requirements
- As we need 3 hours revisit, this should determine the distance between orbital plane nodes as they are quasi polar. The Earth rotates 45º in 3 hours, then we need to distribute the orbital planes nodes separated 45º in the illuminated part of the Earth, such that every point of the Earth crosses an orbital plane with differences of 3 hours in time. **This exercise provides a total number of four orbital planes**.
- The next step is the exact selection of the four orbital planes ascending nodes with respect to the Sun, this selection determines the Mean Local Solar Time (MLST) at ascending (or descending) node. This is one of the most important parameter of an optical mission as it defines the solar illumination in the satellite image

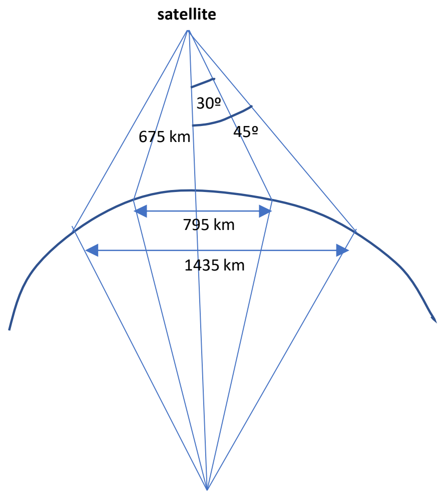
CONSTELLATION DESIGN: SELECTION OF ORBITAL PLANES

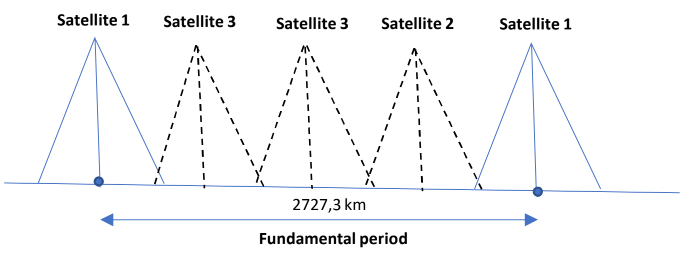
- This figure illustrates the optimum selection of the orbital plane orientation
- We assume that the Sun direction is along the X-axis (it happens on March 21st every year)
- The ascending nodes of the 4 orbital planes must be selected with a separation of 45 degrees and taking into account the following considerations:
  - A MLST of 12:00 is bad because Sun glint effects produces problems in the camera
  - A MLST close to 6:00 or 18:00 is bad because it gives large shadows in the satellite images
- The optimum solution is to choose MLST at: 7:30, 10:30, 13:30 and 16:30
- The right ascension of the ascending node for the four planes is then:
  - Plane #1: 292.5º
  - Plane #2: 337.5º
  - Plane #3: 22.5º
  - Plane #4: 67.5º



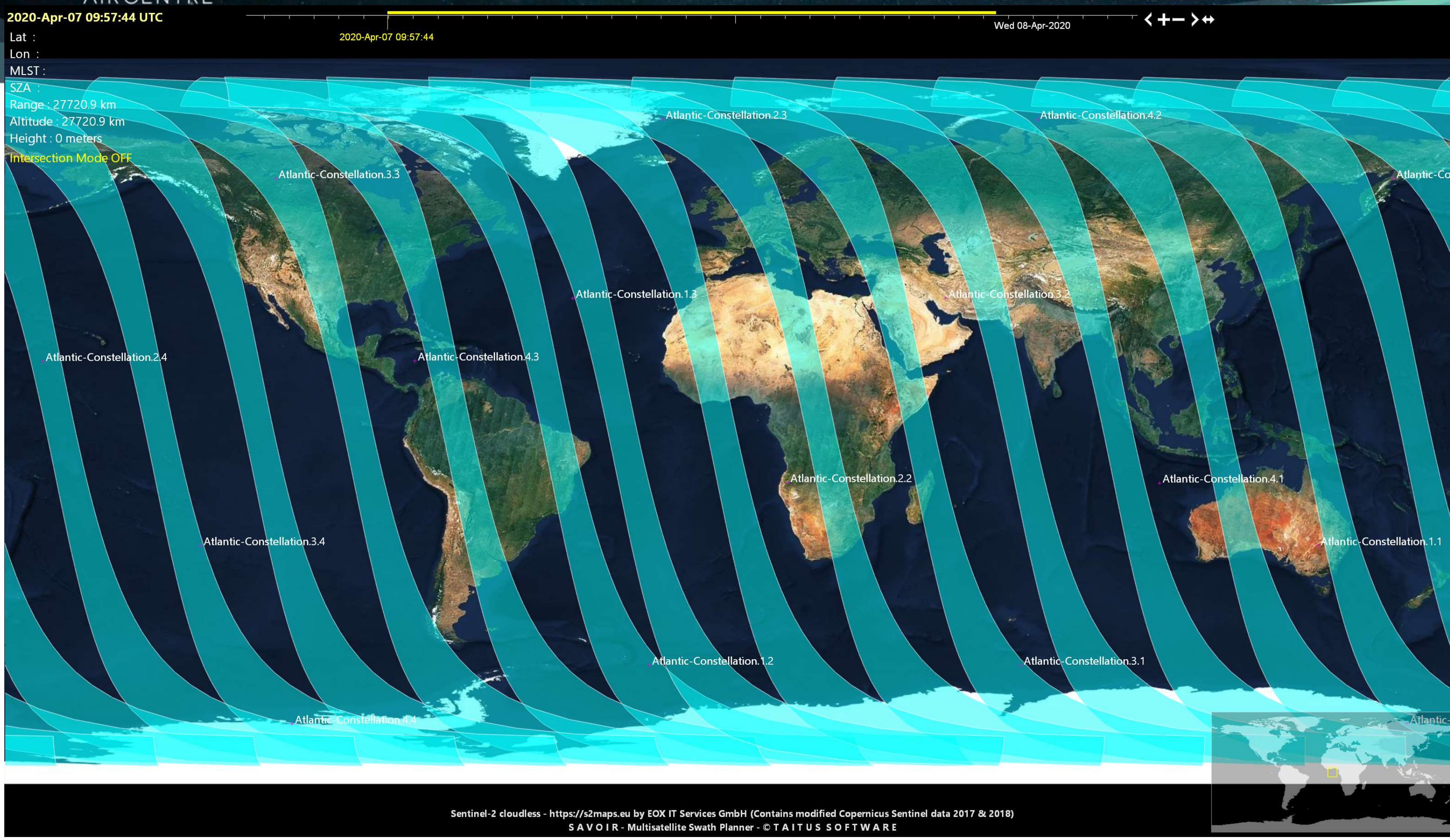
CONSTELLATION DESIGN: SELECTION OF NUMBER OF SATELLITES PER PLANE

- The final step is the selection of the number of satellites per plane
- This number is the minimum number that guarantees that every point in the earth is observed by the satellites of a constellation plane every day
- For this calculation we first obtain the width of the field of regard of a single satellite in the worst case (over the equator at about 675 km altitude), illustrated in the figure, it is 795 km for +/- 30º off nadir (nominal case) and 1435 km form +/- 45º off nadir (only emergency)
- Then we calculate the fundamental period length, this is the distance that the Earth moves between two consecutive passes of a satellite in a single orbit, as the period is 5890,91 seconds, the Earth moves at the equator 2727,3 km
- The total number of satellites that we need is the division of the fundamental period by the field of regard of a single satellite, for the nominal +/- 30º off nadir this number is: 3,43, therefore **we need 4 satellites per plane** and we are sure that we always obtain a minimum of 1 image per orbital plane per day
- In the case of +/-45º off nadir, this number is 1,9, then we would need only 2 satellites. But as nominal is +/-30º, we select 4 satellites per plane, then in case of emergency we may obtain a minimum of 2 images per plane (8 per day)



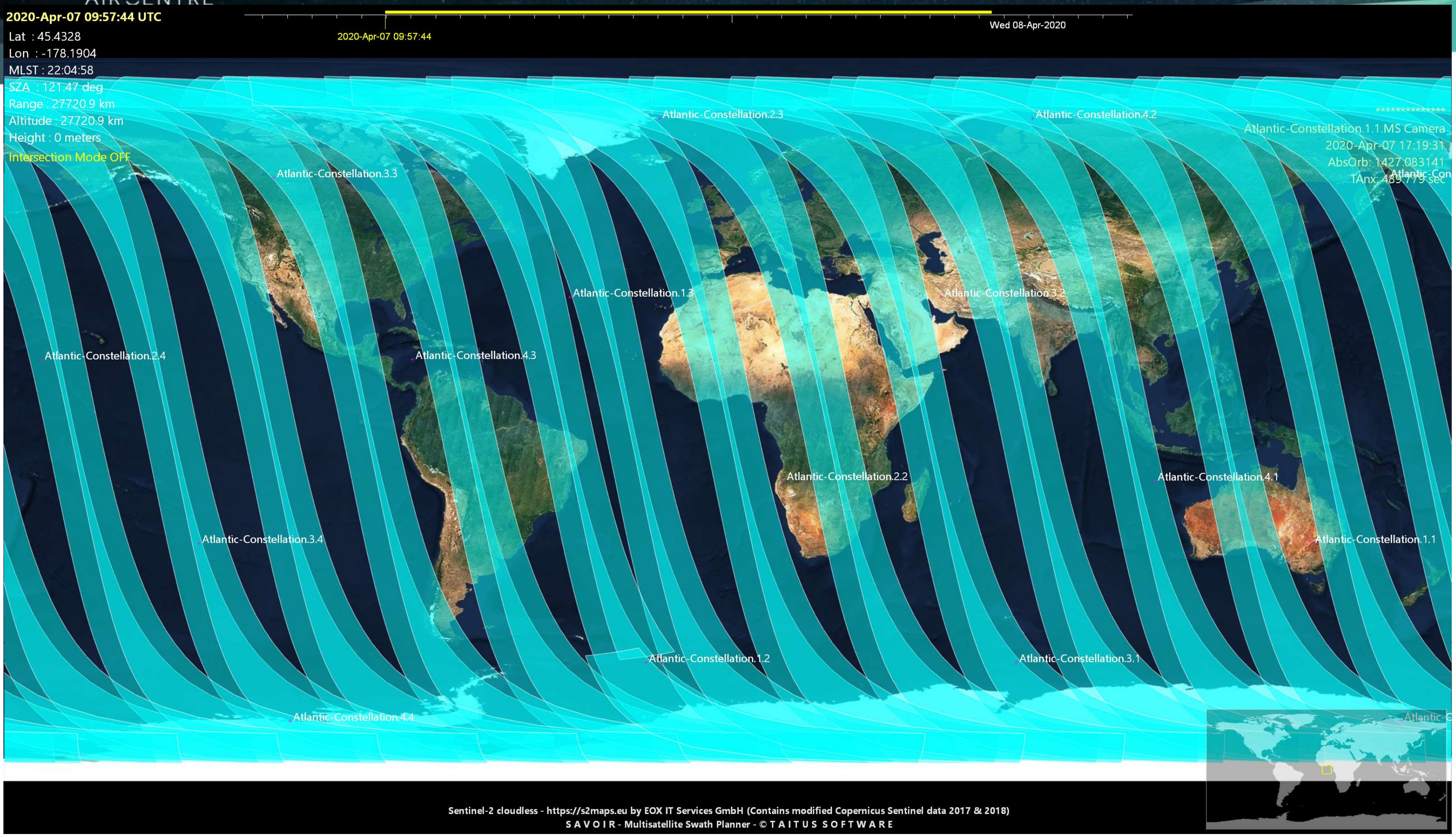


CONSTELLATION DESIGN: DAILY FIELD OF REGARD OF SATELLITE 1 IN ORBITAL PLANE #1



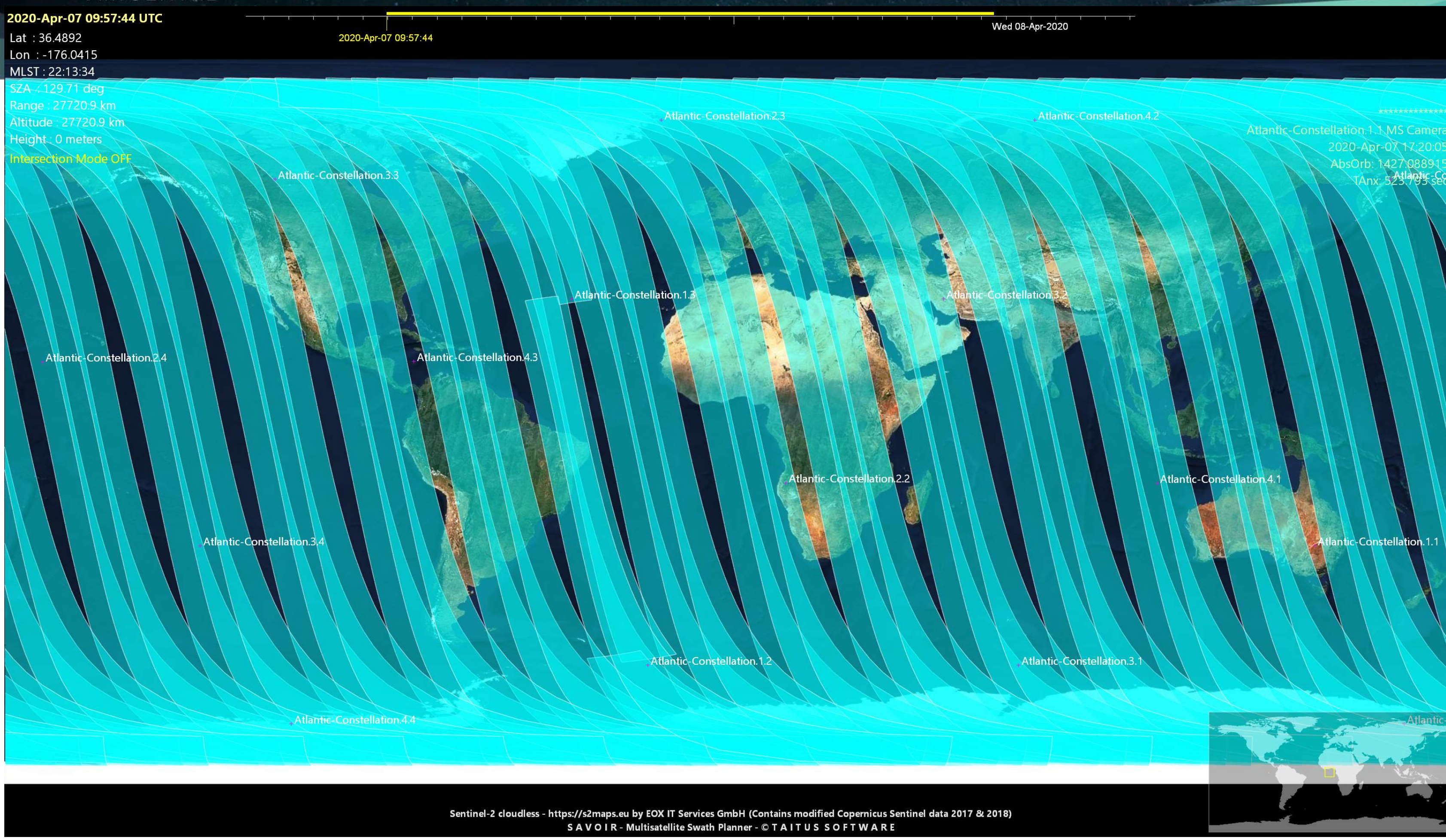
- Visualization of the field of regard of satellite 1 on orbital plane 1 during 24 hours
- Those are the regions that potentially can be imaged with a maximum off-nadir angle of 30 degrees
- The actual taken images is smaller as the swath of the camera is smaller than the field of regard

CONSTELLATION DESIGN: DAILY FILD OF REGARD OF SATELLITES 1 & 2 IN ORBITAL PLANE #1



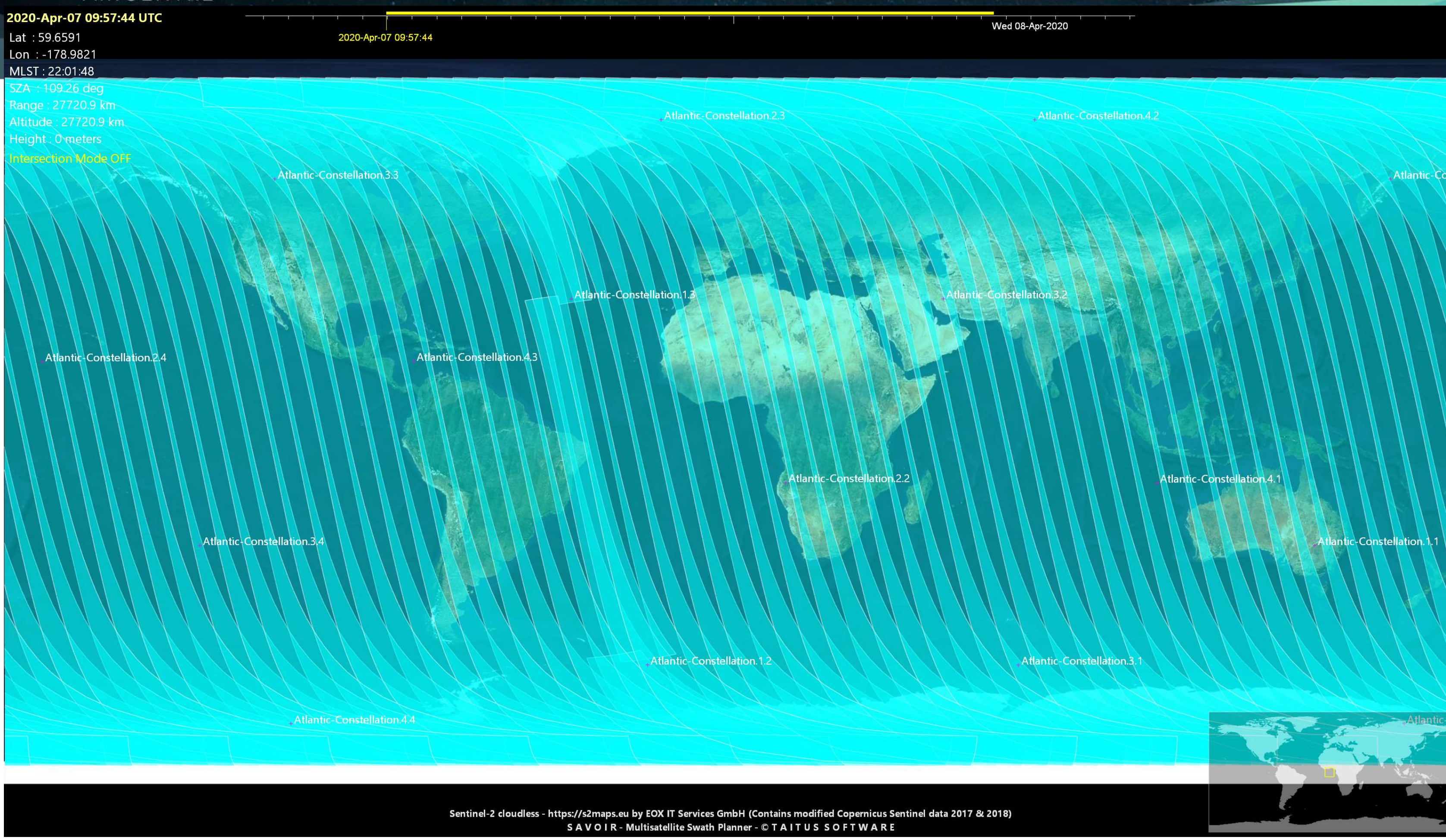
- Visualization of the field of regard of satellites 1 and 2 on the orbital plane 1 during 24 hours
- It must be noted that there is a small overlap between satellites to avoid gaps in visibility

CONSTELLATION DESIGN: DAILY FILD OF REGARD OF SATELLITES 1,2 & 3 IN ORBITAL PLANE #1



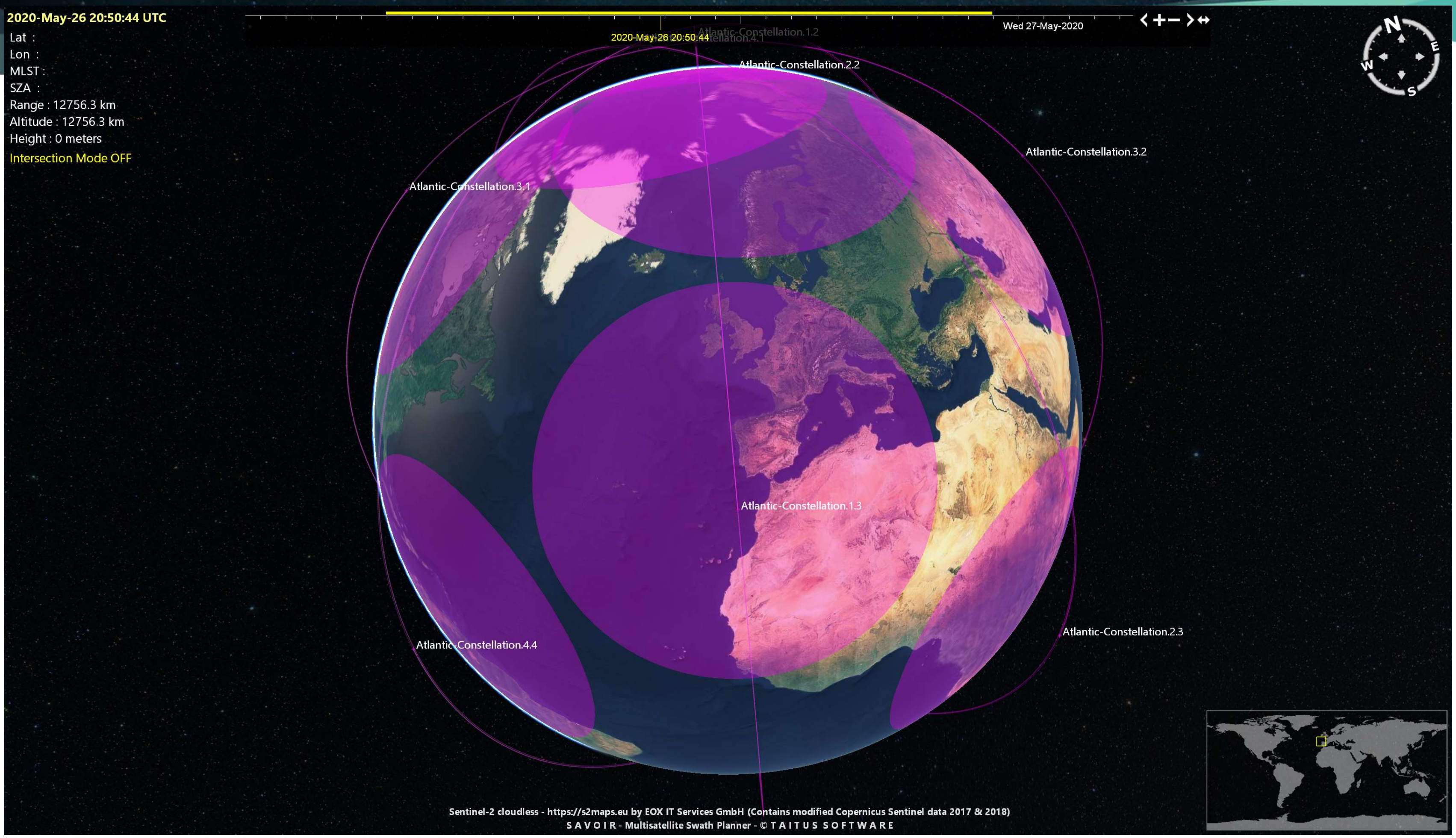
- Visualization of the field of regard of satellites 1, 2 and 3 on the orbital plane 1 during 24 hours
- There are still visibility gaps at lower latitudes

CONSTELLATION DESIGN: DAILY FILD OF REGARD OF SATELLITES 1, 2, 3 & 4 IN ORBITAL PLANE #1



- Visualization of the field of regard of satellites 1, 2, 3 and 4 on orbital plane 1 in 1 day
- This image demonstrate that 4 satellites per plane are required to cover the whole Earth in one day
- There are regions visited only once, but there are also regions of 2, 3 and up to 4 images per plane and per day

CONSTELLATION DESIGN: 3D VIEW



- 3D Visualization of the Atlantic Constellation with visibility of the cone of coverage of each satellite

CONSTELLATION DESIGN: ORBITAL ELEMENTS OF ALL SATELLITES

- Osculating orbital elements in Mean Earth Equator of Day of the 16 satellites of the Atlantic Constellation on March 22st at 12h

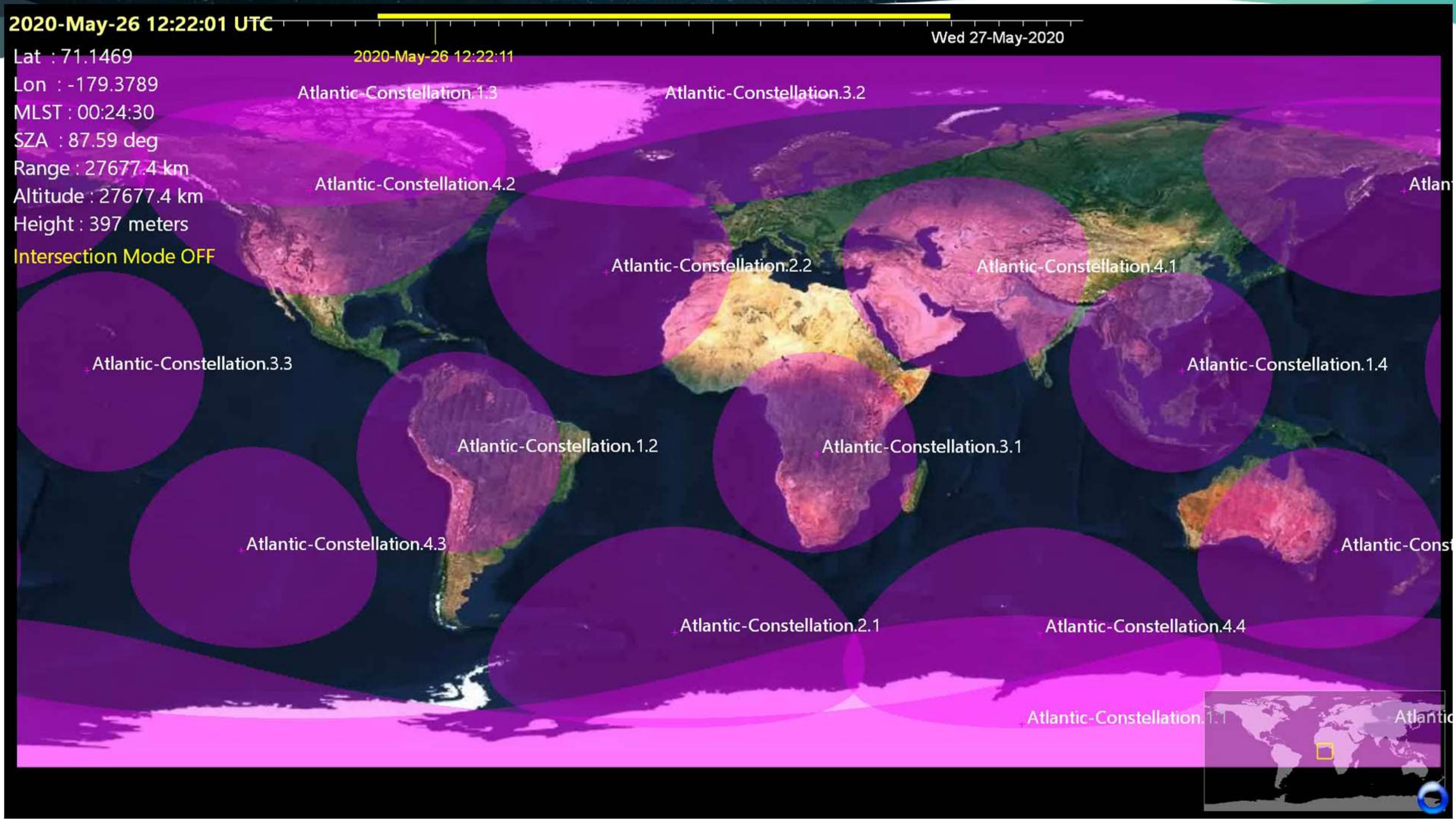
Orbital Plane #1				
	Satellite 1.1	Satellite 1.2	Satellite 1.3	Satellite 1.4
Semimajor axis km	7053.306	7034.919	7053.306	7034.919
Eccentricity	0.0012172	0.0005875	0.0028403	0.0028403
Inclination º	98.06968	98.08029	98.06968	98.08029
R.A. of Asc. Node º	292.5	292.5	292.5	292.5
Arg. Of Perigee º	67.7296	269.99901	112.27146	90.000257
Mean anomaly º	292.2704	180.00099	67.728589	179.99981

Orbital Plane #2				
	Satellite 2.1	Satellite 2.2	Satellite 2.3	Satellite 2.4
Semimajor axis km	7044.1176	7044.1128	7044.1126	7044.113
Eccentricity	0.0012435	0.0012432	0.001468	0.001468
Inclination º	98.074981	98.074988	98.074998	98.074985
R.A. of Asc. Node º	337.5	337.5	337.5	337.5
Arg. Of Perigee º	127.15705	52.814007	59.310088	120.69068
Mean anomaly º	277.8834	82.130714	165.74531	194.25423

Orbital Plane #3				
	Satellite 3.1	Satellite 3.2	Satellite 3.3	Satellite 3.4
Semimajor axis km	7053.306	7034.919	7053.306	7034.919
Eccentricity	0.0012172	0.0005875	0.0028403	0.0028403
Inclination º	98.06968	98.08029	98.06968	98.08029
R.A. of Asc. Node º	22.5	22.5	22.5	22.5
Arg. Of Perigee º	67.7296	269.99901	112.27146	90.000257
Mean anomaly º	292.2704	180.00099	67.728589	179.99981

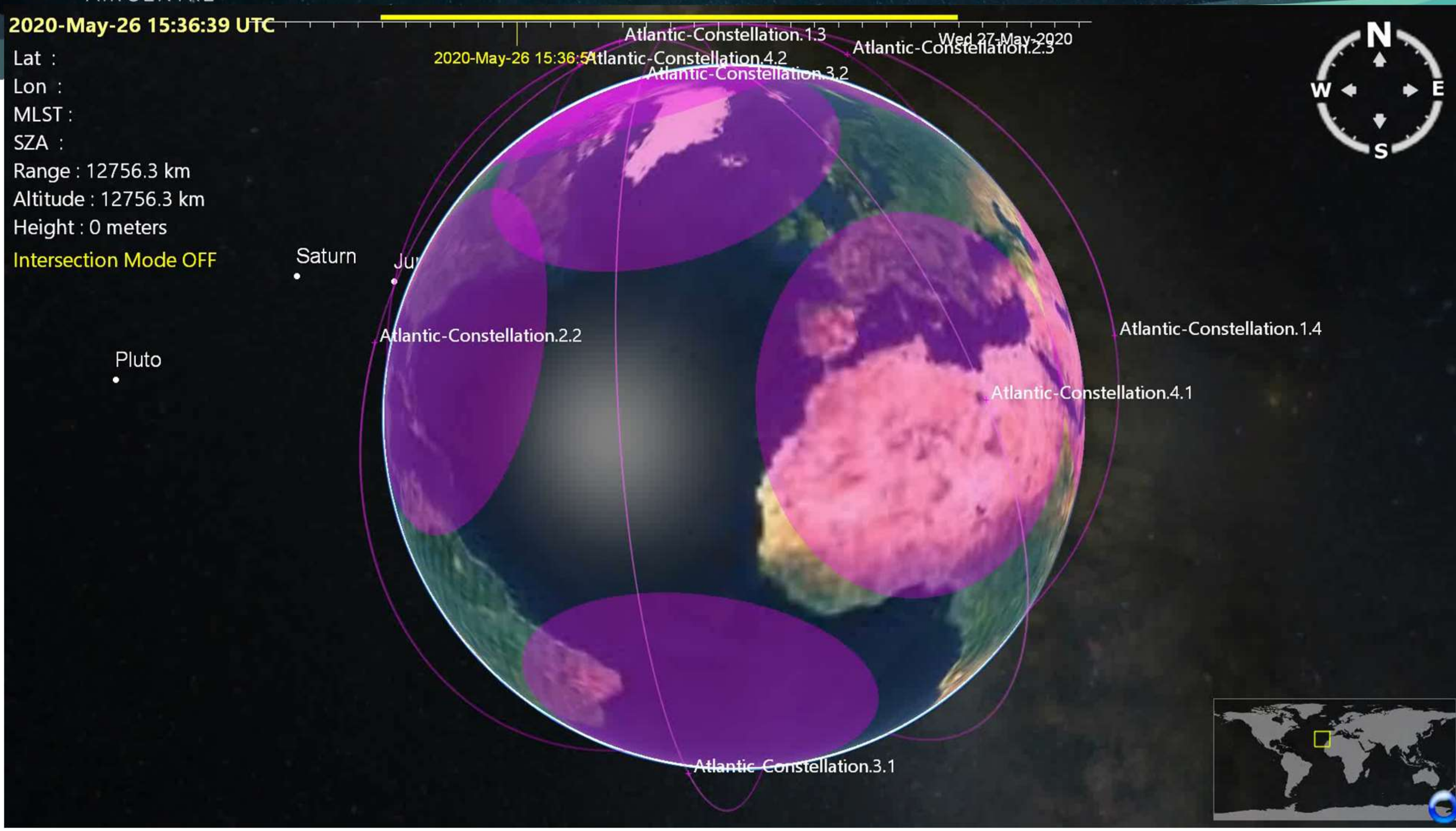
Orbital Plane #4				
	Satellite 4.1	Satellite 4.2	Satellite 4.3	Satellite 4.4
Semimajor axis km	7044.1176	7044.1128	7044.1126	7044.113
Eccentricity	0.0012435	0.0012432	0.001468	0.001468
Inclination º	98.074981	98.074988	98.074998	98.074985
R.A. of Asc. Node º	67.5	67.5	67.5	67.5
Arg. Of Perigee º	127.15705	52.814007	59.310088	120.69068
Mean anomaly º	277.8834	82.130714	165.74531	194.25423

CONSTELLATION DESIGN: 2D VIDEO



- 2D graphical animation of the Atlantic Constellation with visibility of the cone of coverage of each satellite
- The image on the poles are distorted due to the projection used in this video

CONSTELLATION DESIGN: 3D VIDEO



- 3D graphical animation of the Atlantic Constellation with visibility of the cone of coverage of each satellite
- Some gaps of coverage appears on the video, but they are closed always in a few minutes

CONSTELLATION DESIGN: REVISIT TIME PERFORMANCES

- In order to check the adequacy of the designed constellation we have done an analysis of revisit time performance, the objective was a global mean revisit value best than 3 hours with +/-30 degrees of off-nadir pointing capability
- The attached table show the results for a long simulation, the **global averaged mean revisit time is 2.94 hours**, which satisfies the required value lower than 3 hours, **this result validates the design of the constellation**
- Standar deviation, minimum, 99% percentile and maximum revisit time are also presented
- As those optical instrument does not work during the night, the maximum value is about 15 hours, due to the time spent of some location in the dark side of the Earth
- It is interesting to observe that in only 2 hours the constellation can see nearly 40% of the Earth (only 50% is illuminated) and in 4 hours this value goes up to 55%

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EARTH OBSERVATION SYSTEM PERFORMANCE PARAMETERS
===============================================

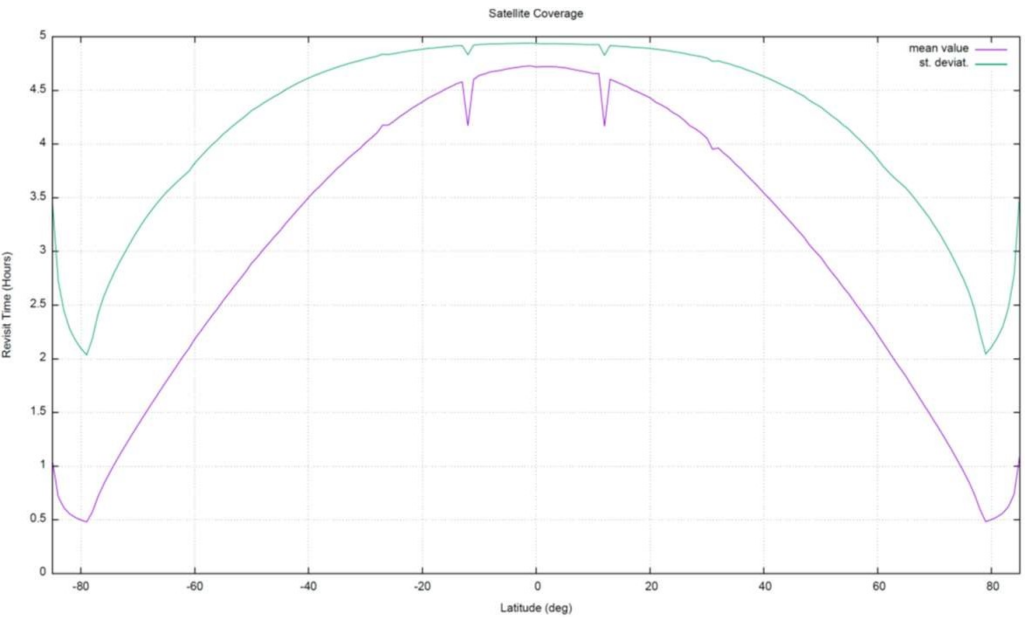
GLOBAL MEAN REVISIT TIME (HOURS)       =   2.94075
GLOBAL ST. DEV. REVISIT TIME (HOURS)   =   4.42107
GLOBAL MINIMUM REVISIT TIME (HOURS)    =   0.00270
GLOBAL 99% PERC. REVISIT TIME (HOURS)  =  14.94063
GLOBAL MAXIMUM REVISIT TIME (HOURS)    =  18.22088

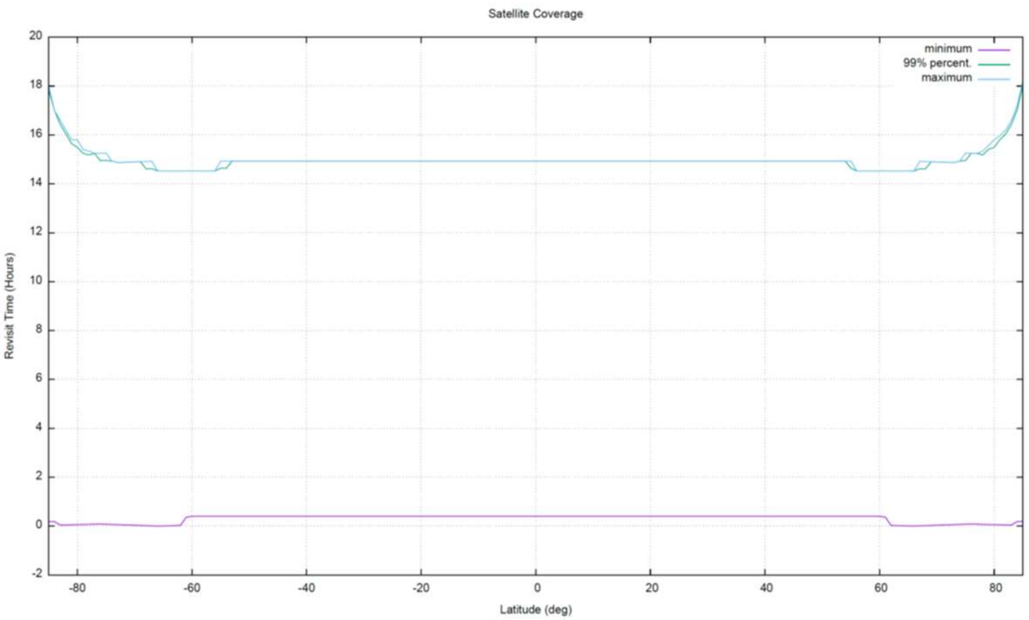

WORST MINUMUM OBSERVATION ANGLE (DEG)  =  26.90151


WORLD AREA COVERED IN  2 HOURS (%)=  37.52558
WORLD AREA COVERED IN  4 HOURS (%)=  55.00926
WORLD AREA COVERED IN  6 HOURS (%)=  63.30280
WORLD AREA COVERED IN  8 HOURS (%)=  71.61826
WORLD AREA COVERED IN 10 HOURS (%)=  79.92642
WORLD AREA COVERED IN 12 HOURS (%)=  88.25651
WORLD AREA COVERED IN 14 HOURS (%)=  96.57684
WORLD AREA COVERED IN 16 HOURS (%)=  99.98051
WORLD AREA COVERED IN 18 HOURS (%)= 100.00000
WORLD AREA COVERED IN 20 HOURS (%)= 100.00000
```

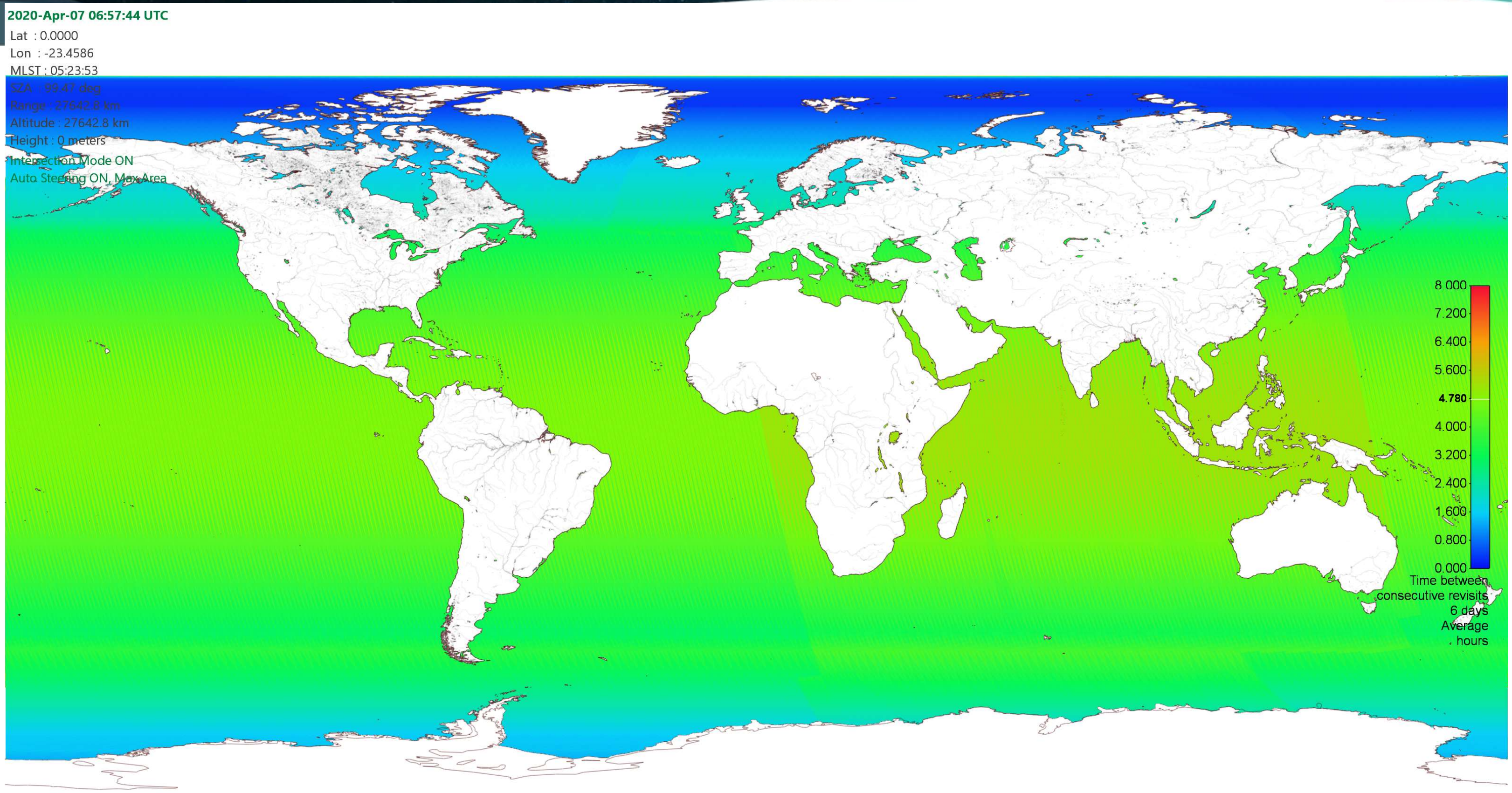
CONSTELATION DESIGN: REVISIT TIME PERFORMANCE ANALYSIS

- Mean and maximum revisit time as a function of the latitude: there is a resonance at +/-12º latitude that gives a pick in the plots, and some side effects at the poles due to the fact that the orbits are not exactly polars (98º inclination)
- The worst mean revisit time is at the equator (4,8 hours), at mid Europe latitudes is about 3 hours and at the pole is only 30 minutes. The worst case maximum revisit time is 15 hours (due to the 12 hours of darkness)





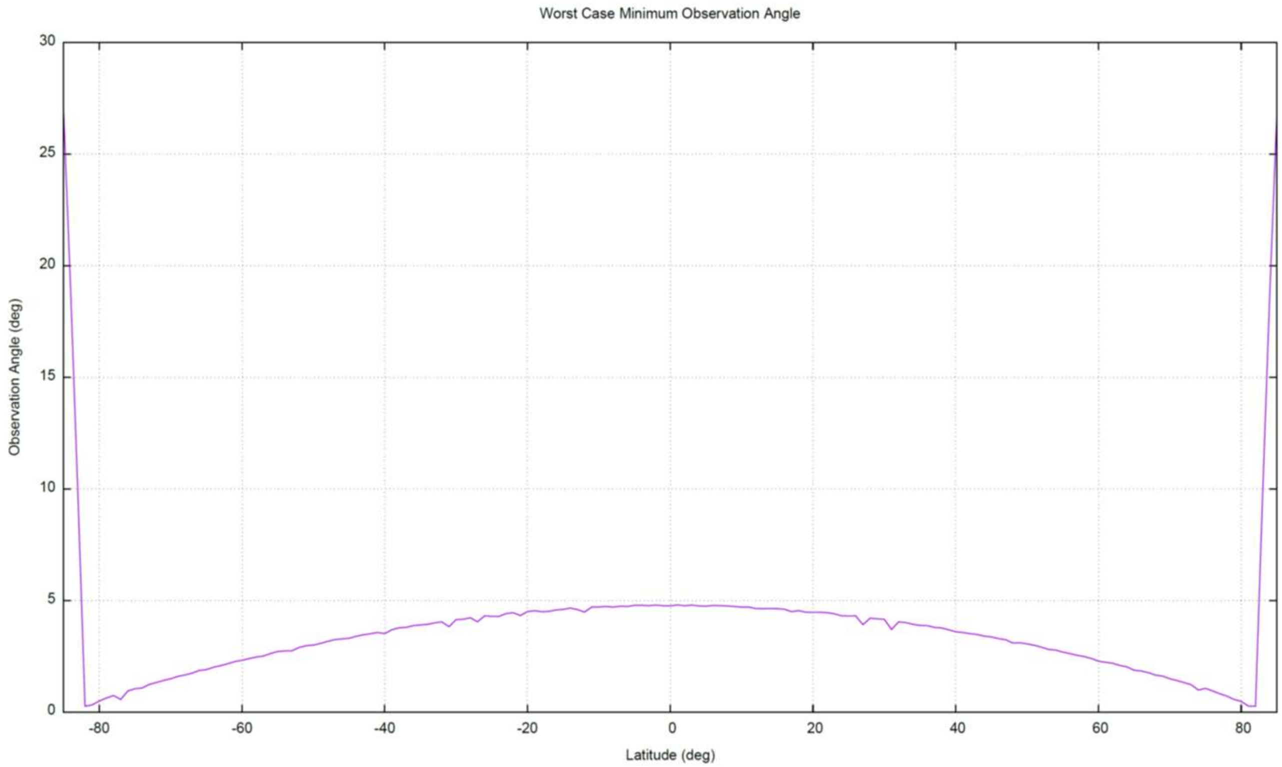
CONSTELATION DESIGN: REVISIT TIME PERFORMANCE ANALYSIS



- 2D visualization of the mean revisit time
- As presented in he latitude averaged values, the worst case is at the equator with 4,78 hours
- It improves at mid latitudes to 3 hours
- The best values are at the pole with only 30 minutes
- That leads to a global average of 2,94 hours, below the requested 3 hours

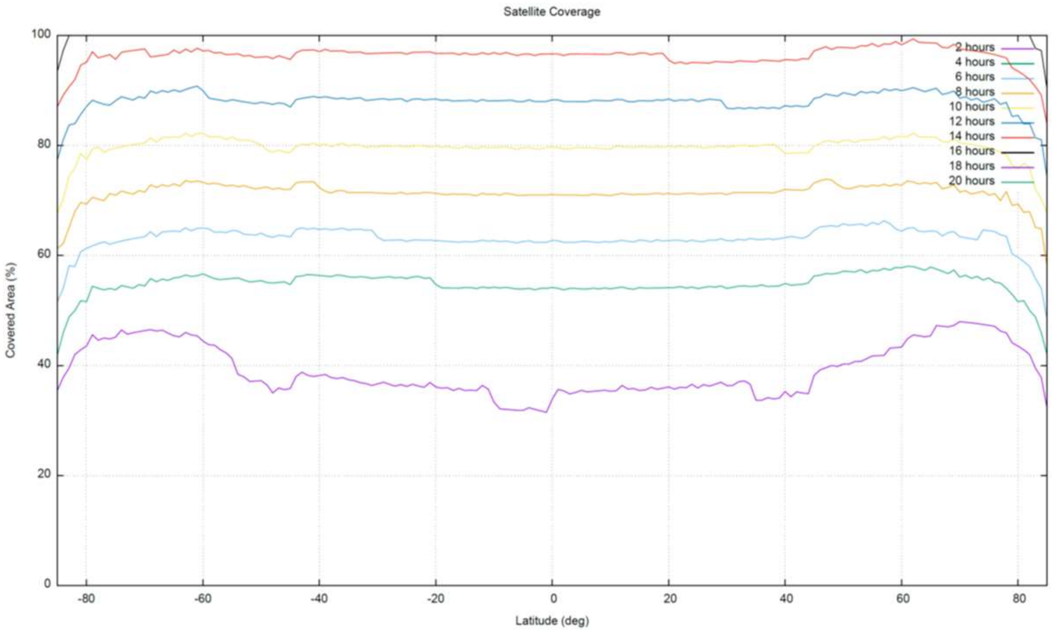
CONSTELATION DESIGN: REVISIT TIME PERFORMANCE ANALYSIS

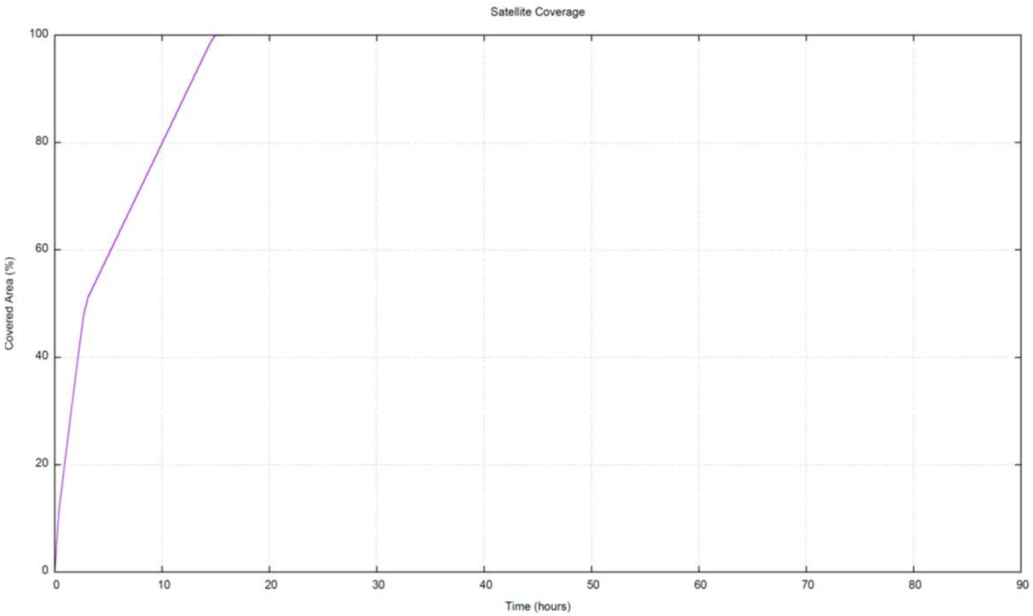
- The worst case off-nadir observation angle is at the equator and it is about 4.5º, which is a very good value; for mid latitudes this value improve down to only 3 degrees and at the pole we have always a nadir image (off-nadir 0º)



CONSTELATION DESIGN: COVERAGE PERFORMANCE ANALYSIS

- The left figure shows the % of earth coverage of the constellation versus latitude, after 2, 4, 6, ..., 20 hours of simulation. It can be seen that in only 2 hours we can see 40% of the Earth in most latitudes (illuminated is ony 50%), after 4 hours is 55% (nearly all illuminated area in this period) and all earth is completd in 15 hours (due to the 12 hours darkness area). On the right we have the global coverage versus time.





CONSTELLATION DESIGN: REVISIT TIME PERFORMANCES (+/- 45º off nadir case)

- Even if it is not the design case, we have analyzed the constellation revisit time performance for the case of +/-45 degrees of off-nadir pointing capability
- The attached table show the results for a long simulation, the **global averaged mean revisit time is only 1.64 hours**, which satisfies with a big margin the required value lower than 3 hours
- Standar deviation, minimum, 99% percentile and maximum revisit time are also presented
- As those optical instrument does not work during the night, the maximum value is about 15 hours, due to the time spent of some location in the dark side of the Earth
- It is interesting to observe that in only 2 hours the constellation can see nearly 45% of the Earth (only 50% is illuminated) and in 4 hours this value goes up to 57%

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EARTH OBSERVATION SYSTEM PERFORMANCE PARAMETERS
===============================================

GLOBAL MEAN REVISIT TIME (HOURS)      =   1.63520
GLOBAL ST. DEV. REVISIT TIME (HOURS)  =   3.39639
GLOBAL MINIMUM REVISIT TIME (HOURS)   =  -0.00270
GLOBAL 99% PERC. REVISIT TIME (HOURS) =  14.54238
GLOBAL MAXIMUM REVISIT TIME (HOURS)   =  15.14842


WORST MINUMUM OBSERVATION ANGLE (DEG) =  26.90151


WORLD AREA COVERED IN  2 HOURS (%)=  44.65452
WORLD AREA COVERED IN  4 HOURS (%)=  57.06072
WORLD AREA COVERED IN  6 HOURS (%)=  65.36156
WORLD AREA COVERED IN  8 HOURS (%)=  73.68190
WORLD AREA COVERED IN 10 HOURS (%)=  81.98762
WORLD AREA COVERED IN 12 HOURS (%)=  90.30553
WORLD AREA COVERED IN 14 HOURS (%)=  98.56008
WORLD AREA COVERED IN 16 HOURS (%)= 100.00000
WORLD AREA COVERED IN 18 HOURS (%)= 100.00000
WORLD AREA COVERED IN 20 HOURS (%)= 100.00000
```
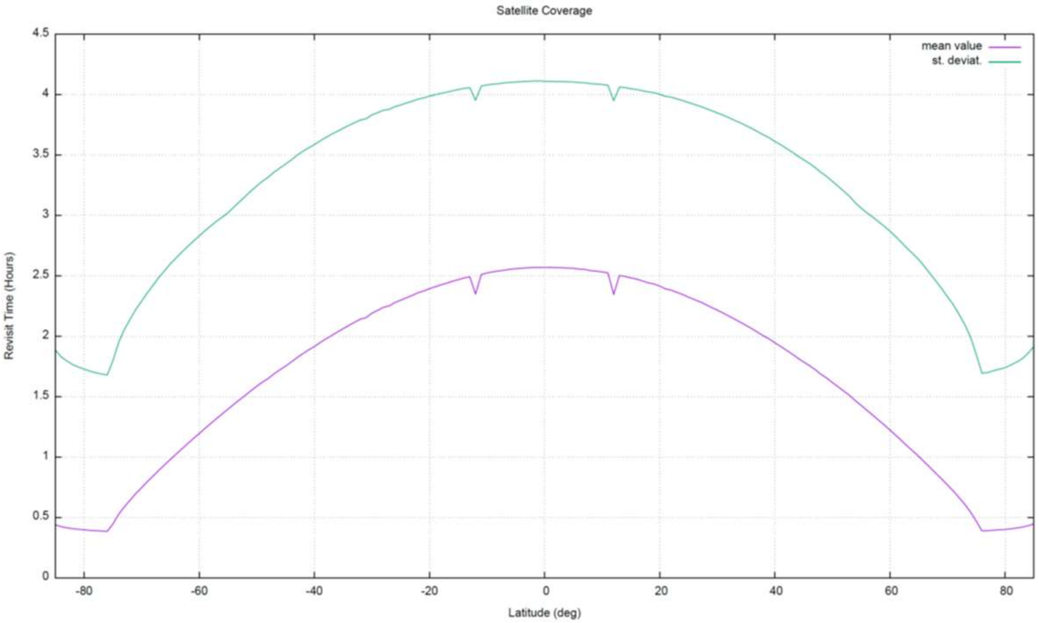
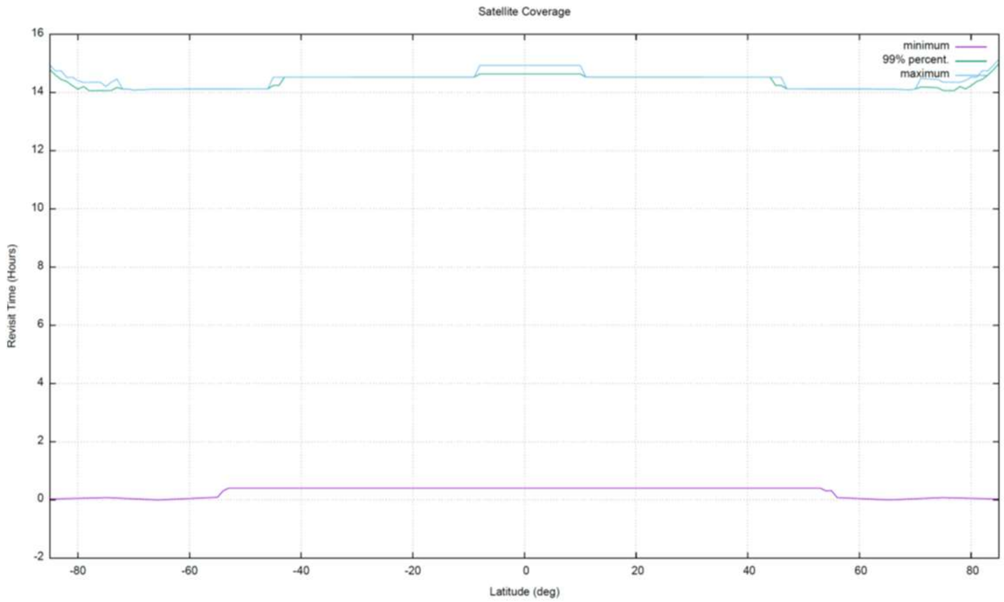

CONSTELATION DESIGN: REVISIT TIME PERFORMANCE ANALYSIS (+/- 45º off nadir case)

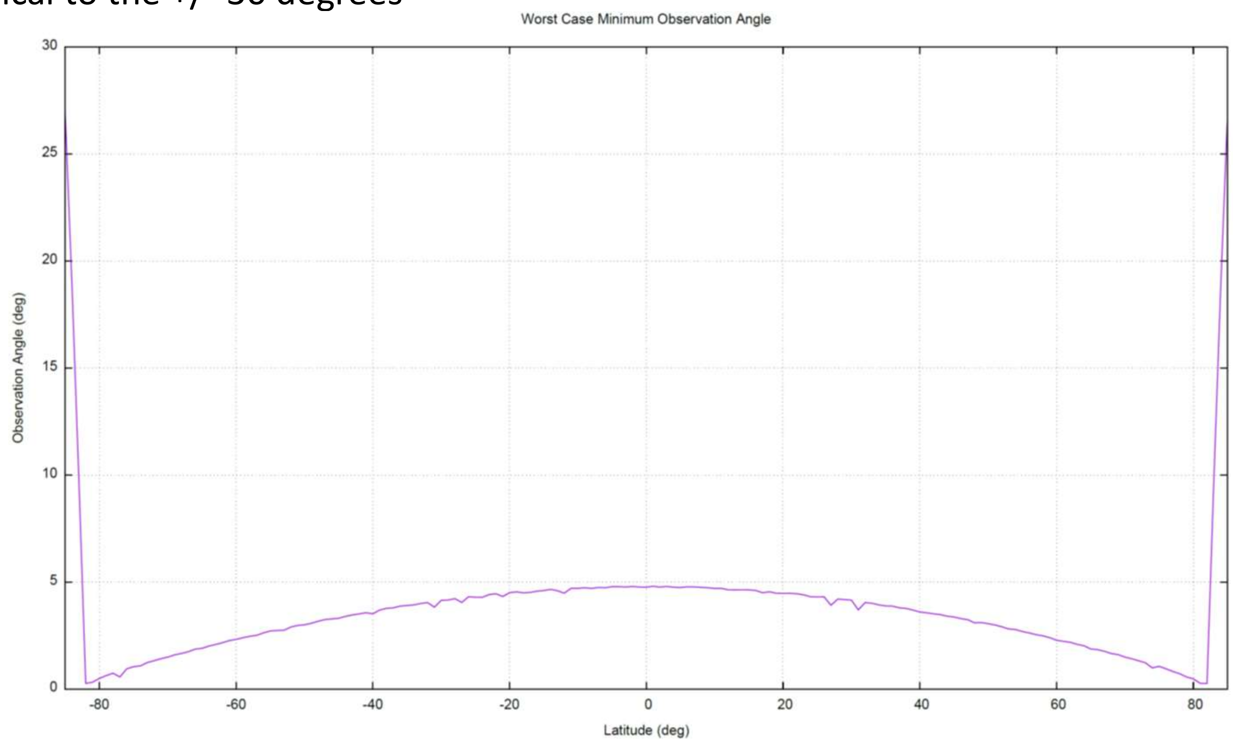
- Mean and maximum revisit time as a function of the latitude: there is also the resonance at +/-12º latitude that gives a pick in the plots, and some side effects at the poles due to the fact that the orbits are not exactly polars (98º inclination)
- The worst mean revisit time is at the equator (2,5 hours), at mid Europe latitudes is about 1,5 hours and at the pole is only 30 minutes. The worst case maximum revisit time is 15 hours (due to the 12 hours of darkness as before)





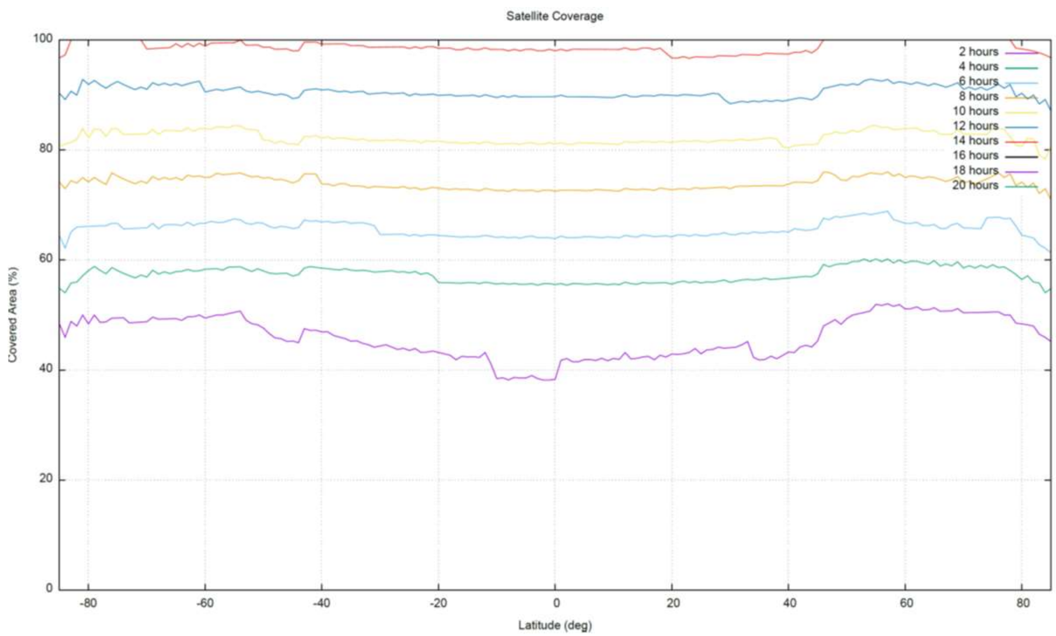
CONSTELATION DESIGN: REVISIT TIME PERFORMANCE ANALYSIS (+/- 45º off nadir case)

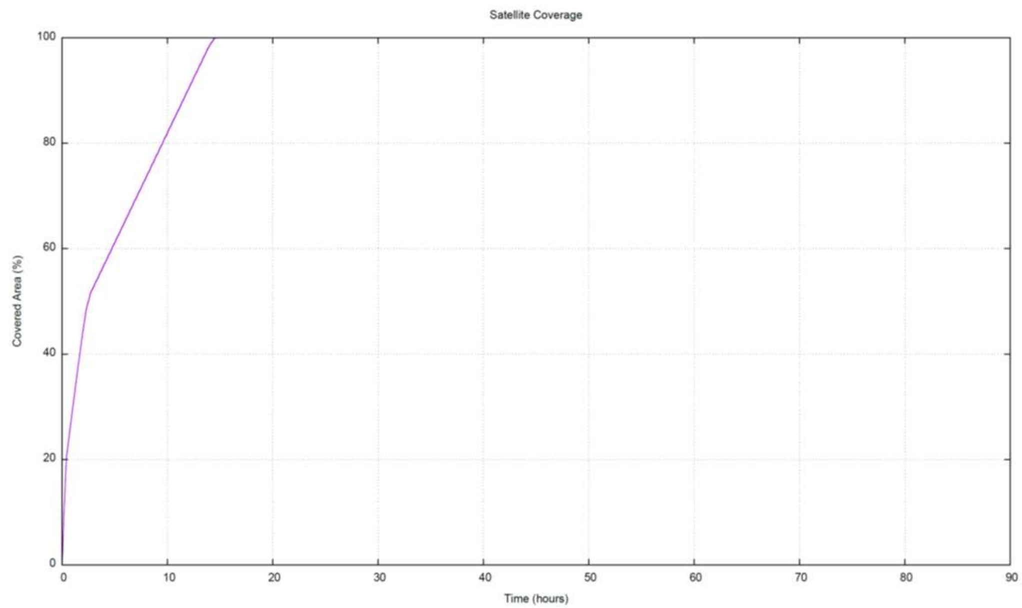
- The worst case off-nadir observation angle is at the equator and it is about 4.5º, which is a very good value; for mid latitudes this value improve down to only 3 degrees and at the pole we have always a nadir image (off-nadir 0º). Those values are identical to the +/- 30 degrees



CONSTELATION DESIGN: COVERAGE PERFORMANCE ANALYSIS (+/- 45º off nadir case)

- The left figure shows the % of earth coverage of the constellation versus latitude, after 2, 4, 6, ..., 20 hours of simulation. It can be seen that in only 2 hours we can see nearly 50% of the Earth in most latitudes (all illuminated area), after 4 hours is 60% and all earth is completed in 15 hours as before (due to the 12 hours darkness area). On the right we have the global coverage versus time.





CONSTELLATION DESIGN: AIS INSTRUMENT PERORMANCE ANALYSIS

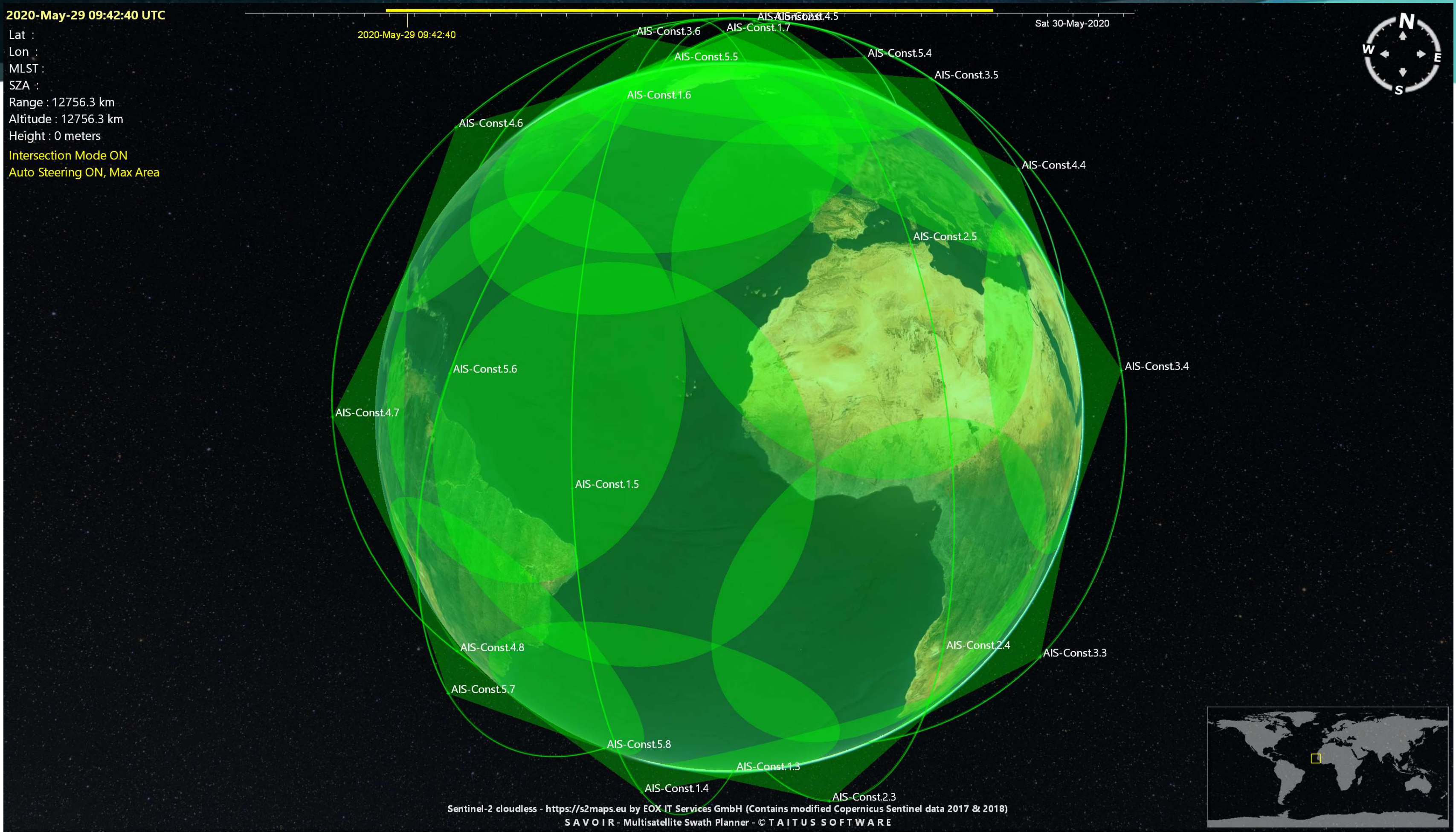
- In order to check the adequacy of the designed constellation we have done also an analysis of the AIS instrument performance
- The attached table show the results for a long simulation, the **global averaged mean AIS gap is 13,7 min**, which satisfies the required value lower than 15 minutes, **this result validates the design of the constellation also as far as AIS instrument requirements**
- The constellation presents an instantaneous latitude averaged coverage of 31% to 50% of the Earth with a global average of 38% of earth visible at any moment
- **The latitude averaged AIS gap is larger at the equator 18 minutes (requirement is < 20 min), between 10 to 15 minutes at mid latitudes and only 5,6 minutes al high latitudes**
- The worst case gap is 20 min at high latitudes and 56 min at equator, satisfying also the requirement of a very worst case global value of less than 1 hour.

Latitude º	% visibility	mean vis. period (min)	mean gap (min)	worst gap (min)
0	31,28%	8,45	18,67	56,00
15	32,64%	8,49	17,63	49,00
30	37,64%	8,60	14,33	42,00
45	49,35%	8,77	9,04	32,00
60	49,55%	5,69	5,81	18,00
75	30,93%	2,52	5,64	20,00
Averaged	38%	7,86	13,70	41,07

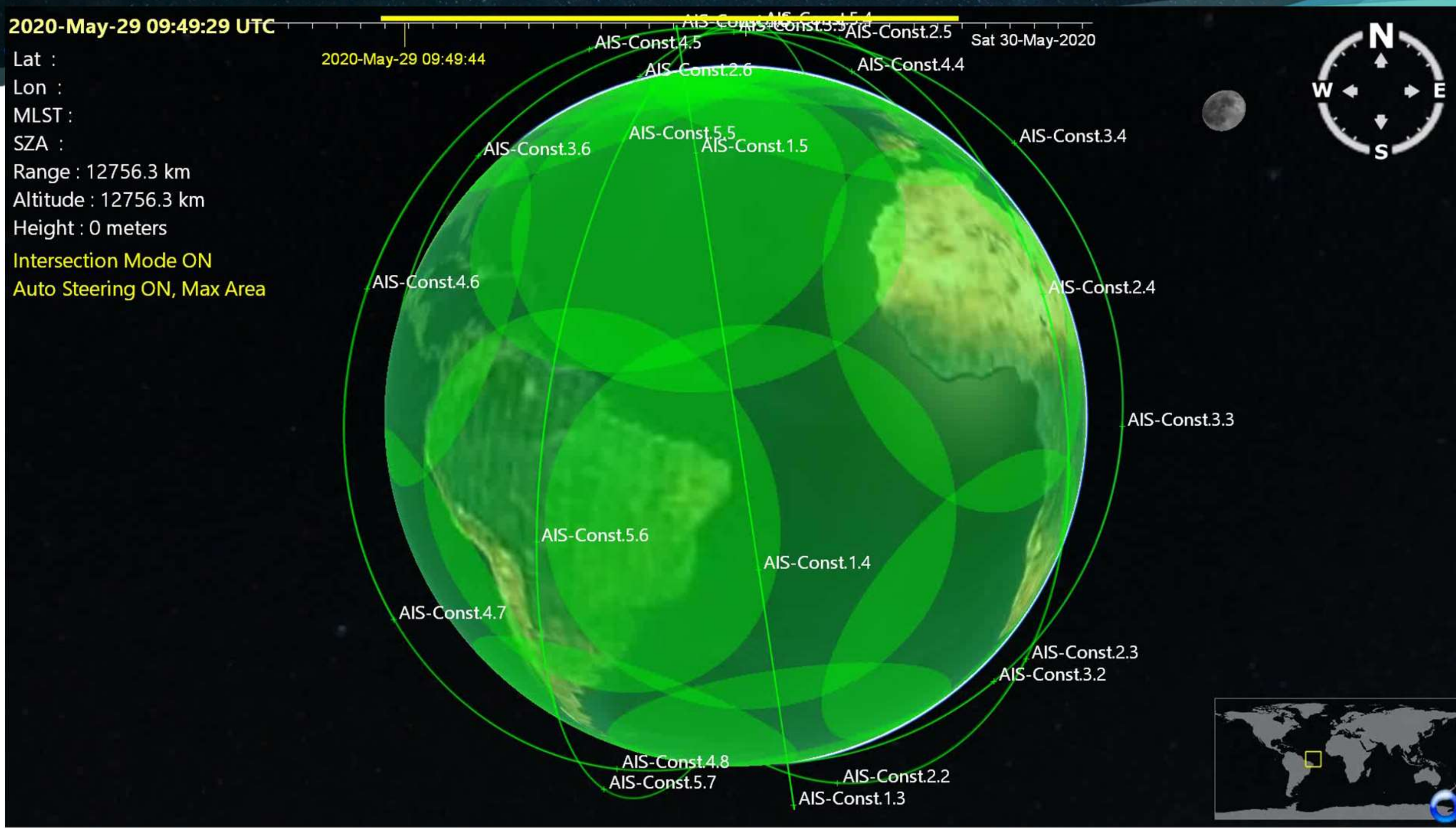
CONSTELLATION DESIGN: AIS INSTRUMENT WITH FULL CONTINUOUS COVERAGE

- If a full continuous coverage of the Earth is required for the AIS monitoring function, then a different constellation design algorithm must be used, it is called "**Streets of Coverage**"
- This method is based on the definition of "streets" of satellites in an orbital plane and the matching of consecutive streets (or planes) to avoid the gaps of coverge on Earth
- If we perform this analysis with Sun-Synchronous frozen orbits around the altitude band previously considered we get the optimum constellation
- In our case, increasing the orbital altitude from 675 km up to **725 km**, we can design a street of coverage constellation with **5 orbital planes and 8 satellites per orbital plane** that covers continuously all the Earth surface
- For the full continuous coverage we need then a total number of **40 satellites**
- Allowing a mean AIS visibility gap of 15 minutes we can reduce this number from 40 down to 16 as we have seen before
- In principle, due to the significative reduction in number of satellites, we keep the 16 satellite constellation (4 planes x 4 satellites per plane) as our baseline, with the penalizatiton of some small gaps in AIS coverage
- The next slides show the visualization of the 40 satellites full continuous coverage constellation

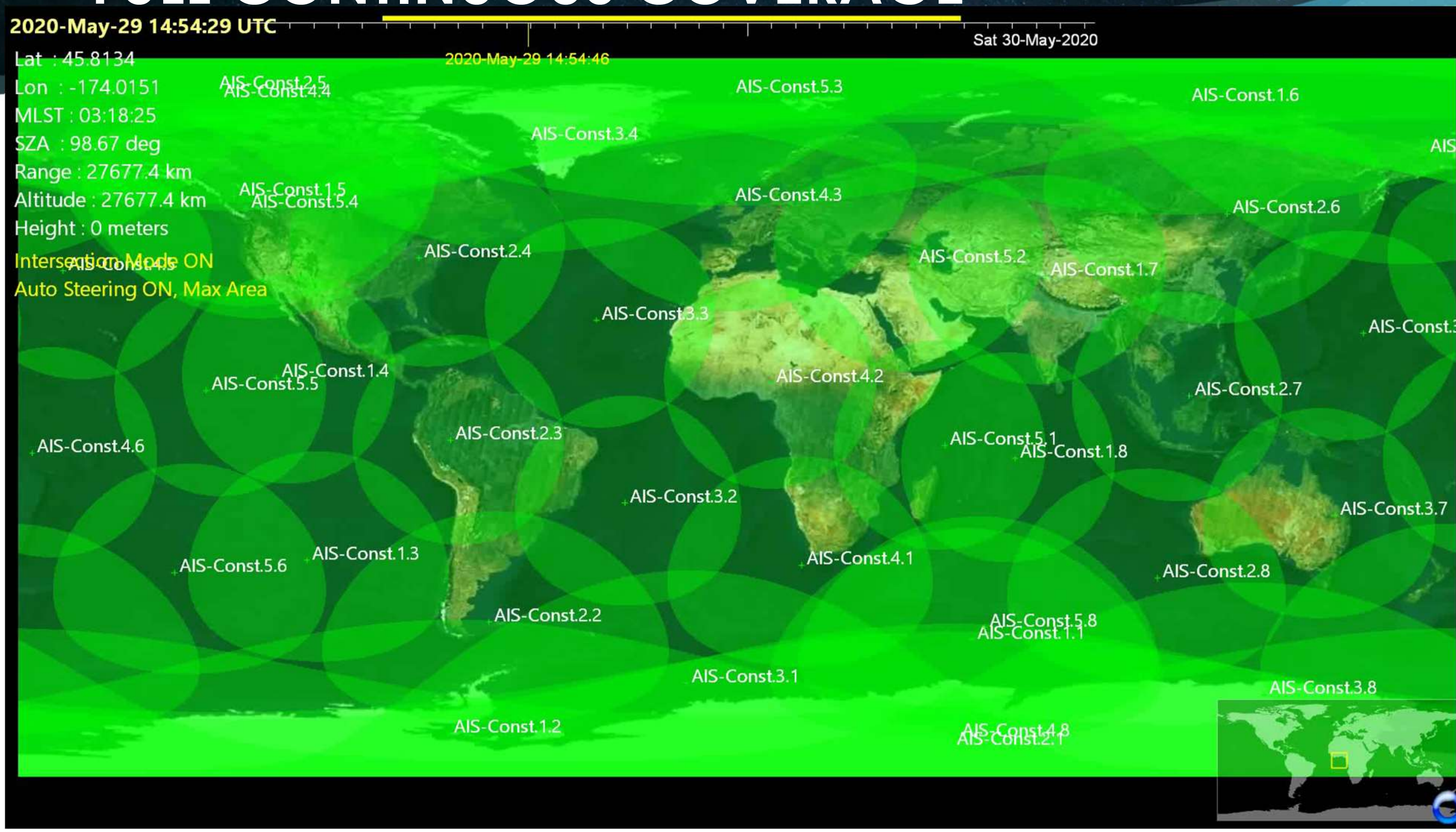
CONSTELLATION DESIGN: AIS INSTRUMENT WITH FULL CONTINUOUS COVERAGE



CONSTELLATION DESIGN: AIS INSTRUMENT WITH FULL CONTINUOUS COVERAGE



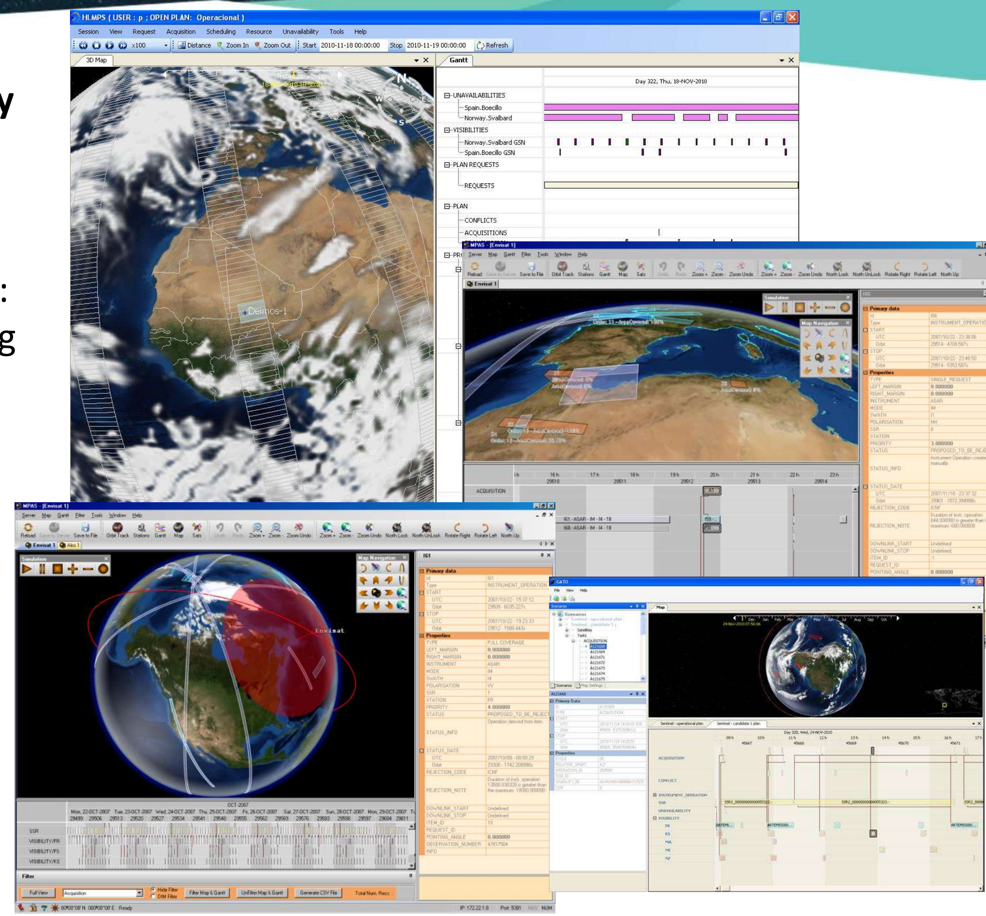
CONSTELLATION DESIGN: AIS INSTRUMENT WITH FULL CONTINUOUS COVERAGE



GOUND SEGMENT

- The **Ground Segment must be designed** to provide a **latency of less than 1 hour**, this is the most challenging design parameter

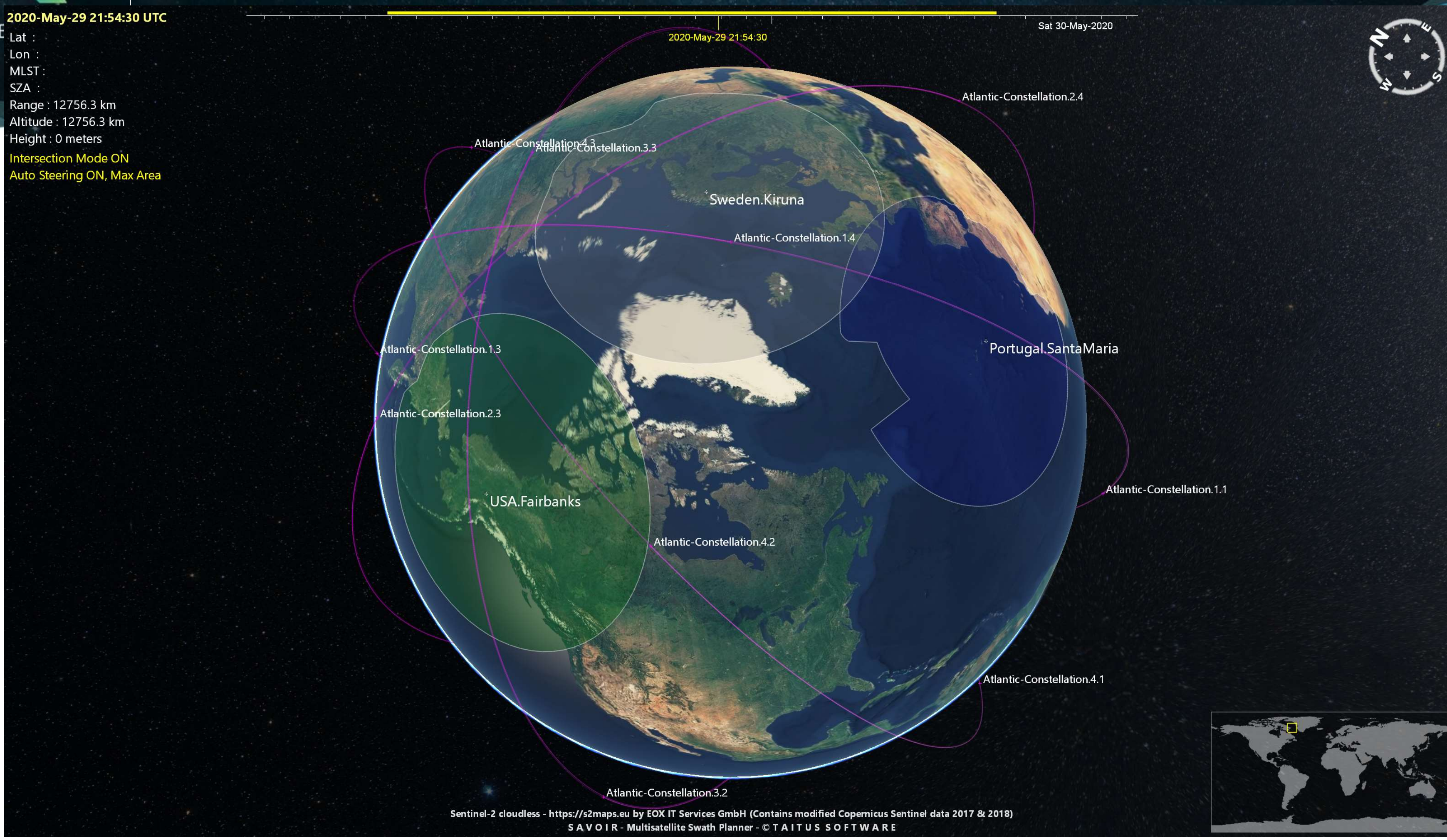
- The **Ground Segment** shall perform the following functions:
  - **Groundstations** to contact the satellite for commanding and download of instrument data
  - **Telemetry/Telecommand** with all the satellites
  - **Monitoring and Control** of the whole constellation
  - **Flight Dynamics and Space Debris Collision Avoidance** facility for all satellites, the risk of collision increases with the number of operated satellites
  - **Mission Planning** function to coordinate and optimize the combined use of all satellites
  - **Calibration and Validation** of satellites images
  - **Instruments Processing Facilities** to derive final products (L2) from the received row data (L0)



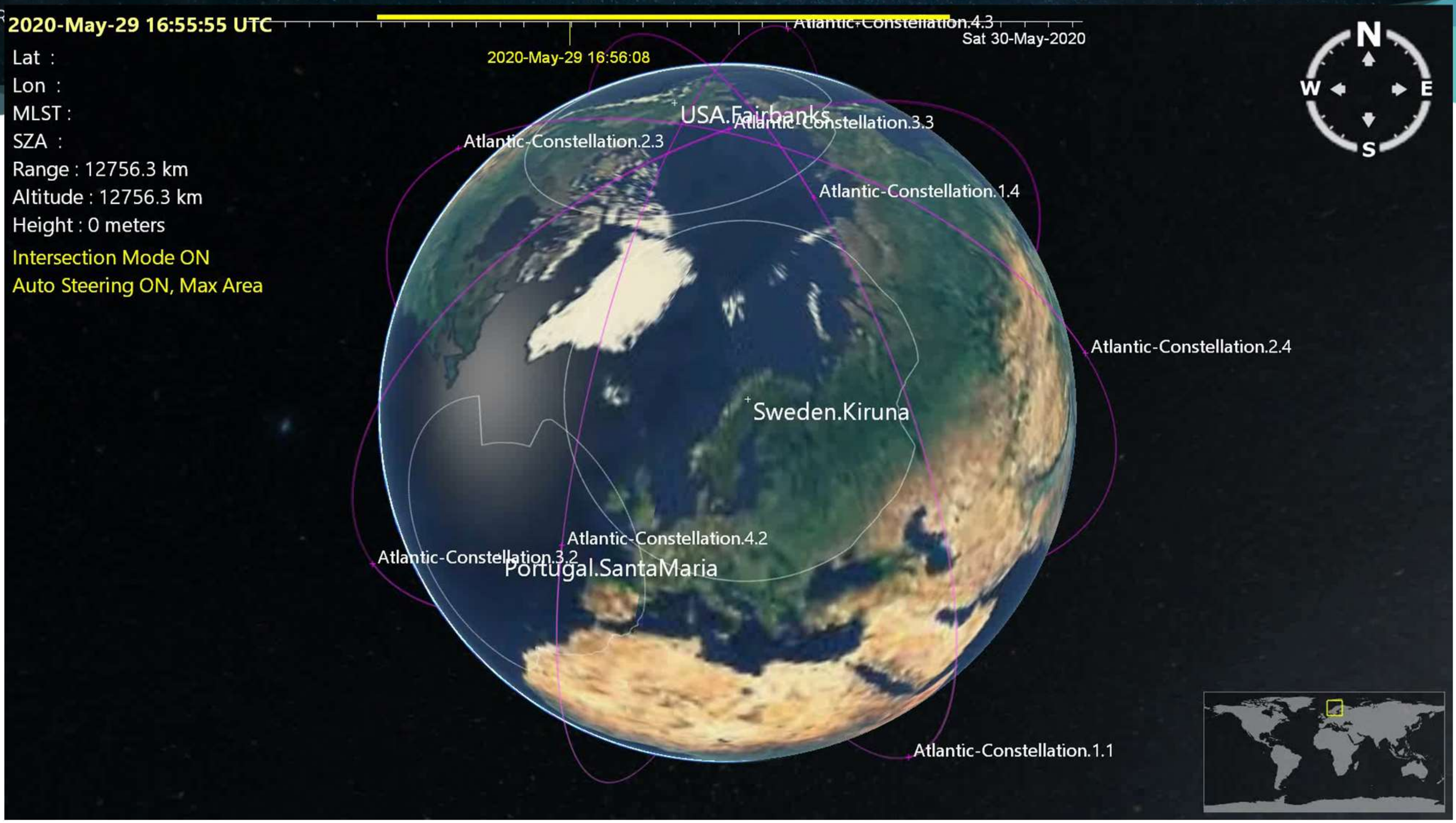
GOUND SEGMENT: GROUND STATIONS

- The selection of the set of groundstations is of paramount importance to get the required latency objective
- A **polar station** has about 5 times more contact time than an station on the equator due to the fact that we are using polar orbits
- As the optical instruments are observing only in daylight and we have designed ascending node solar passes, the optimum is the use of **North Pole station**, as the data is downloaded immediately after its acquisition, with only a fraction of an orbit of delay, this ensures very short latencies
- A station close to the control center (Santa Maria in Azores) is also important to ensure safe operations in case of emergency and to have always the possibility to contact the satellite from local station
- With all above consideration, we select as initial set of groundstations: **Santa Maria** in Azores, **Kiruna** in Sweden and **Fairbanks** in Alaska.

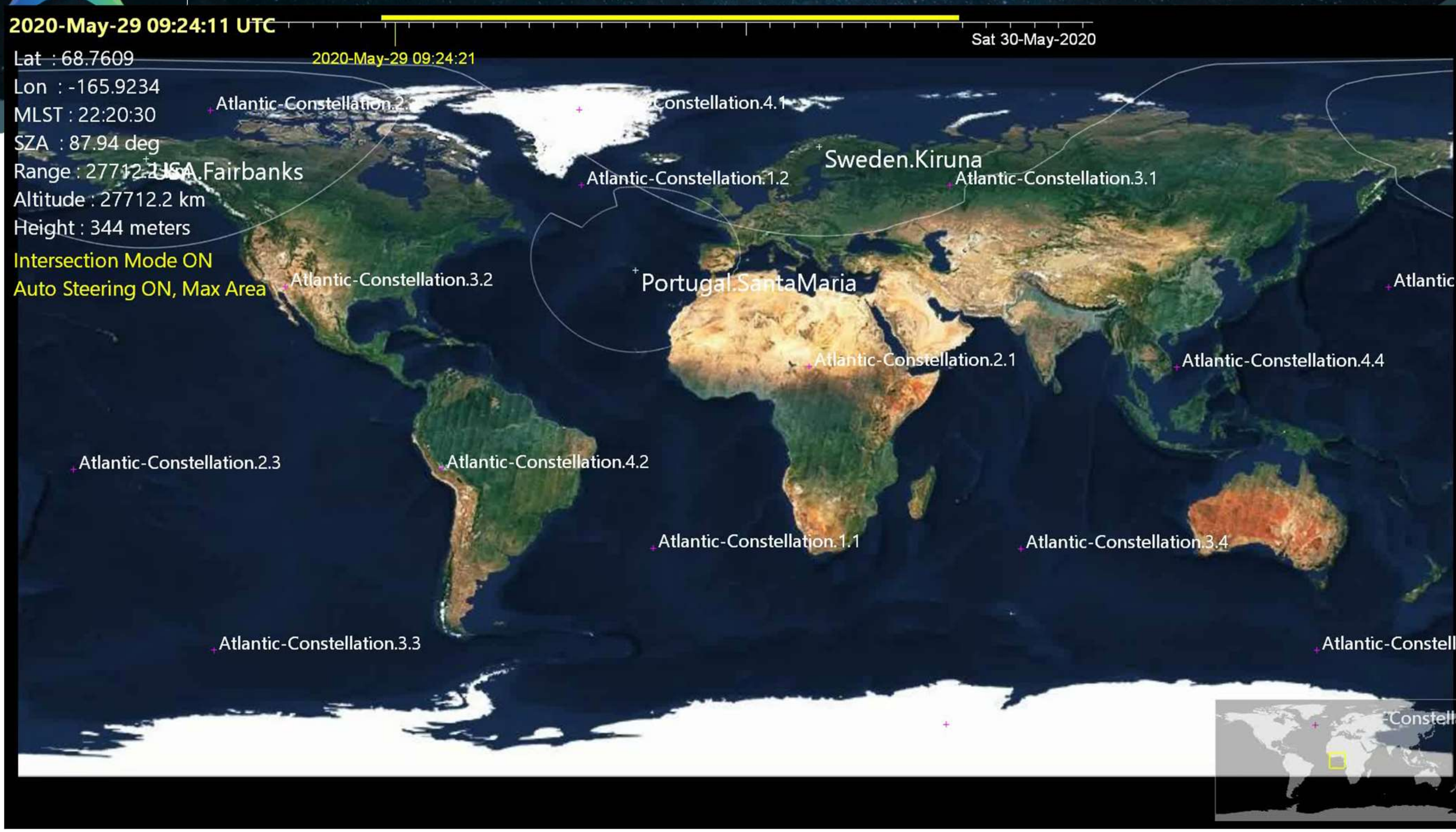
GOUND SEGMENT: GROUND STATIONS



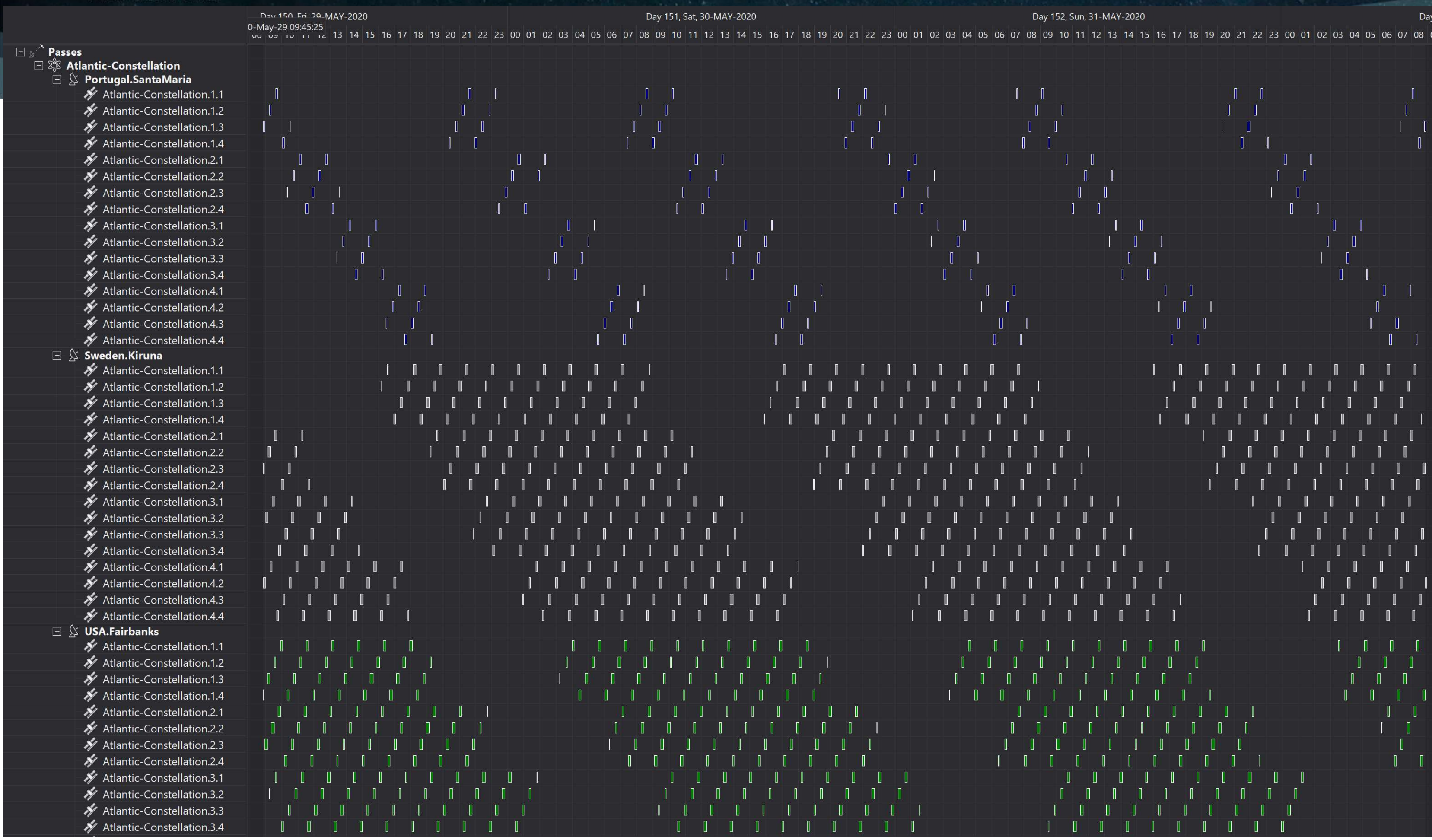
GOUND SEGMENT: GROUND STATIONS



GOUND SEGMENT: GROUND STATIONS

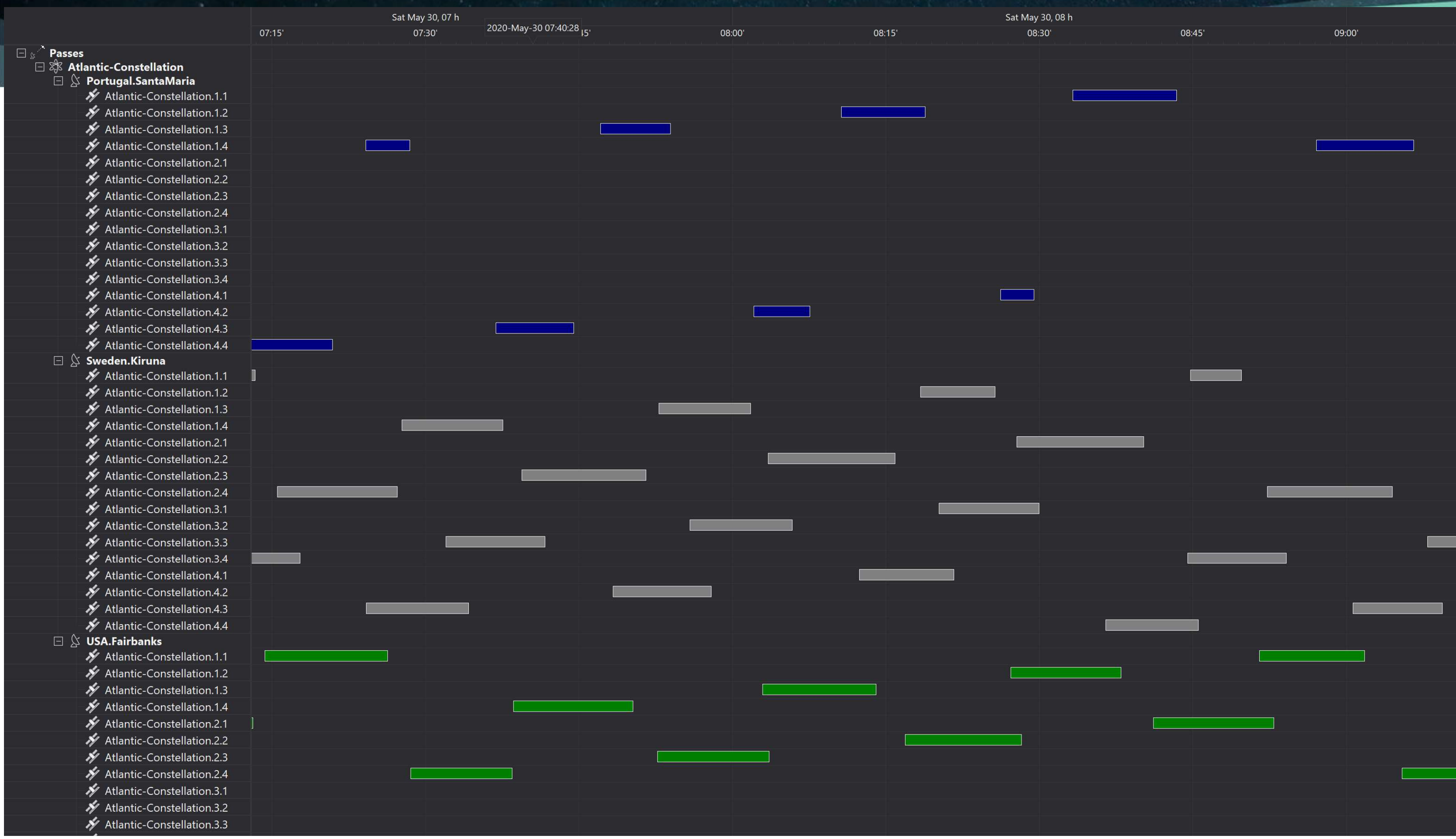


GOUND SEGMENT: GROUND STATIONS



- Gantt chart visualization of all satellite contacts passes with the 3 groud stations
- This pattern is repeated every 3 days as we have selected a frozen orbit with repetition cycle of 3 days
- Polar stations contact the satellites 11 times per day, while Santa Maria contact 2 at daytime and 2 during the night

GOUND SEGMENT: GROUND STATIONS



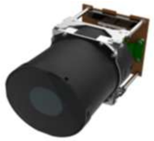
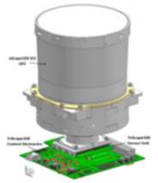
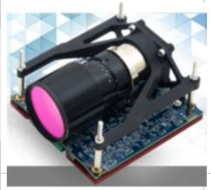
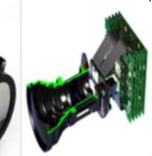
- Gantt chart visualization of only 2 hours of operations
- There is no conflict in Santa Maria, a single antenna can provide the full service
- There are conflict at polar stations as 2 and up to 3 satellites can be visible simultaneously
- We may need 2 or 3 antennae in the polar stations to serve the whole constellation

GOUND SEGMENT: GROUND STATIONS

- The analysis of groundstation shows that in a 3 day cycle Santa Maria can contact 13 times with each satellite with a mean pass duration of 446 seconds, giving a total of 97 min of contact per satellite, a 2,23% of the time. For the whole constellation Santa Maria provides 25,41 hours of contact. If the bit rate is 500 Mbps, the total download data in Santa Maria may reach 5583 GB in 3 days.
- In the same 3 day cycle, Kiruna can contact 32 times with each satellite with a mean pass duration of 612 seconds, giving a total of 323 min of contact per satellite, a 7,49% of the time. For the whole constellation Kiruna provides 86,4 hours of contact. At above bit rate, the total download data in Kiruna is 18984 GB in 3 days.
- The corresponding values for Fairbanks are 31 contacts with each satellite with a mean pass duration of 590 seconds, giving a total of 307 min of contact per satellite, a 7,1% of the time. For the whole constellation Fairbanks provides 81,6 hours of contact. The total download data in Fairbanks is 17930 GB in 3 days.
- Global values for the 3 stations are 76 contacts with each satellite with a mean pass duration of 580 seconds, giving a total of 727 min of contact per satellite, a 18,6% of the time. For the whole constellation 193,4 hours of contact and a total download data of 42495 GB in 3 days.

Groundstation	#passes per satellite	mean pass dur (sec)	total contact per sat (min)	% satellite visibility	Total const. Contact (hours)	Downlink data (Gbytes)
Santa Maria	13	446	97	2,23%	25,41	5583,25
Kiruna	32	612	323	7,49%	86,40	18984,38
Fairbanks	31	590	307	7,10%	81,60	17929,69
Global	**76**	**580**	**727**	**16,80%**	**193,40**	**42495,12**

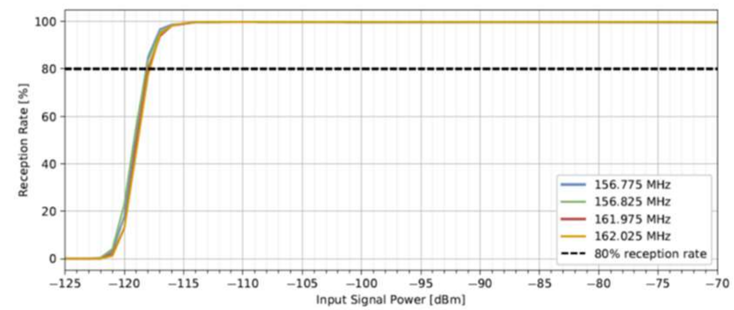
SURVEY OF EXISTING COTS MS AND HS CAMERAS FOR SMALL SATELLITES

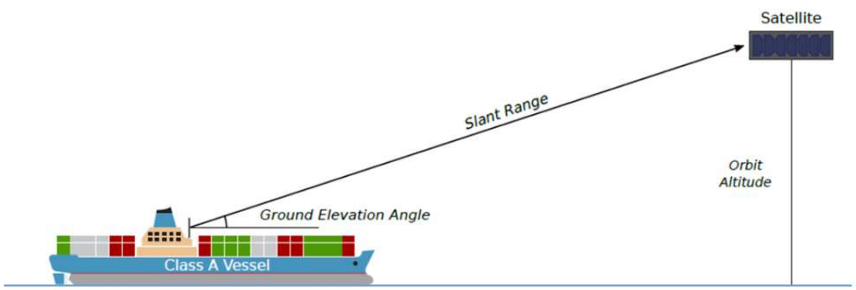
Product	SIMERA MultiScape 100	SIMERA TriScape 100	OPTO Mini Korsch	OPTO E3UCAM	OPTO NanoMUX	SCS Gecko Imager	SCS Chamalleon Imager	SCS Tegu Imager	COSINE Hyperscout	COSINE Hyperscout 2	MDA SIRC EO	PATRAS HyperEye
												
Sensor	CCD CMOS	CMOS 12,6 Mpixel	TMA	TMA	TMA							
Mode	pushbroom	snapshot (180 frames/s)										
GSD	4,66 m @ 500 km	4,75 @ 500 km	3,5 @ 500 km	6,8 @ 500 km	20m @ 500 km	10m PAN/20 MS; 39m RGB	9,6m PAN,19m MS,29m HS	2 m PAN 4-8 m HS	40 m @ 300 km	75m VIR,390m TIR 590 km	120 m @ 450 km	15m @ 500 km
Swath	19,1 km @ 500 km	19,4 x 14,6 km	14,5 km @ 500 km	28 km @ 500 km	80 km @ 500 km	41 km PAN/MS; 80 km RGB	up to 32 km	15 km	164 km @ 300 km	310 x 150 km @ 590 km	85 km @ 450 km	15 km @ 500 km
Bands	7 bands VNIR	RGB	4 (R, G, Red Edge, NIR)	4 (R, G, B, NIR)	4 (R, G, B, NIR)	PAN + 4MS or RGB	RGB, PAN+8MS or 150 HS	8 (VIS, NIR)	50 (400-1000 nm)	45 VNIR 4 TIR		100 (470-900 nm)
Optics	Modified Cassegrian	Modified Cassegrian	On-axis Korsch	On-axis Korsch								
Storage	128 GB	128 GB	32 GB			128 GB	160 GB	8 Tb				512 GB
Max. Strip memory	17,500 km	8700 frames										
Max. Contin. strip	800 km											
Focal Length	5780 mm	5800 mm										
Aperture	95 mm	95 mm	82 x 120 mm	82 x 120 mm	35 mm							
Field of View	2,18º	2,2º								31º x 16º	7º x 9º	5º x 3,8º
# pixels	4096	4096 x 3072	4096	4096	4096				4096 x 1850		1024 x 768	
Pixel size	5,4 micras	5,5 micras	5,4 micras	5,4 micras	5,4 micras							
Pixel depth	12 bits	10 bits	10 bits			8 or 10 bits	10 or 12 bits	10 bits			14 bits	12 bit
TDI stages	up to 256 per band	no TDI	256	256	256							
Line rate	up to 2650 Hz	180 frames/s										
Transmittance	49% @ 550 nm	61% @ 550 nm										
Compression	optional	optional				yes	yes					yes
Power supply	5 V DC	5 V DC	12-24 V DC			5 V DC	5 V or 28 V DC	28 V DC				
Power imaging	5 w	6 w DC				< 3,5 w PAN/MS; 2,7w RGB	< 3,5 w	< 35 w		12 w	2 w	
Power read or Iddle	2,5 w	1,1 w				< 2,4 w PAN/MS; 1,4w RGB	< 2,5	< 20 w				
Mass	1,2 kg	1,1 kg	< 4 kg			500 g PAN/MS; 390 g RGB	1,35 kg	< 24 kg	1,1 kg	1,7 kg	1,2 kg	< 2kg
Dimensions	98 x 98 x 176 mm	98 x 98 x 176 mm	100 x 100 x 340 mm	3U compatible	3U compatible	97 x 96 x 58 mm	200 x 94 x 94 mm	782 x 280 x 280 mm	1 U compatible	2 lit	100 x 100 x 160 mm	2U
SNR	140	70				200 PAN/150 MS; 100 RGB	200 PAN, 120 MS, 150 HS	> 125		50-100 VNIR 0,5-3 TIR		> 90

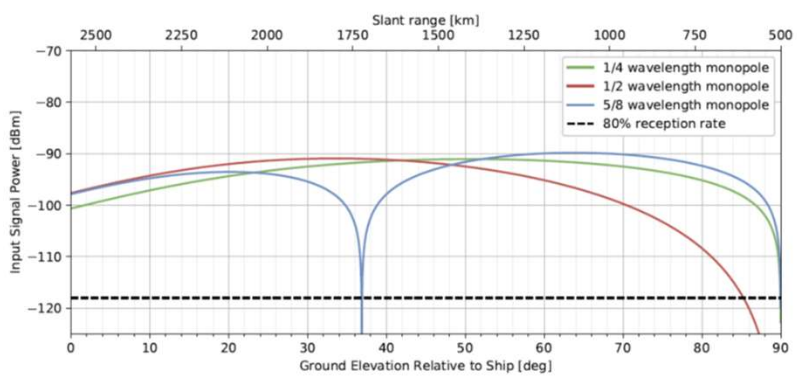
SURVEY OF EXISTING COTS AIS SENSORS (I)

- **Satlab Polaris 4-channel AIS sensor**

Parameter	Specification
Frequency coverage	156.000 to 162.025 MHz
AIS channel frequencies	156.775, 156.825, 161.975, 162.025 MHz
Sensitivity	-118 dBm (80% reception rate)
Noise figure	2 dB
Frame store capacity	261120 frames
Input voltage	4.5 - 40 V
Typical power consumption	1350 mW (5 V input, 25℃)
Operating temperature	-40℃ to +85℃
CAN-bus	Up to 1 Mbit/s
RS-422	Full duplex, up to 3 Mbit/s
Ethernet	Full duplex, 100 Mbit/s
Primary storage	128 MB NOR-flash
Secondary storage	1 GB SLC SD card
Dimensions	93.0 x 87.2 x 12.5 mm
Mass	185 g







SURVEY OF EXISTING COTS AIS SENSORS (I)

- **SpaceQuest STS 300 AIS receiver**

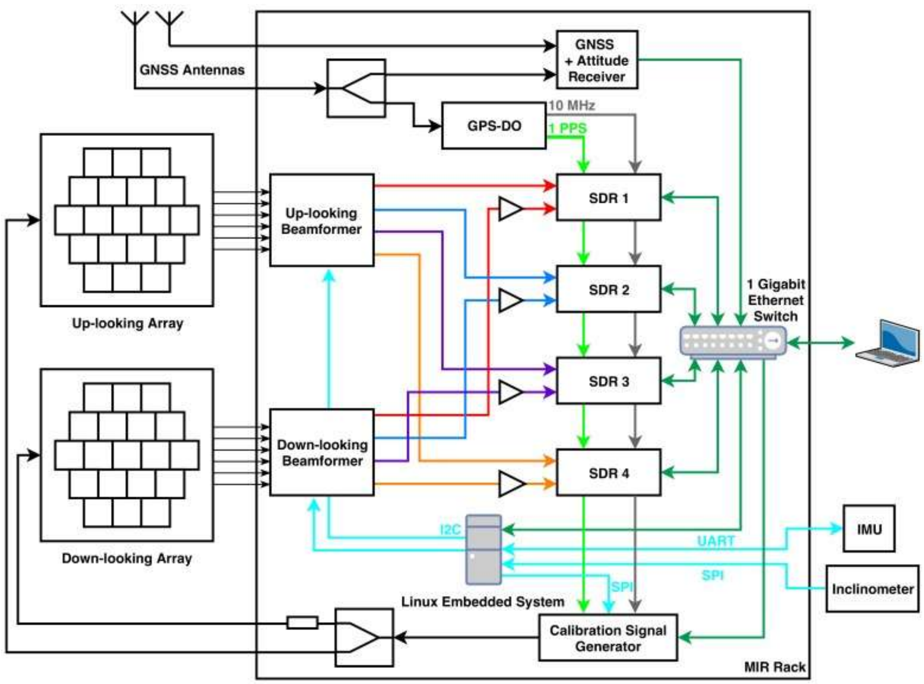
Channel Coverage:	All AIS Channels in Maritime Band (156 to 162 MHz)
Input Voltage:	2.5V – 5.0V DC
Power Consumption:	400mW – 650mW
Data Output:	115 kHz Asynchronous Serial, 3.3 Volt TTL
Mass:	180g (Including Aluminum Enclosure)
Packet Threshold:	-95 dBm at 90% Throughput

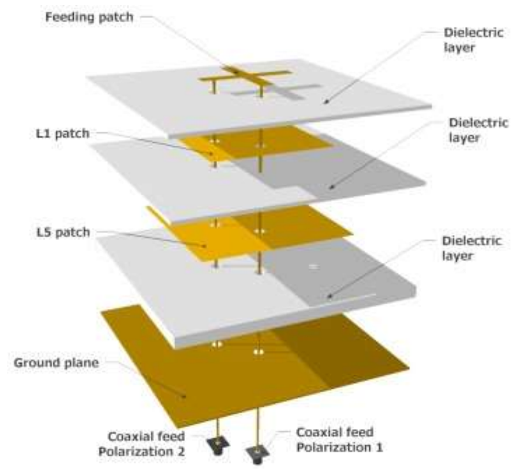
Receivers:	6 Independently Tunable FM Receivers
Frequency Range:	156 MHz – 163 MHz Tunable in 1 kHz Steps
IF Bandwidth:	12 kHz or 15 kHz Filter Options
1st IF Image Rejection:	45 dB Minimum @ Frx – 2*18.745 MHz
2nd IF Image Rejection:	43 dB Minimum @ Frx + 2*455kHz
Out of Band Rejection:	> 90 dB Suppression of Signals between 400 and 2500 MHz

Connector:	104-pin CubeSat Standard or 60-pin Samtec FT5
Enclosure:	Sold With or Without Aluminum Enclosure
Volume:	95.9mm x 90.2mm x 20mm (Cubesat Configuration) 80mm x 85mm x 20mm (Samtec FT5 Configuration)

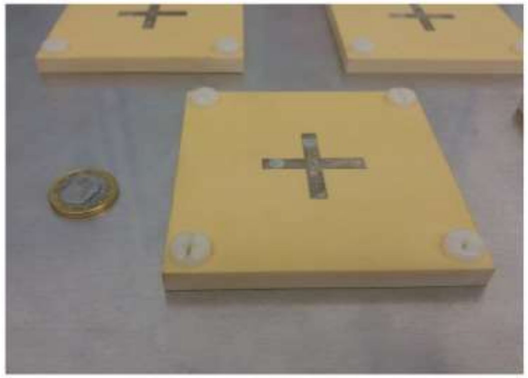
SURVEY OF EXISTING COTS GNSS-R SENSOR

- **MIR GNSS-R L1/L5 sensor (+ patch antenna 95x95x8 mm)**





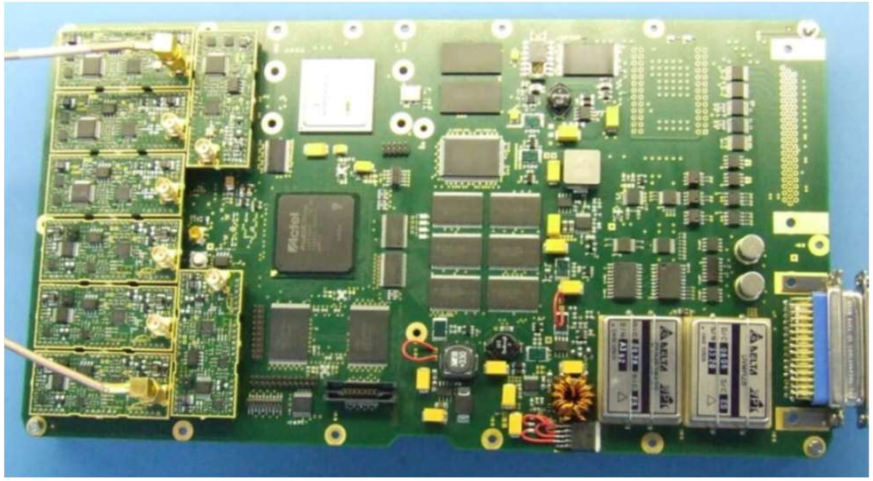
(a)



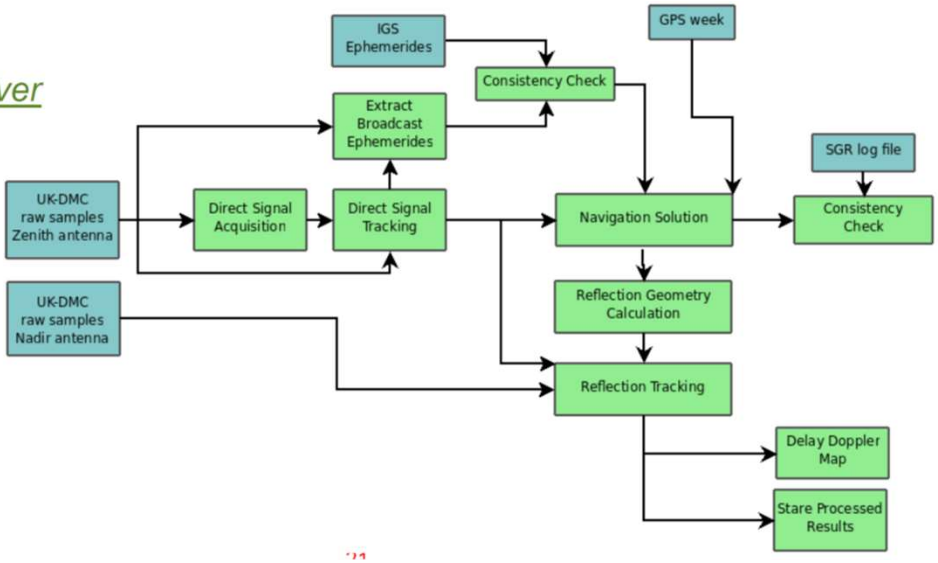
(b)

SURVEY OF EXISTING COTS GNSS-R SENSOR

- **SSTL GNSS-R instrument**



Software receiver

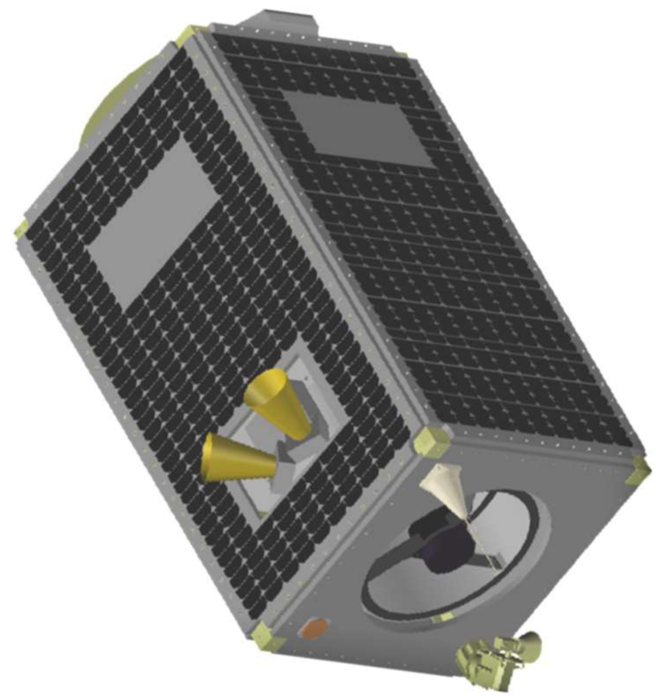


PAYLOAD MASS, SIZE AND POWER REQUIREMENTS

- From the analysis of the state of the art available COTS, we can derive the expected requirements for the sensors:
  - **The multispectral camera (MS)** of 5m resolution, with 20 km swath can fit in a 2U volume (10 x 10 x 20 cm), with a mass of 1,2 kg, a power in imaging mode of 5w and 2,5 w in reading or iddle modes
  - **The hyperspectral camera (HS)** better than 50m resolution, with 100 km swath can fit also in a 2U volume (10 x 10 x 20 cm), with a mass of 1,2 kg, a power in imaging mode of 5w and 2,5 w in reading or idle modes
  - **The AIS receiver** has a mass of 185 gr with a size of 10x10x2 cm and a power consumption of about 1 wat, we must add the VHF antenna to this system
  - **The GNSS R receiver** has a size of about 1 U including the patch antenna, with a mass of about 500 gr and a power consumption of 3 wat
- In summary our payload instruments have a volume between 5 and 6 U, with a total required peak power of about 13 w if all are working simultaneously and a total mass of about 3,5 kg

SATELLITE MASS, SIZE, AOCS, DOWNLOAD AND POWER REQUIREMENTS

- Taking into account classical space relation coefficients, we can extrapolate that our satellite the following requirements:
  - It should be a **12 U nanosatellite** (20 x 20 x 30 cm), with a total mass of about 15 kg
  - The solar panels must be able to generate 25 w of power (13 w for payload and 12 w for platform)
  - The batery capacity must be at least 5 Ah
  - A downlink capability of 500 Mbps in X or Ka Bands, with uplink capability of 250 Kbps in S-Band or VHF
  - The pointing accuracy must be 0,1º (3-sigma) and pointing knowledge 0,05º (3 sigma)
  - The satellite must be able to point +/- 30º off-nadir (desirable +/- 45º)
  - There must be at least 256 GB of on board memory storage
  - There must be a propulsion system with a minimum thrust level of 1 mN



CONSTELLATION POWER ANALYSIS (I)

- There are two possible configuration of solar panels:
  - **Body fixed solar panels**: this is the more simple, cheap and robust configuration, allowing a constant nadir pointing mode, but it generates less power
  - **Deployable solar panels:** it generates more power but it is more complex, expensive and requires a Sun pointing AOCS mode
- The selection of one type or another depends on the power balance. The first analysis is to study the power generated by a 12U nanosatellite body fixed solar panel scheme in our constellation
- The power generated depends on the orbital plane and the epoch of the year (due to geometric Sun illumination)

Epoch	Orbital plane # 1		Orbital plane # 2		Orbital plane # 3		Orbital plane # 4	
value	mean	peak	mean	peak	mean	peak	mean	peak
Winter	18,43 w	28,03 w	12,67 w	24,96 w	13,86 w	26,33 w	21,85 w	26,74 w
Spring/Autum	23,39 w	26,33 w	13,49 w	26,32 w	13,46 w	26,00 w	23,33 w	26,33 w
Summer	21,79 w	26,73 w	13,74 w	26,33 w	12,53 w	24,96 w	18,38 w	28,03 w

CONSTELLATION POWER ANALYSIS (II)

- From the table of the previous slide we conclude that:
  - **<u>Worst case</u>**: satellites in orbital plane 3 in Summer (very similar to orbital plane 2 in Winter)
  - **<u>Best case</u>:** satellites in orbital plane 1 in Spring/Autum (very similar to orbital plane 4 at same epoch)
- For this solar panel body fixed power generation analysis, the following assumptions are considered:

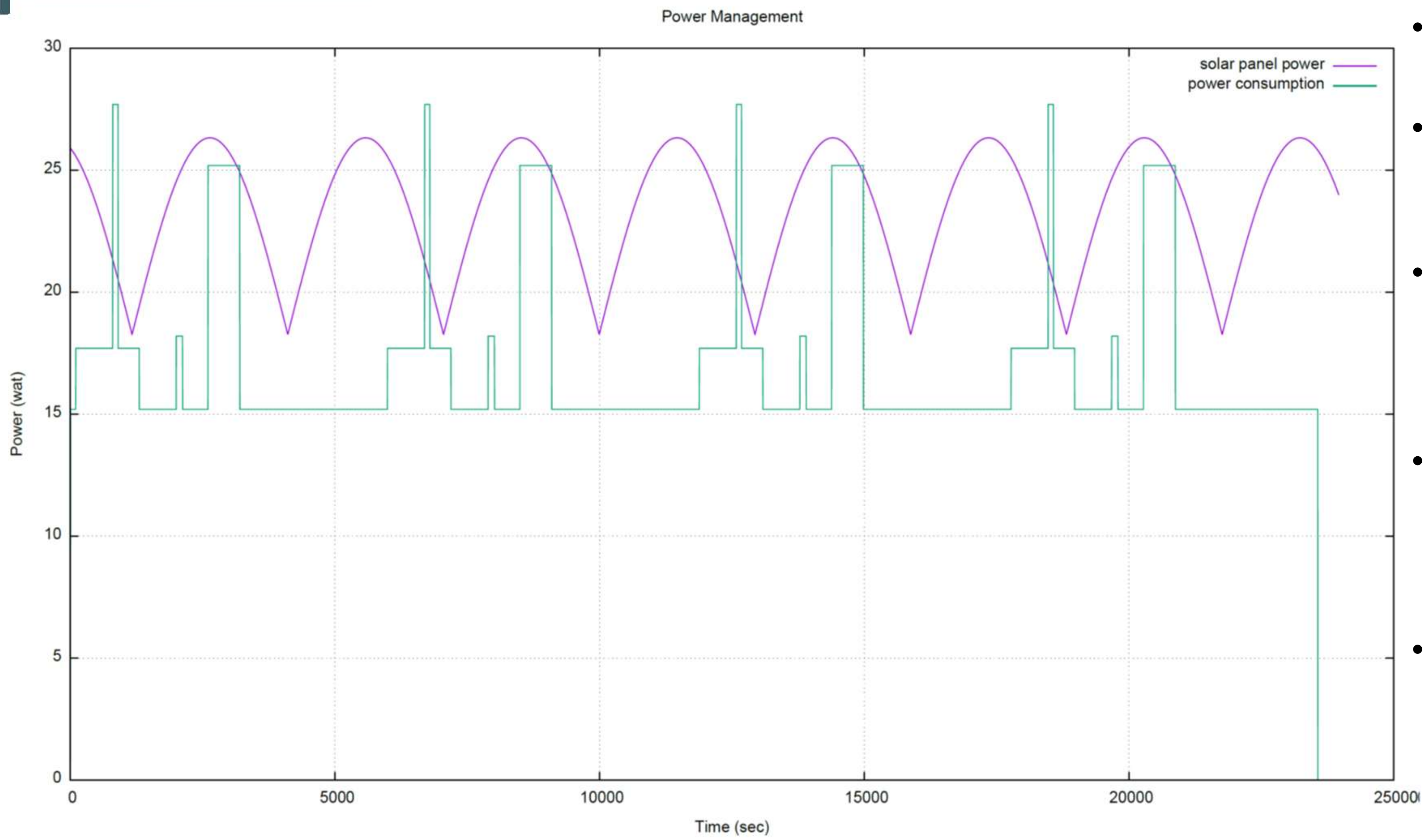
```
POWER MANAGEMENT PROGRAM
========================
REF. SURFACE OF PANEL (M**2) :    0.06
SOLAR CELL EFFICIENCY (%)    :   30.00
CELL COVERING LOSS (%)       :    1.00
CELL CALIBRATION LOSS (%)    :    1.00
CELL MISMATCH LOSS (%)       :    0.50
CELL INTERCONNECTION LOSS (%):    1.00
CELL EOL RAD. (5 YS) LOSS (%):    1.50
CELL LOSS AT MAX. TEMPER. (%):    5.00
SOLAR PA. TO BCR MISMATCH (%):    0.50
BCR EFFICIENCY (%)           :   95.00
```

CONSTELLATION POWER ANALYSIS (III)

AIR CENTRE

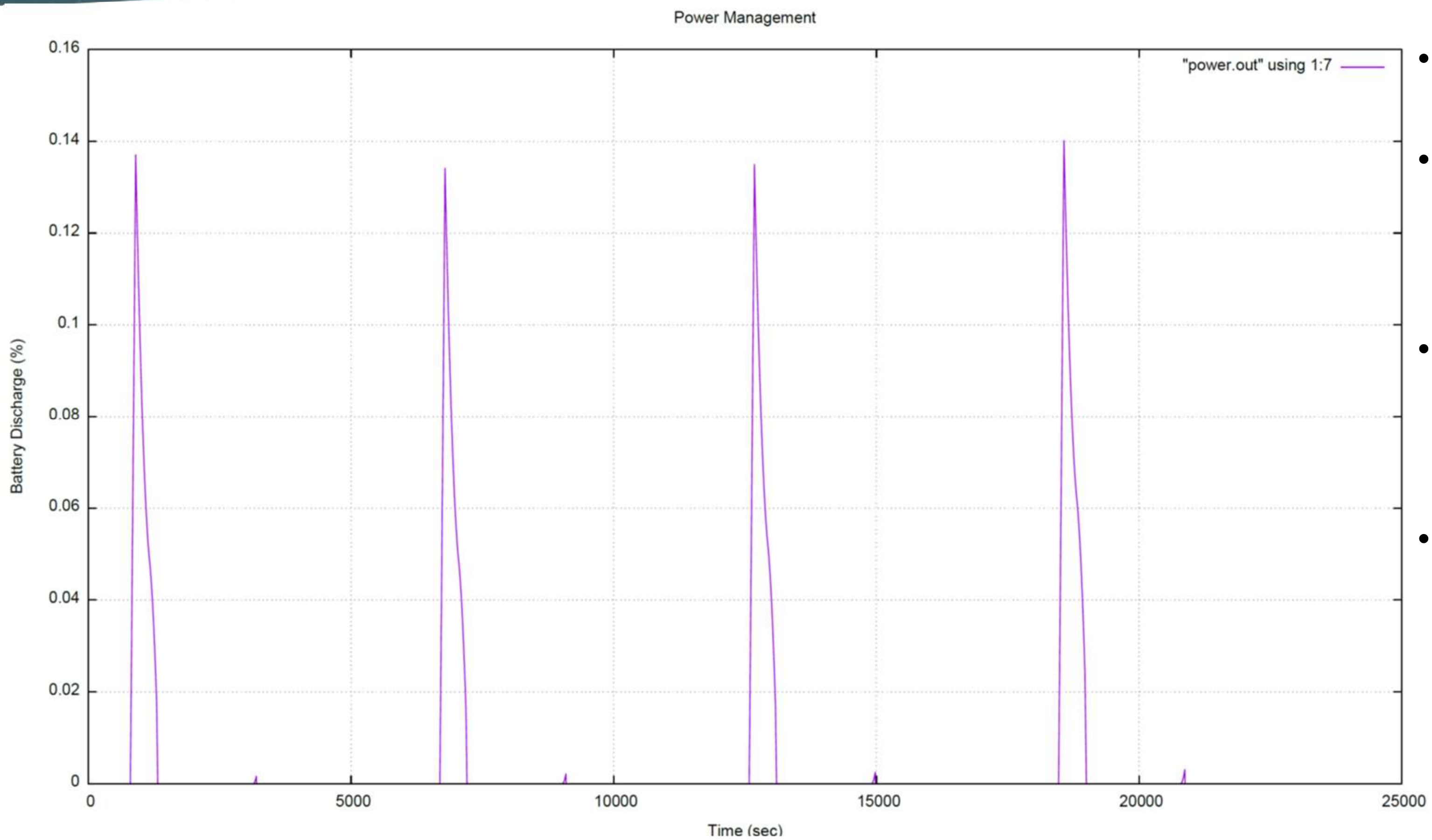
- In order to check if body fixed solar panels are feasible, we shall make a complete power balance analysis for the best and the worst configuration (no need to take the 12 possible cases), with the following assumptions:
  - We assume that we use the imaging systems (MS and HS cameras) an average of 20 minutes per orbit, which is equivalent to large image strips of about 9,000 km long
  - AIS and GNSS-R sensors are continuously operating
  - The platform consumption (always on) is (those assumptions must be verified at later stage):
    - On board computer: 2w
    - GPS receiver: 2,5 w
    - Power system: 1 w
    - S-Band receiver: 2 w
    - Reaction wheels: 3 w
    - Magnetotorquers: 0,5 w
    - Magnetometers: 0,5 w
    - AOCS system: 3 w
    - S-Band transmitter (used only 3 minutes per orbit at station contact): 3 w
    - X-Band transmitter (used only 10 minutes per orbit at station contact): 10 w
- The battery capacity is 5Ah

CONSTELLATION POWER BALANCE BEST CASE ORBITAL PLANE 1 SPRING/AUTUM



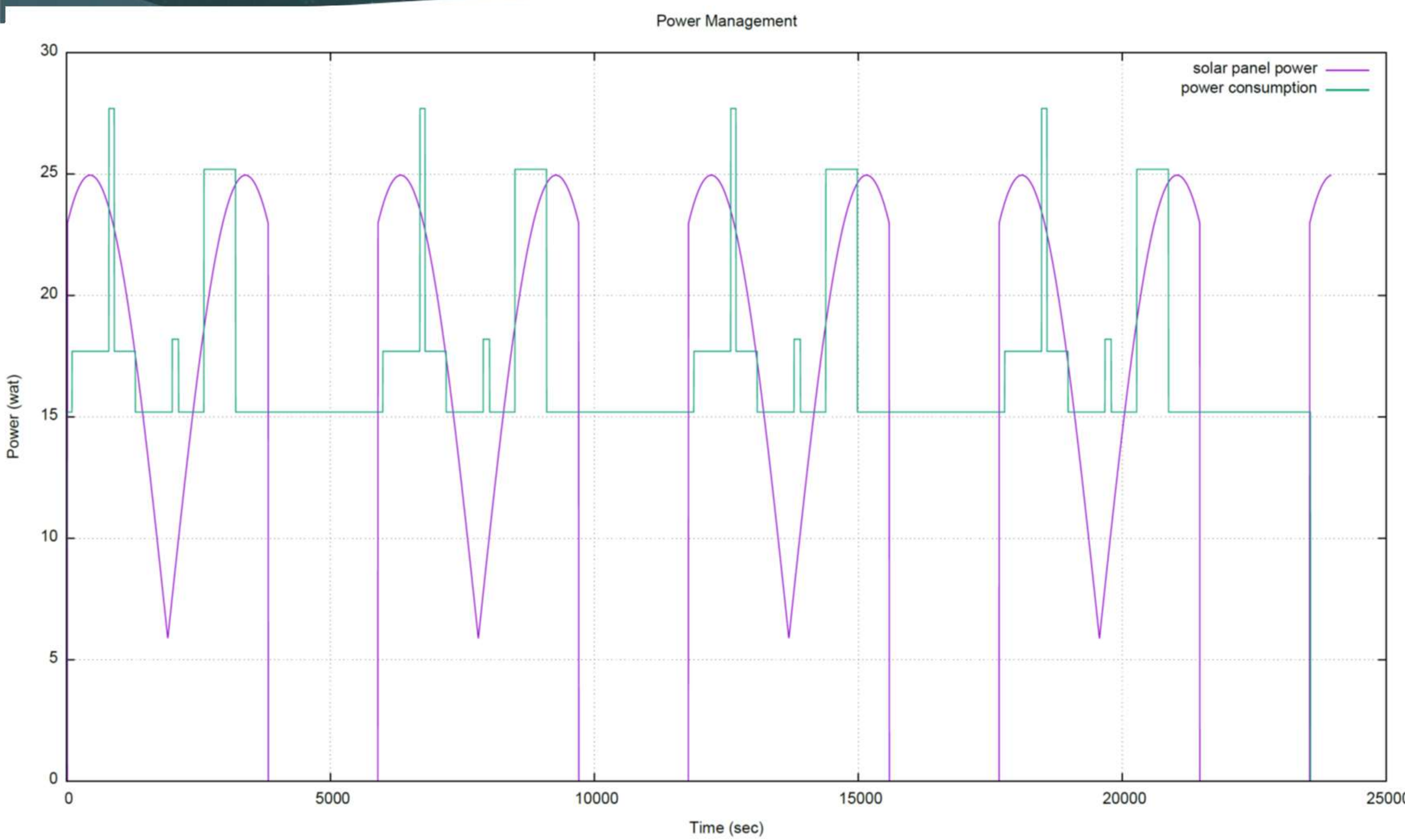
- This is a 4 orbit power balance simulation
- The blue line represent the generation of power, there is no eclipse in this orbit
- Maximum power (26,33 w) are generated at the poles and minimum (18,3 w) at the equator
- The power consumption is also presented, with peaks due to the use of imaging systems or X-Band downlink
- Average consumption is 16,7 w, as the average generation was 23,4 w, **we have a positive margin of 40%**

CONSTELLATION POWER BALANCE BEST CASE ORBITAL PLANE 1 SPRING/AUTUM



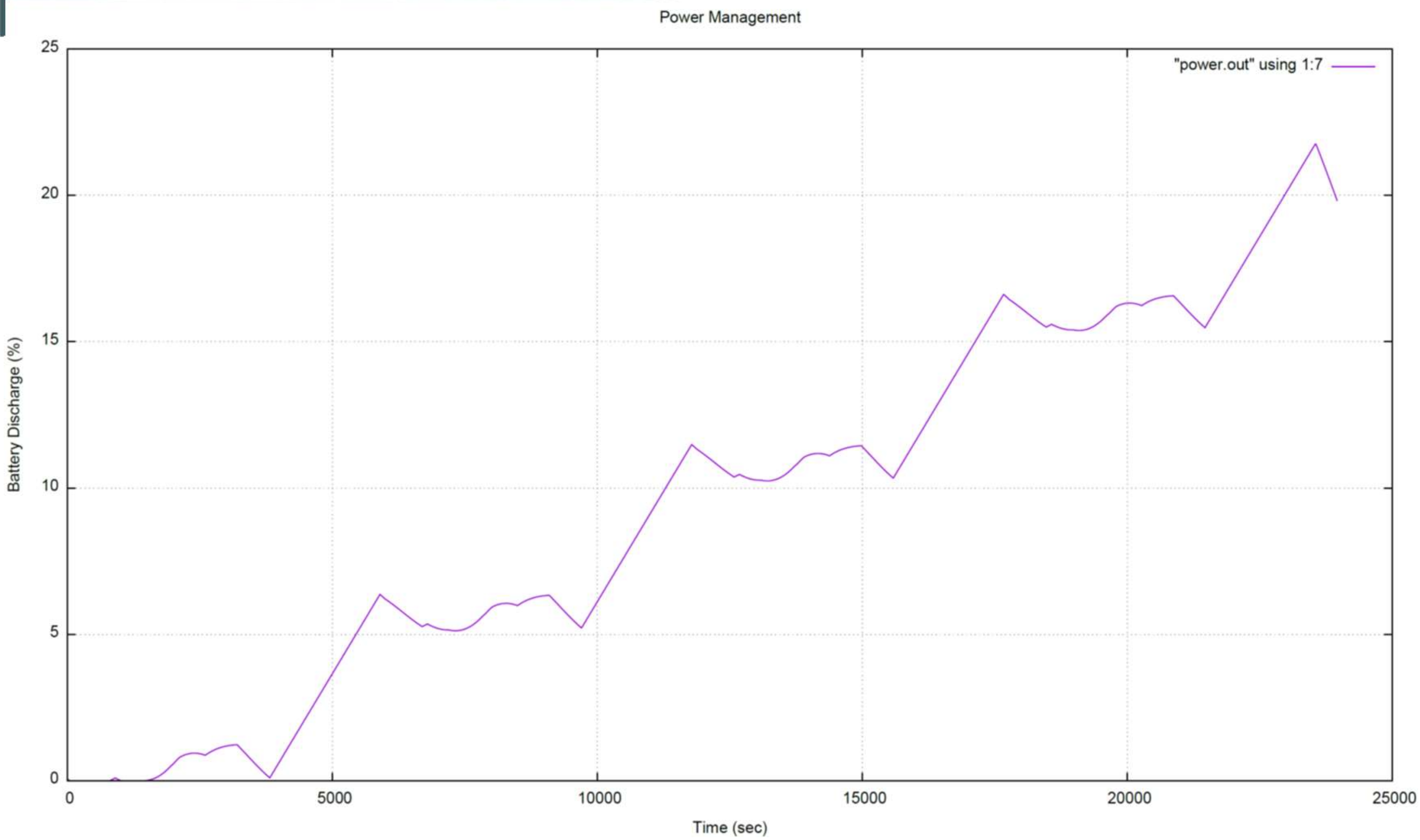
- This is a 4 orbit battery discharge simulation
- As the generated power is nearly always above the consumption, there is no discharge
- Only at X-Band download there is a need of battery, with a discharge of only 0,14% which is very small
- **This confirms that for this case of orbital plane 1 in Spring/ Autumn (similar to orbital plane 4) the body fixed solar panel system scheme is enough**

CONSTELLATION POWER BALANCE WORST CASE ORBITAL PLANE 3 SUMMER



- This is a 4 orbit power balance simulation
- In this case we have eclipses of 35 minutes duration
- Maximum power (24,96 w) are generated at the poles and minimum is 0 w at eclipse and 5,9 w at equator
- The power consumption is also presented, with peaks due to the use of imaging systems or X-Band downlink
- Average consumption is 16,7 w, as the average generation was 12,53 w, **we have a negative margin of 33%**

CONSTELLATION POWER BALANCE BEST CASE ORBITAL PLANE 3 SUMMER

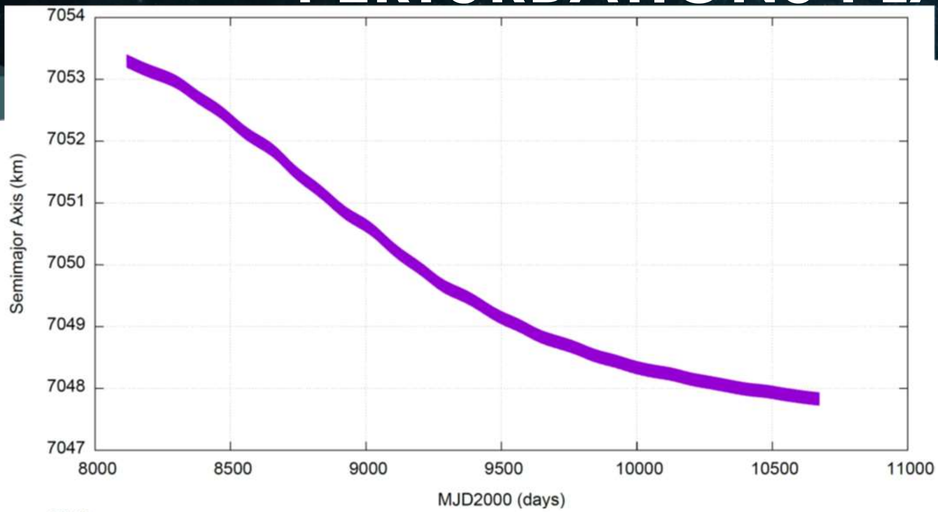


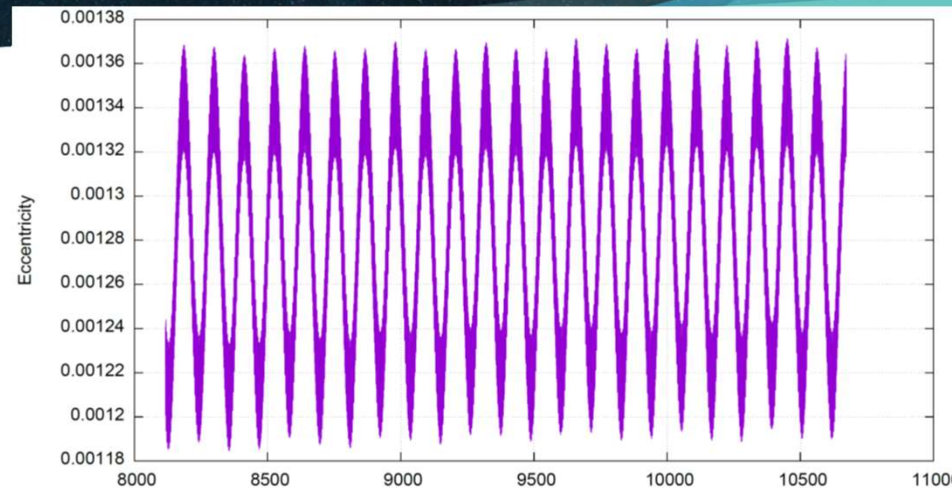
- This is a 4 orbit battery discharge simulation
- Due to the eclipse we have a large battery discharge and it never recovers the full capacity
- In 4 orbits the battery has been discharged more than 20%
- **This confirms that for this case of orbital plane 3 in Summer (similar to orbital plane 2) the body fixed solar panel system scheme is not enough**
- **Therefore we have to go to a deployable solar panel system unless we can improve power management efficiency**

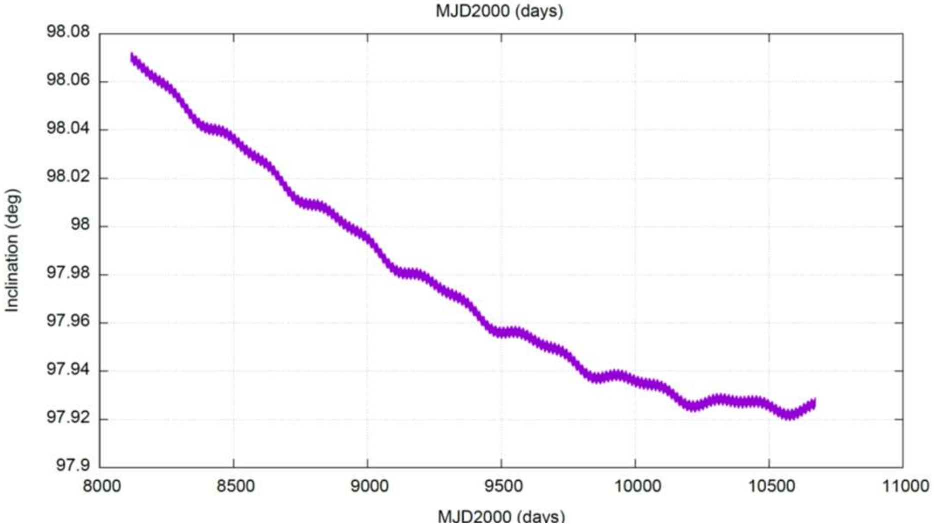
CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS

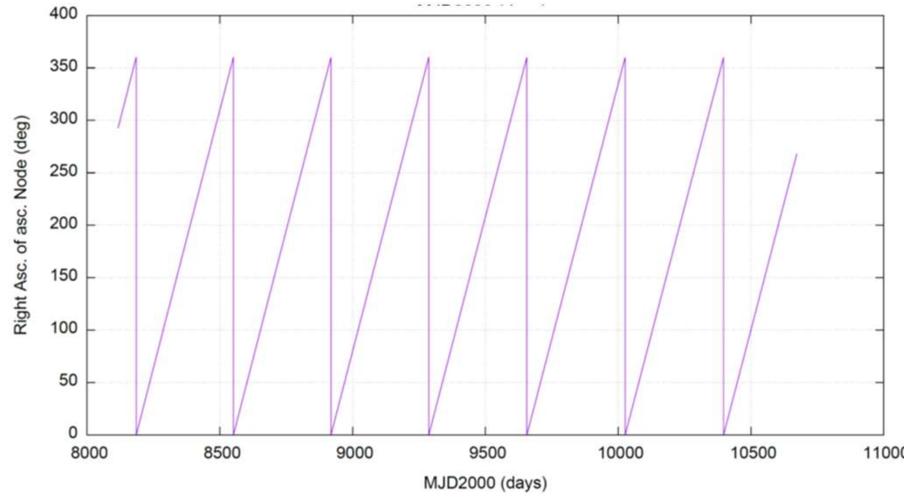
- For the analysis of orbital perturbations we are considering the following effects:
  - **Earth gravitational field:** expansion in spherical harmonics, considering zonals and tesserals up to order 30 and degree 30
  - **Atmospheric drag:** Use of MSIS Thermospheric model with a frontal surface of 0,06 m2 (12U), a mass of 15 kg and a drag coefficient Cd = 2,375. This model is very sensitive to solar radiation pameters (F10.7 and Ap), for those parameters we use NASA estimation. There are 4 scenarii with solar radiation at percentile 5%, 50%, 75% and 95%. For the normal orbit perturbation analysis we use 50%, but for dimensioning the propellant needed to compensate drag we use 95% as this is the worst case
  - **Third body perturbation:** attraction by Sun and Moon are considered
  - **Solar radiation pressure:** with a frontal surface of 0,06 m2, a mass of 15 kg and a reflectivity coefficient of Cr = 1,15 are considered
  - Other perturbations like relativistic effects, solid and ocean tides or albedo are neglected as their order of magnitude is much smaller than above effects
- For each orbital plane we analyze the effect of those perturbations by propagating 7 years without manuvres, at a later stage we incorporate a control manoeuvres strategy and recalculate the orbital evolution

CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #1

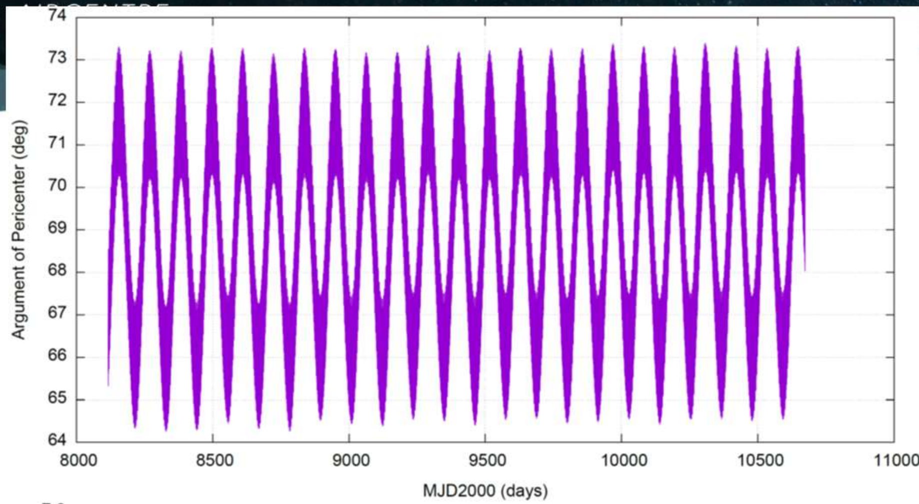


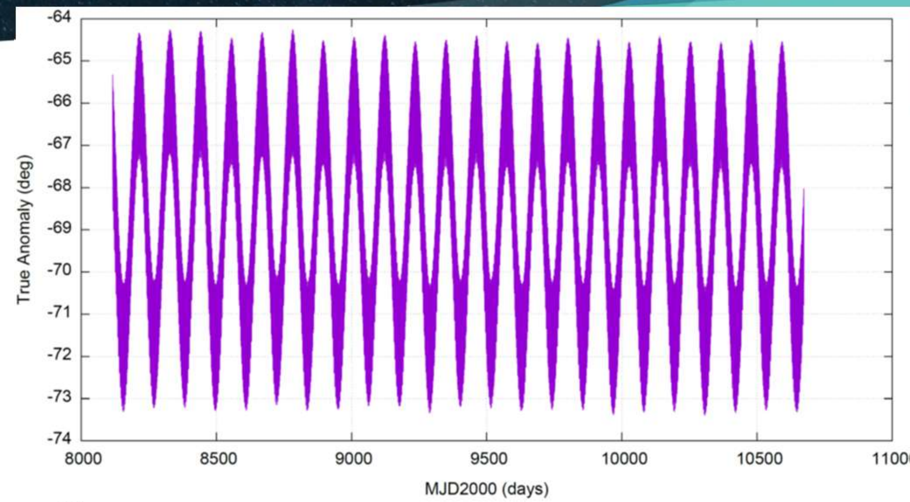


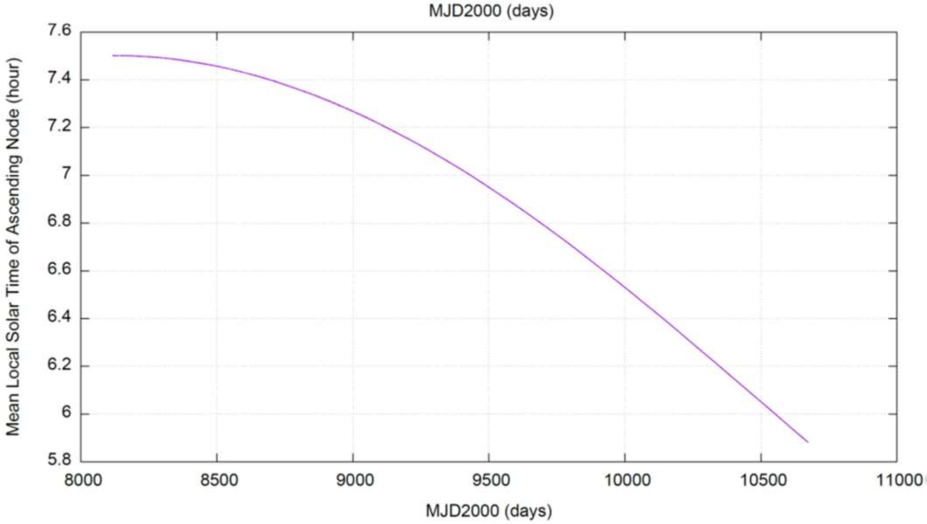


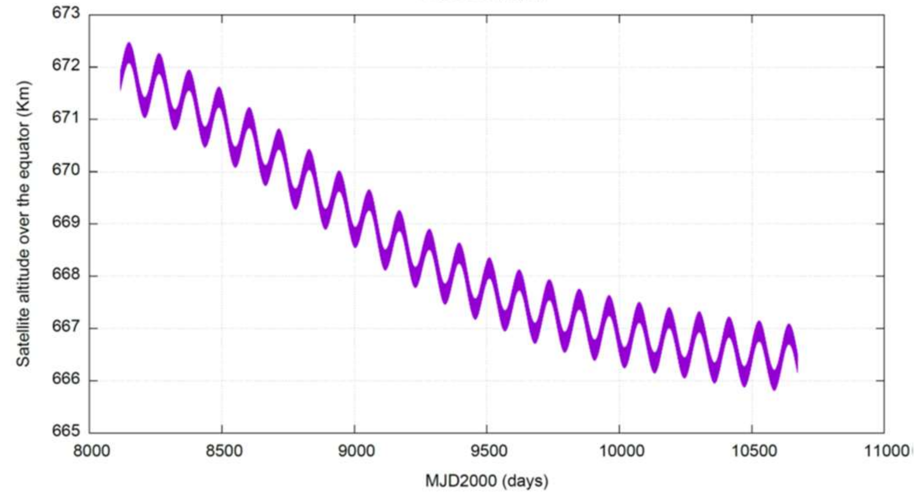


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #1

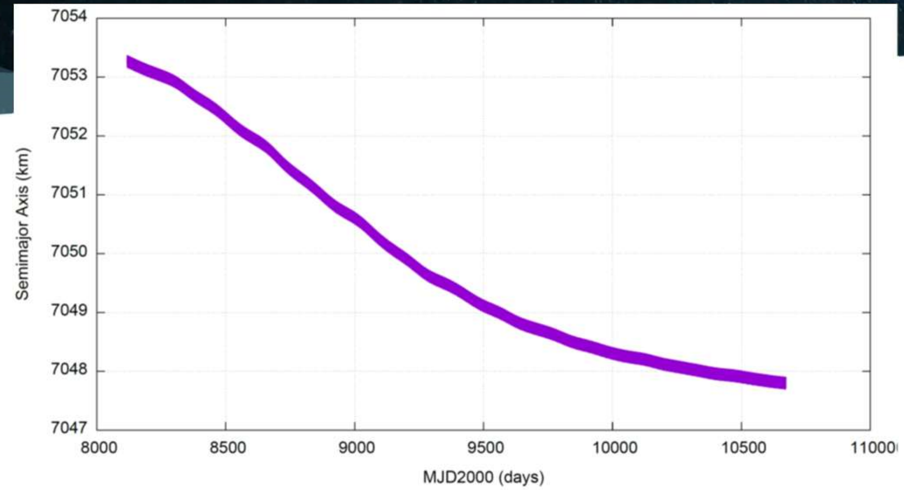


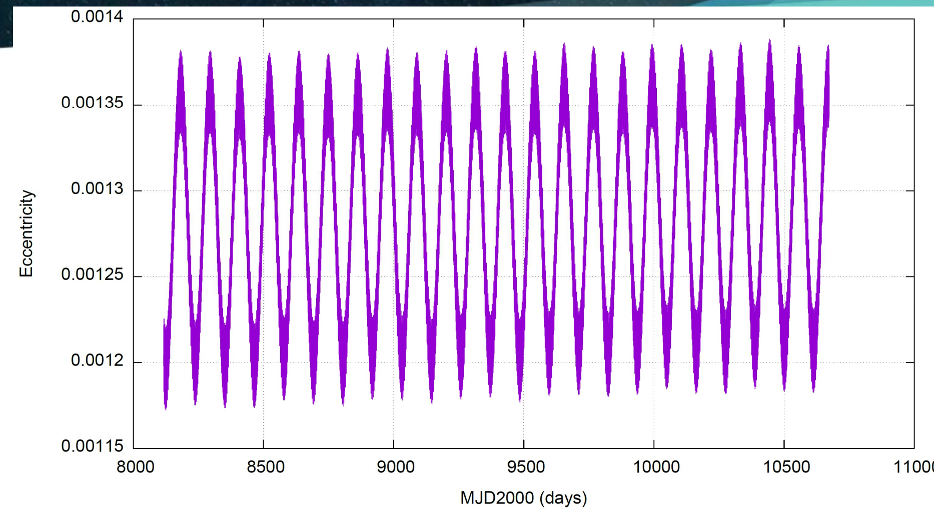


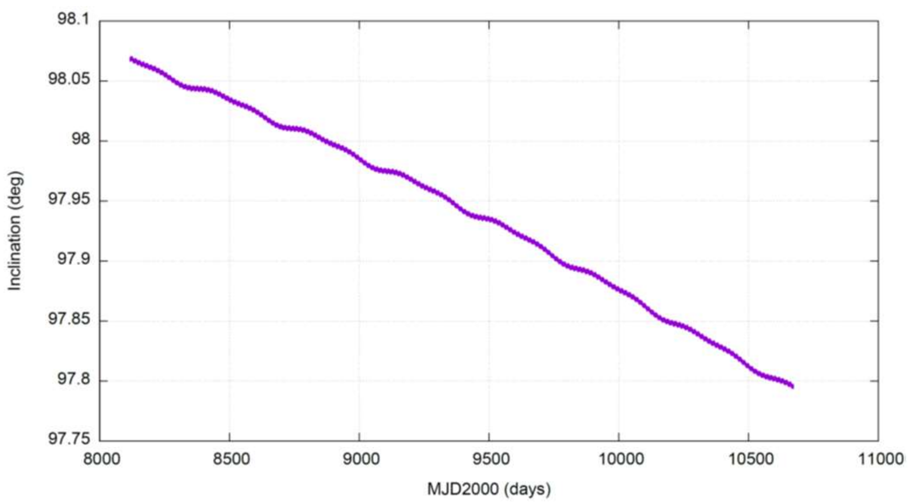


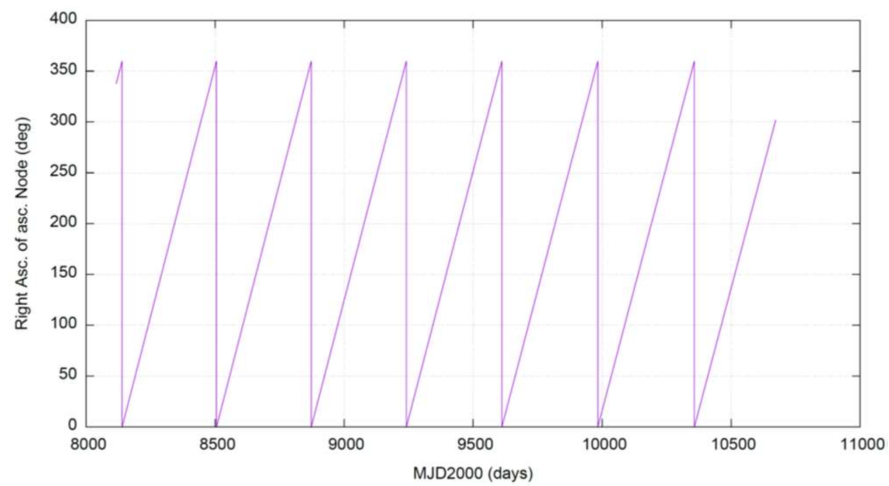


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #2

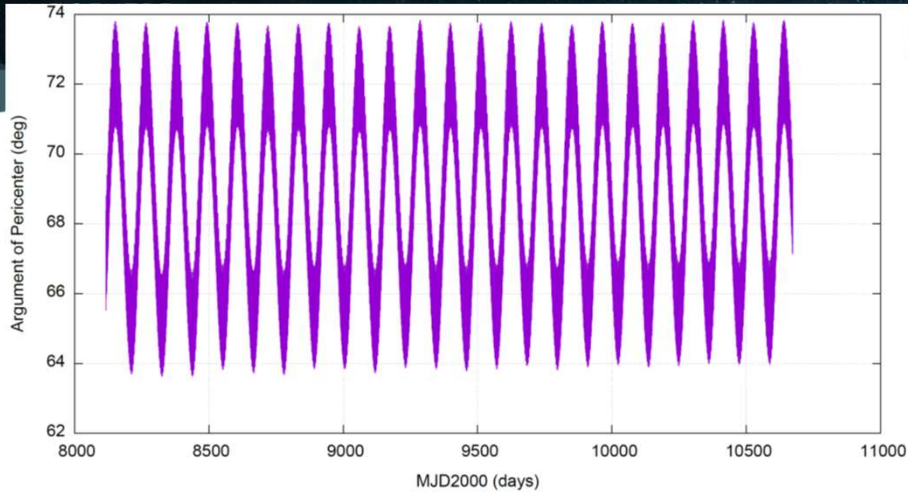


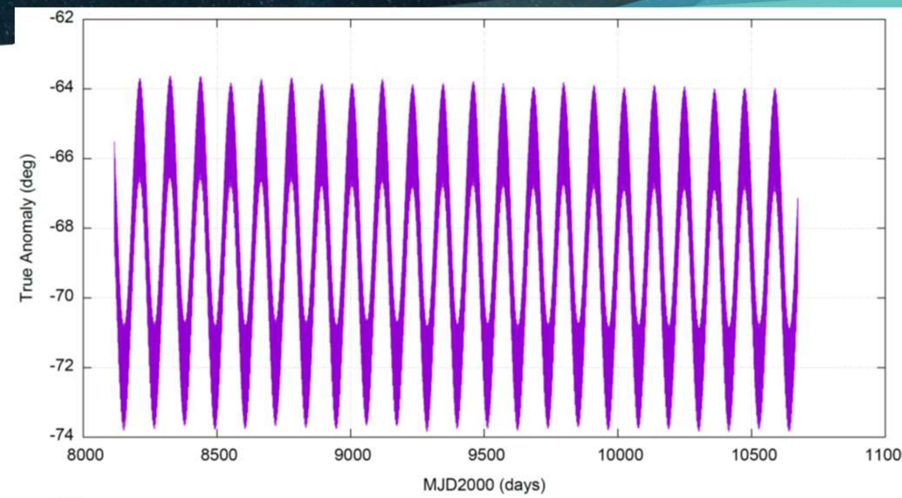


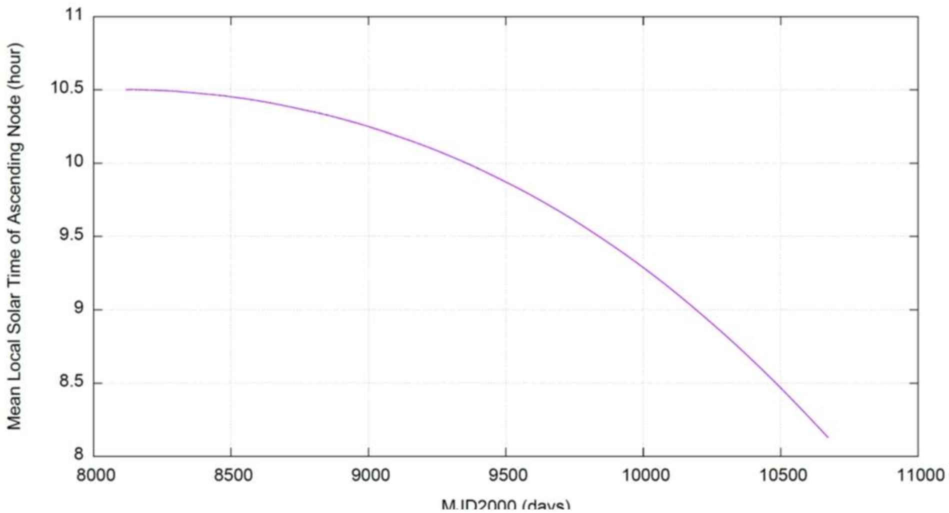


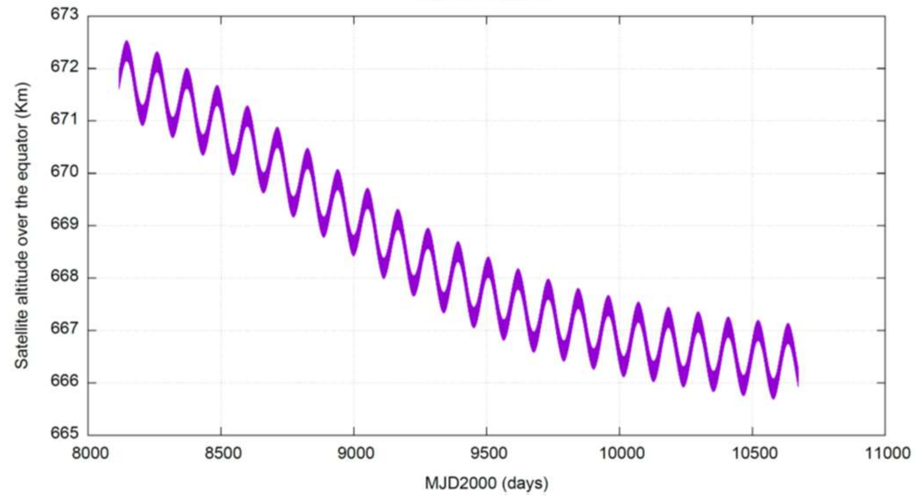


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #2

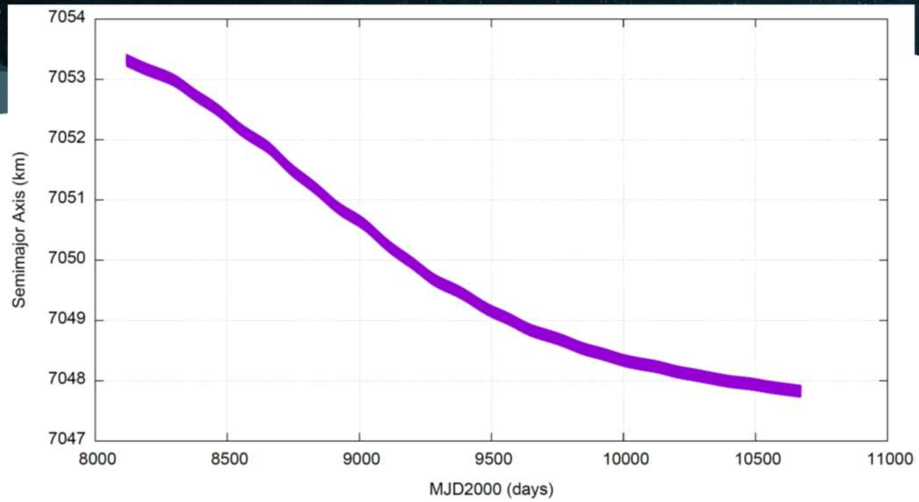


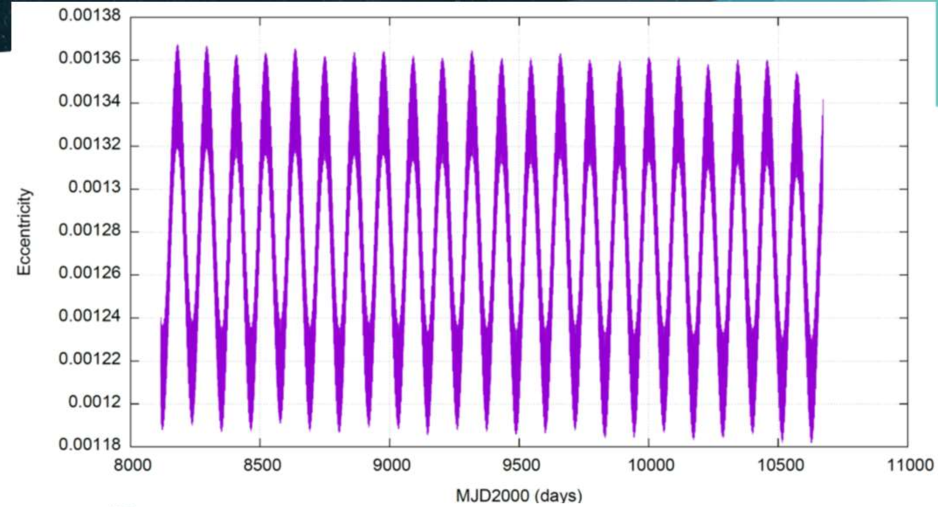


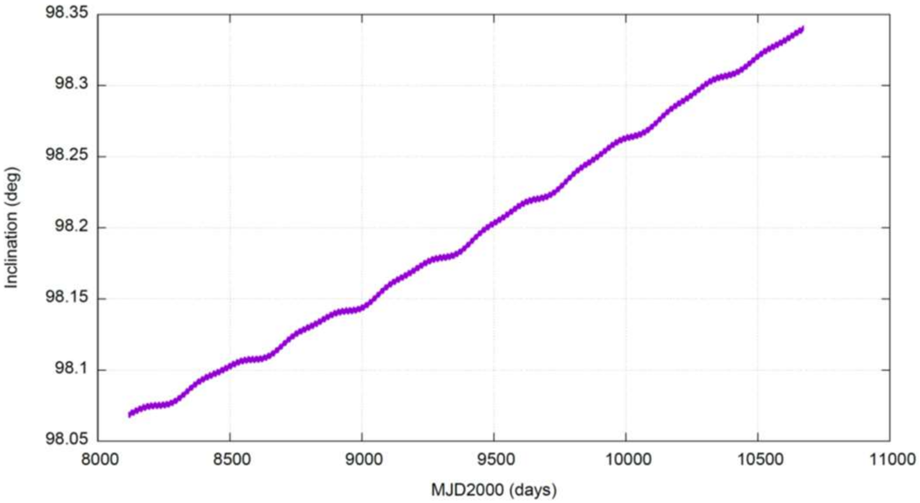


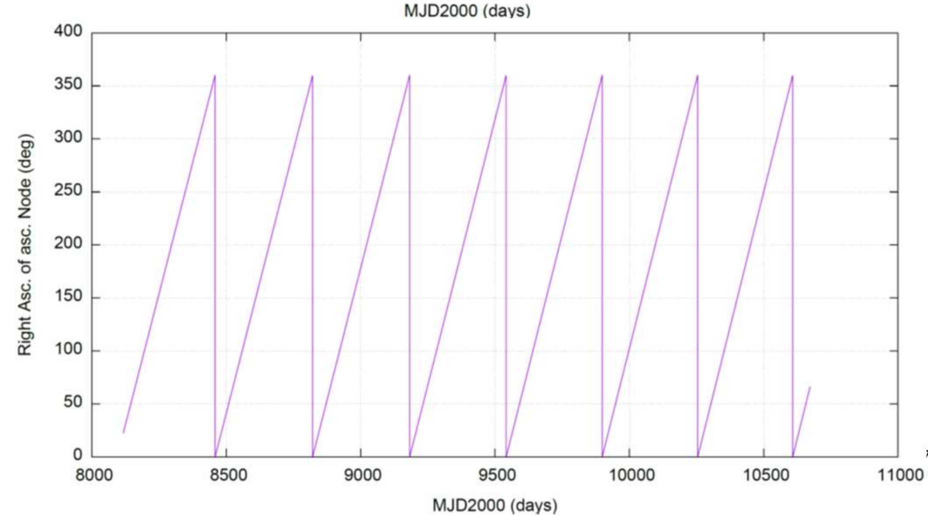


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #3

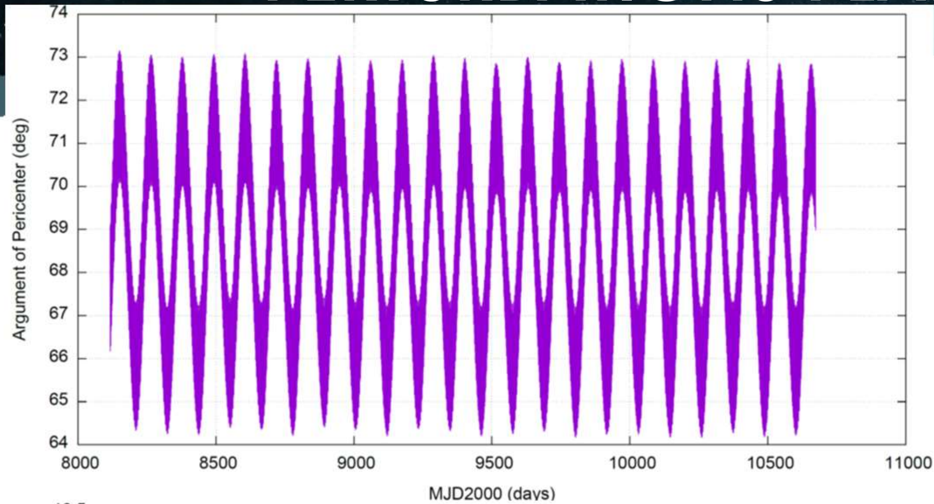


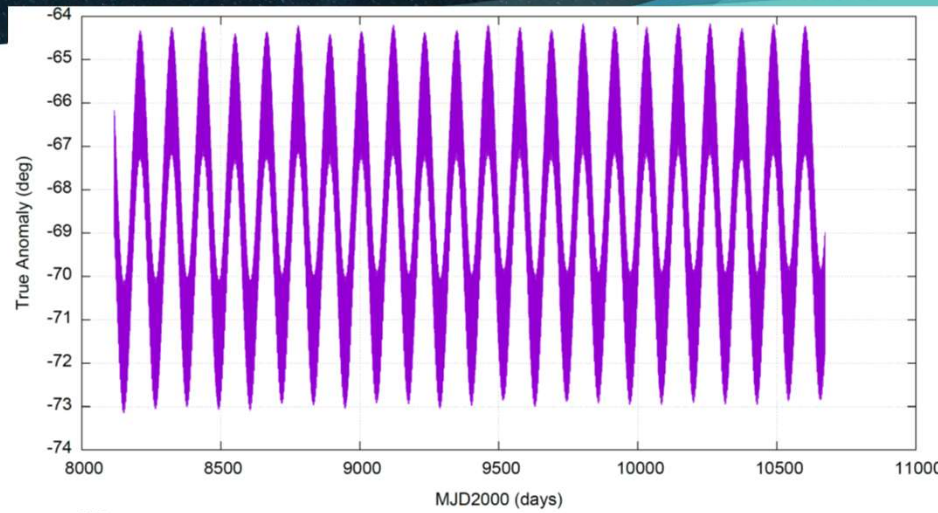


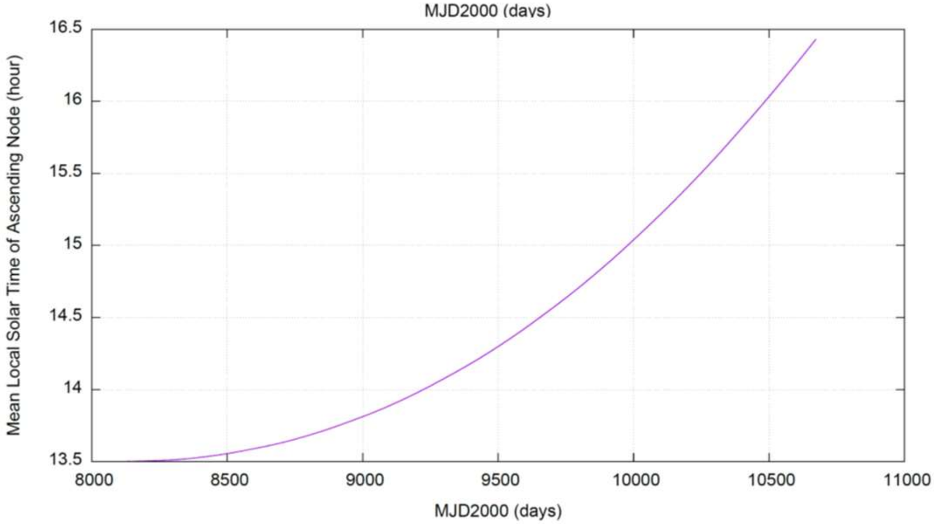


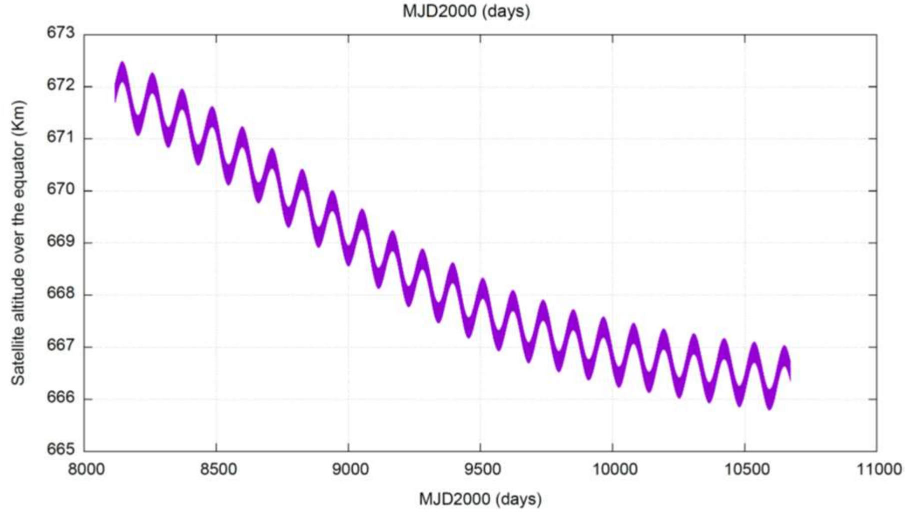


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #3

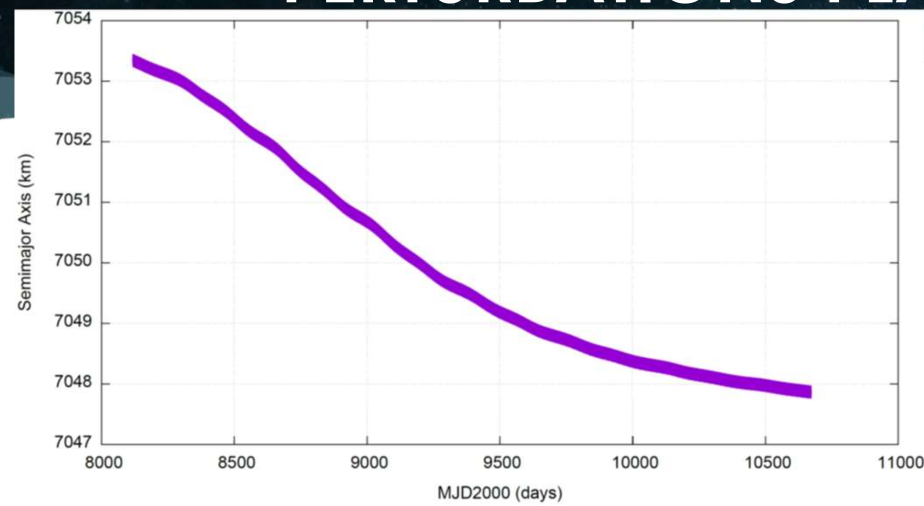


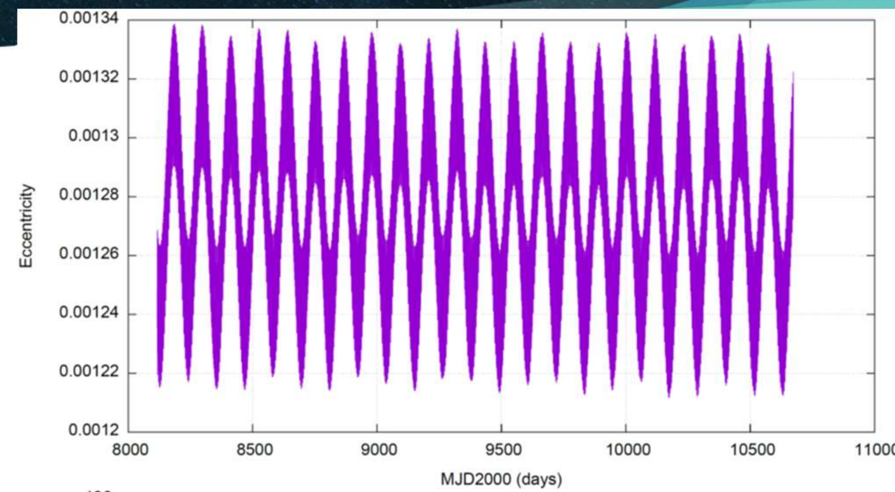


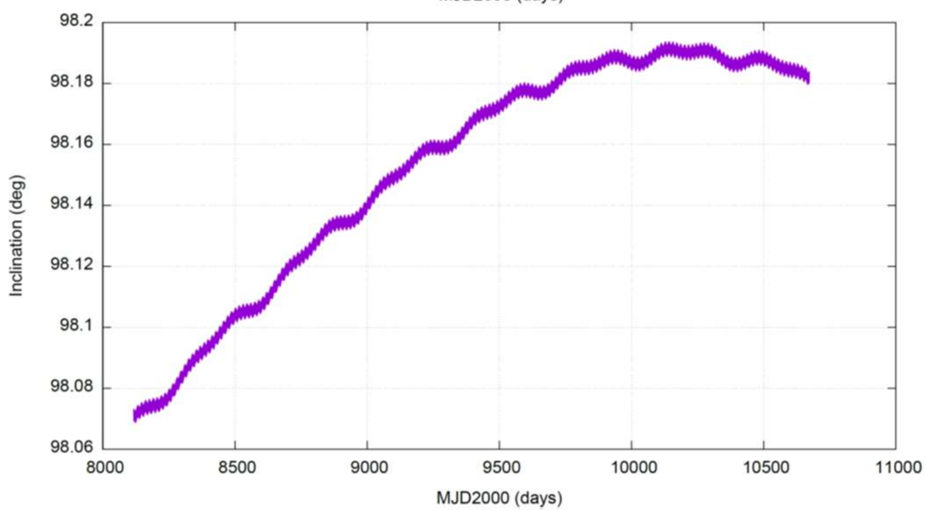


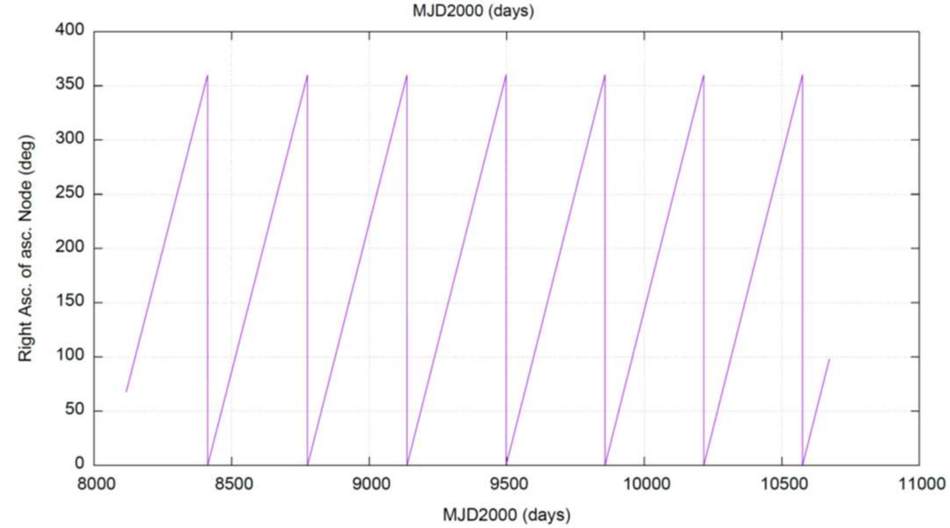


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #4

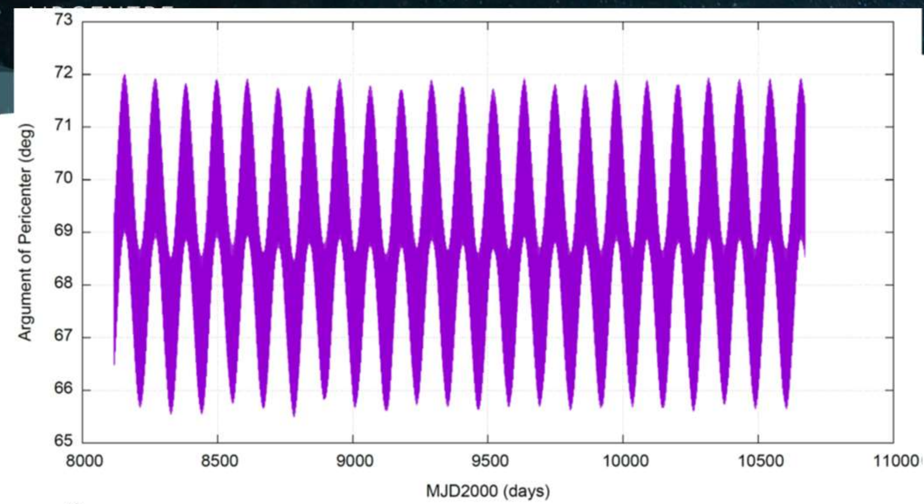


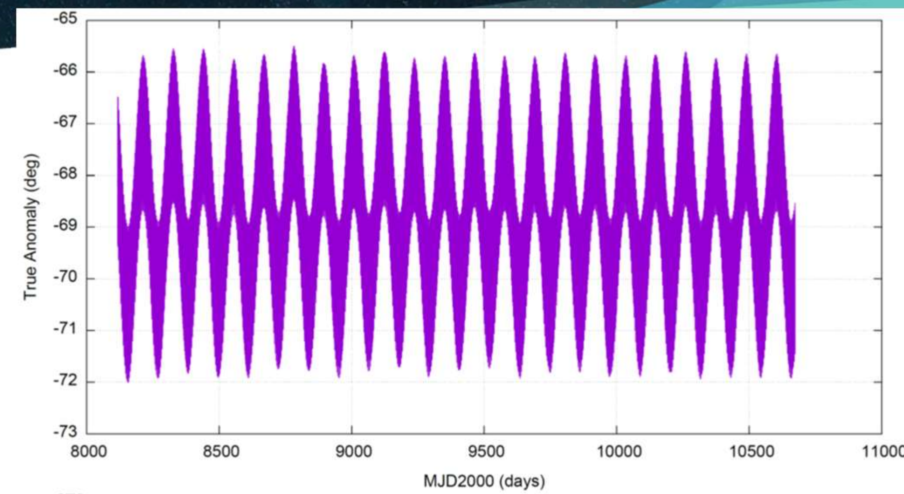


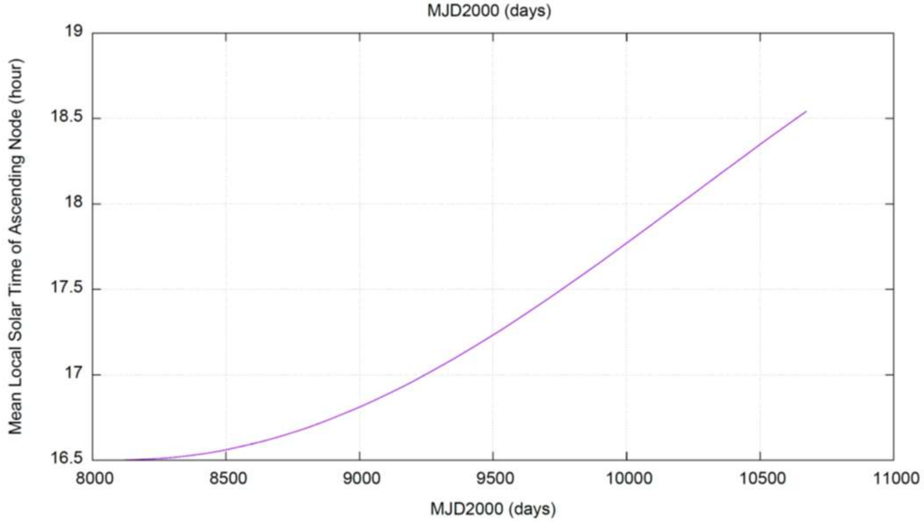


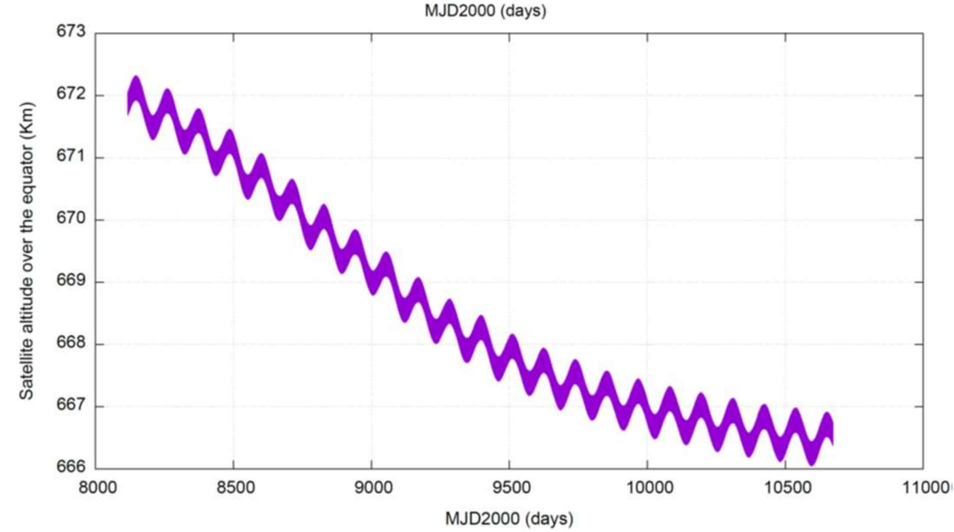


CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS PLANE #4









CONSTELLATION MISSION ANALYSIS: ORBITAL PERTURBATIONS CONCLUSIONS

- The main conclusions of this 7 year orbit perturbation analysis are:
  - **Semimajor axis:** there is an identical decay of about 5,5 km (for solar activity 50% percentile) in 7 years due to the atmospheric drag, this can be easily compensated by altitude control manoeuvres
  - **Eccentricity, argument of perigee and true anomaly at ascending node:** all satellite present periodic variation in those elements, but the amplitude is very small and there is no long term variation. The only effect is a periodic variation in the altitude over a given latitude of the order of 1km, that it is not important, therefore we do not perform correction manoeuvres for the variation of those elements.
  - **Orbital inclination:** this is the most complex perturbation as it is different for each orital plane and produce a differential rotation of the orbital planes. In plane #1 the inclination decreases 0.15º moving the plane anticlockwise such that the mean local solar time moves from 7:30 to 5:55 (night side); plane #2 decreases the inclination 0.27º moving the plane anticlockwise and the MLST from 10:30 to 8:10; plane #3 increases the inclination 0.27º moving the plane clockwise and the MLST from 13:30 to 16:25 and plane #4 increases the inclination 0.12º moving the plane clockwise and the MLST from 16:30 to 18:30 (also at night side). Those perturbations can not be tolerated as they destroy the configuration of the constellation, on the other hand we can not correct them by manouevres as plane change manoeuvres are very expensive. They way to deal with this perturbation is by introducing biases (small deviations) in the target inclination and MLST of the orbits in a differential way such that the variations are within reasonable limits.

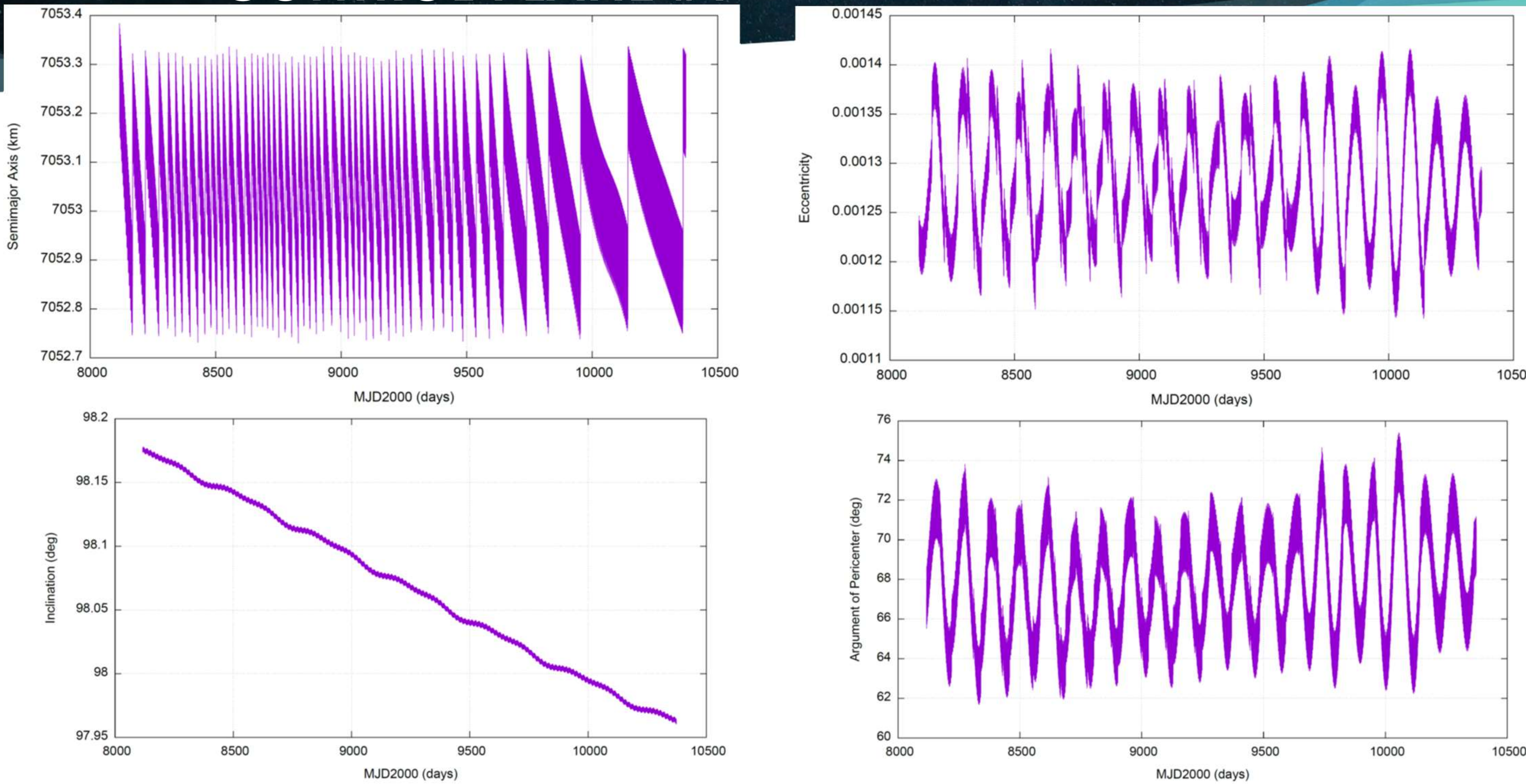
CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL

- For the analysis of the propulsion system we must calculate the total propellant budget that shall consider:
  - **Launcher dispersion error correction:** all launchers inject into the final orbit with some level accuracy, the correction of those error depends on the selected launcher and a 3-sigma error value must be negotiated in the launch contract
  - **Constellation deployment:** all satellite for an orbital plane shall be deployed together, there is a need to manoeuvre to separate them and distribute them along the orbit, this is done in the first days of operation
  - **Orbital maintenance:** orbit perturbations must be compensated by orbit control manoeuvres, normally at least the drag effect is compensated to keep the nominal orbital altitude
  - **Constellation maintenance:** the relative situation of the satellites in the orbital plane and with respect to satellites in other plane must be kept in order to provide always optimum performance
  - **Collision avoidance manoeuvres**: evasion manoeuvres to avoid collision with space debris or other orbiting objects are every day more frequent, as a design parameter, at least 1 collision avoidance manieuvre shall be considered every 6 months of operation per each satellite
  - **Final end of life disposal maneuvre**: it is important to be compliant with international space debris standards, for this reason at the end of the life of the satellites we must perform a disposal manoeuvre to ensure that the satellite shall re-enter the Earth atmosphere in less than 25 years

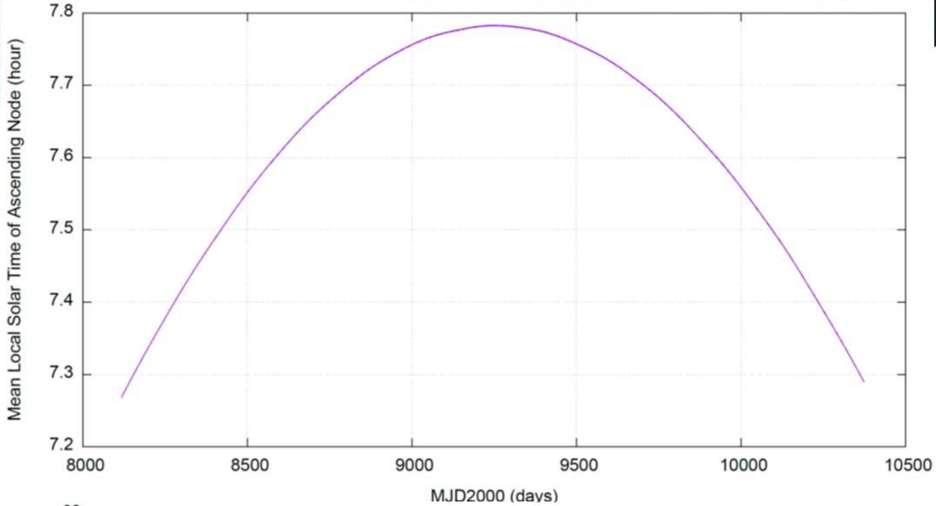
CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL

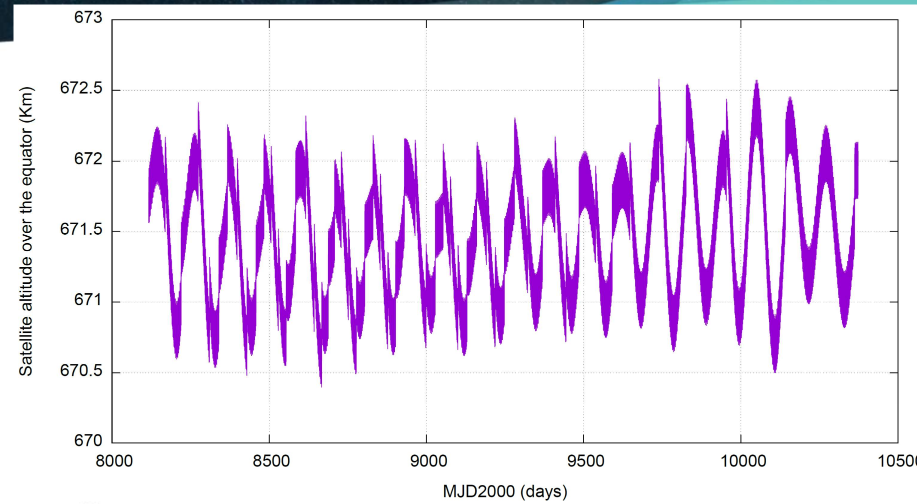
- Taking into account the previous perturbation analysis we shall implement an orbit control strategy:
  - **Propulsion system:** we consider a propulsion system with a thrust of 10 mN, a maximum manoeuvre duration of 300 sec and two options:electric propulsion with specific impulse of 1000 sec or cold gas system with specific impulse of 100 sec
  - **Altitude correction manoeuvres:** once the semimajor axis of a given satellite fall bellow a threshold value a manoeuvre is performed at the North or South pole (optimum power) to raise its value
  - **Passive control of Inclination and MLST:** we calculate small corrections (biases) in the initial inclination and right ascension of the ascending node for all satellites, such that the variations of above pameters keep the value of the MLST in a narrow band during 7 years of operations, independent calculations must be done for each orbital plane
- This strategy is successfully presented in the next slides for a satellite in each orbital plane
- The evolution of the most important parameter with time, along the 7 years of operations is also presented

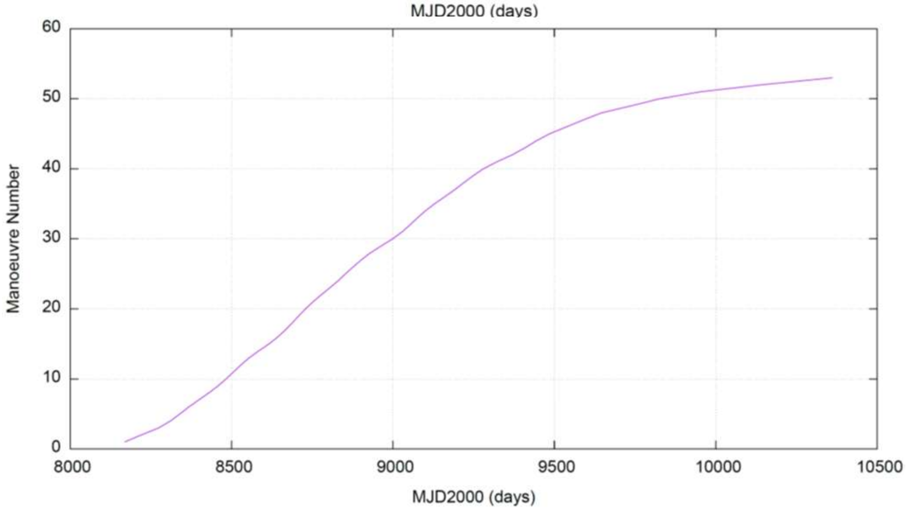
CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #1

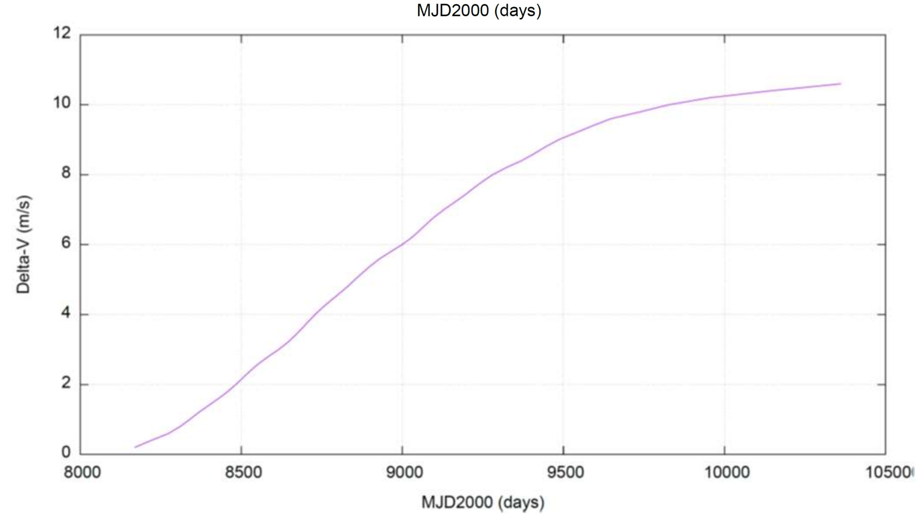


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #1

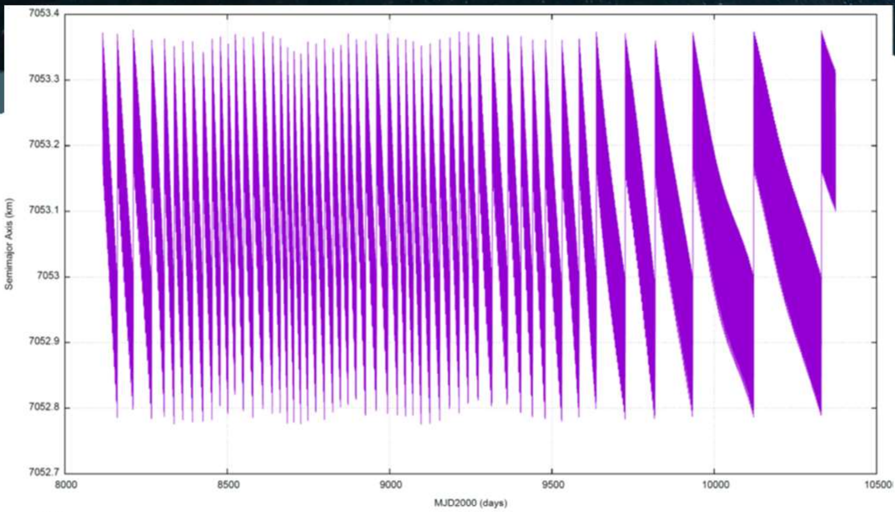


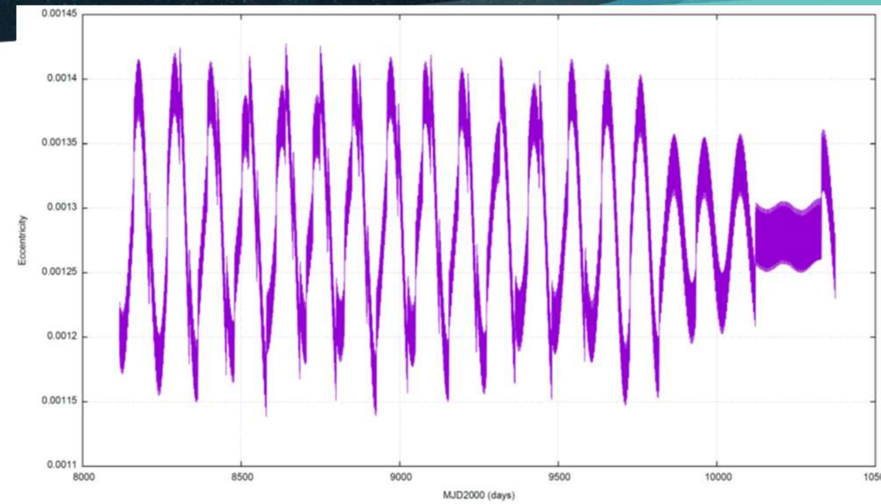


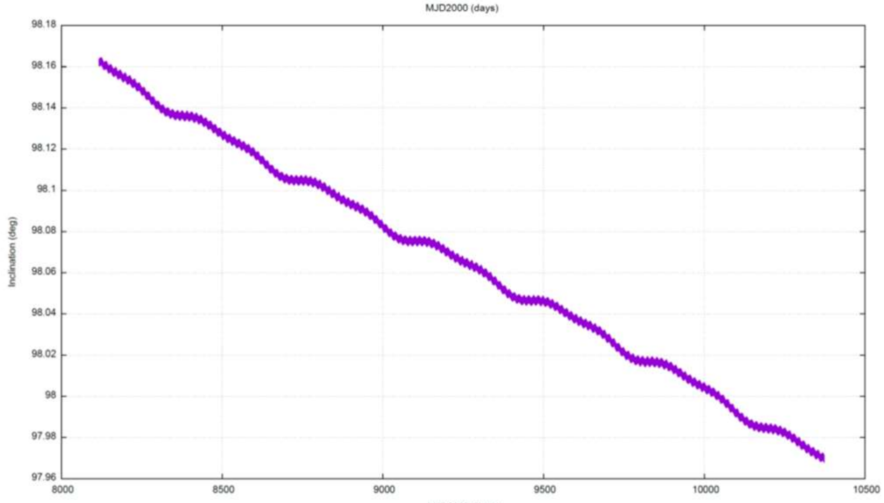


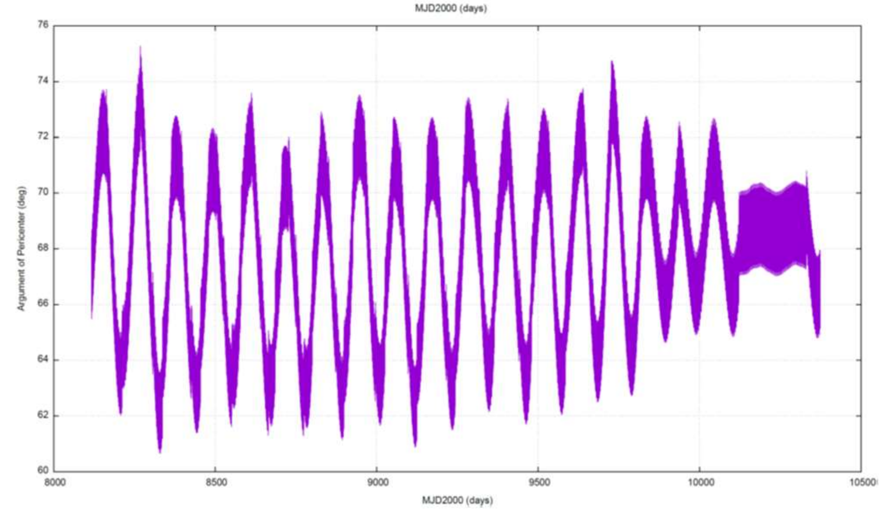


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #2

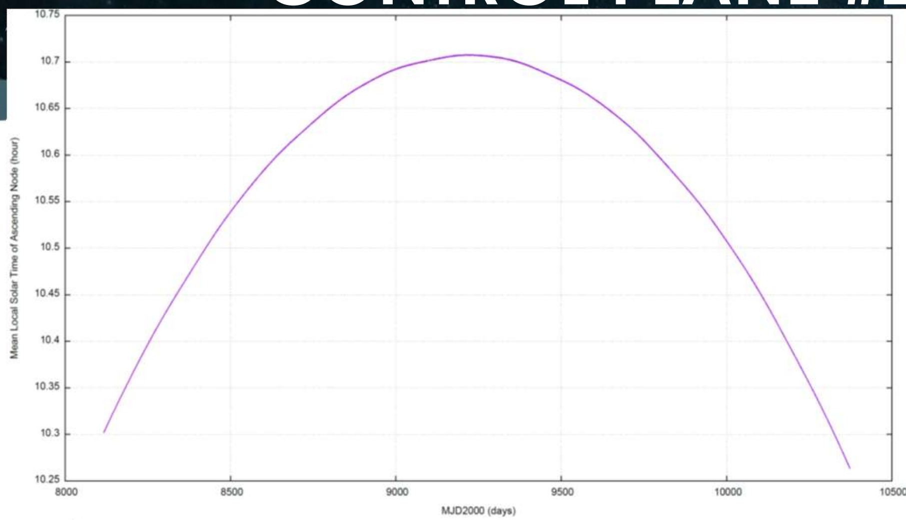


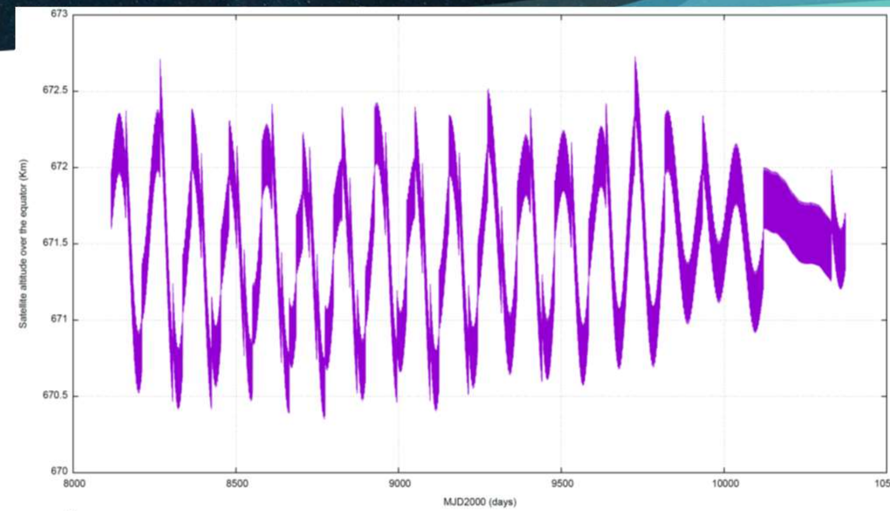


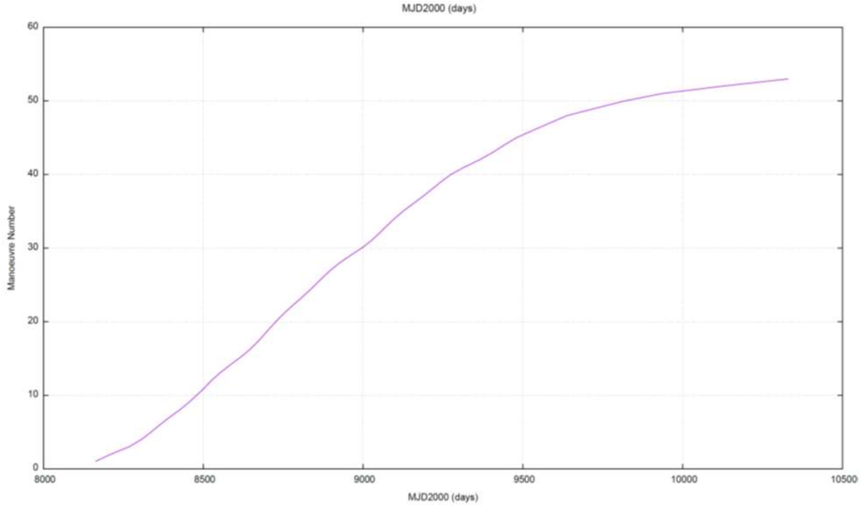


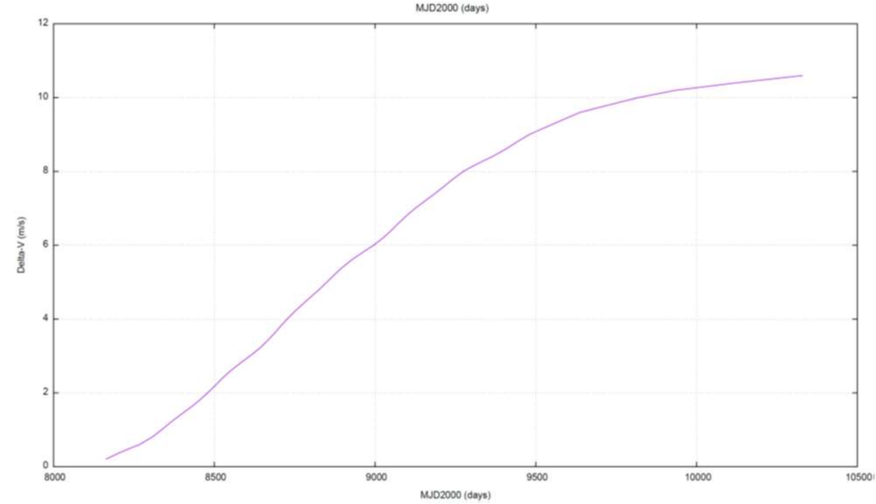


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #2

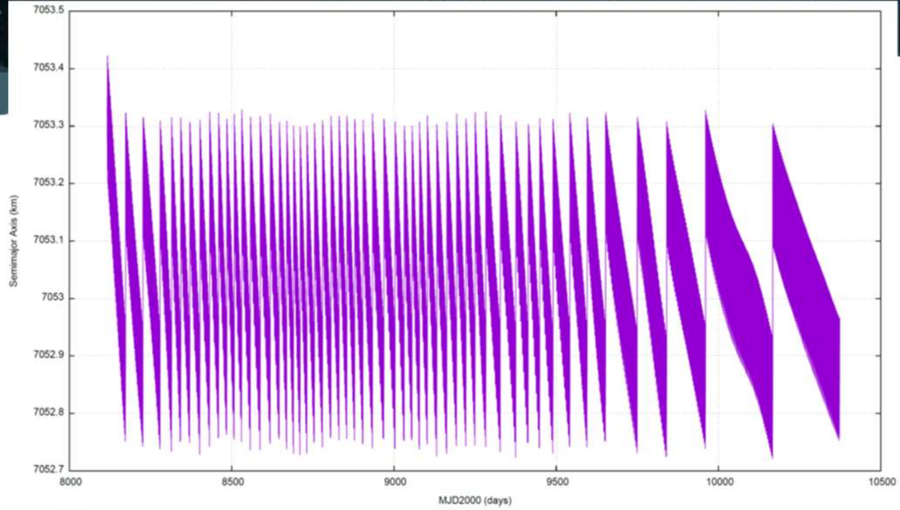


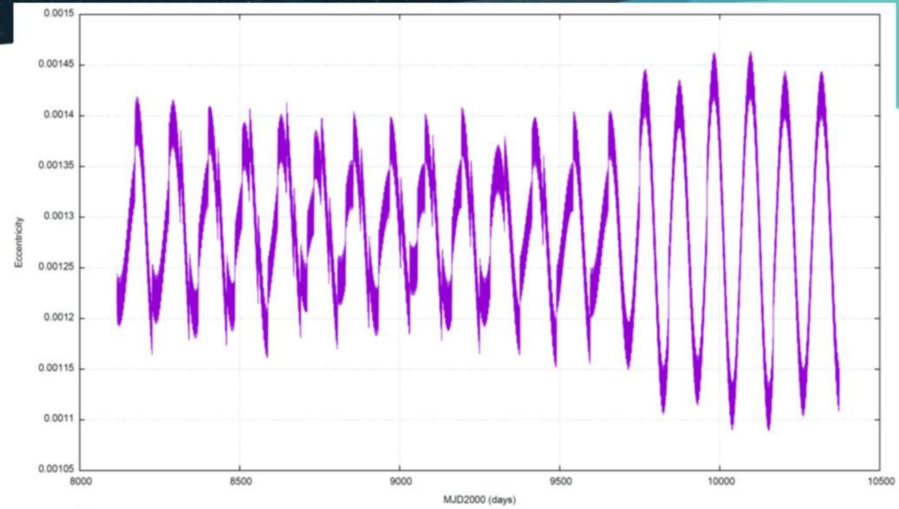


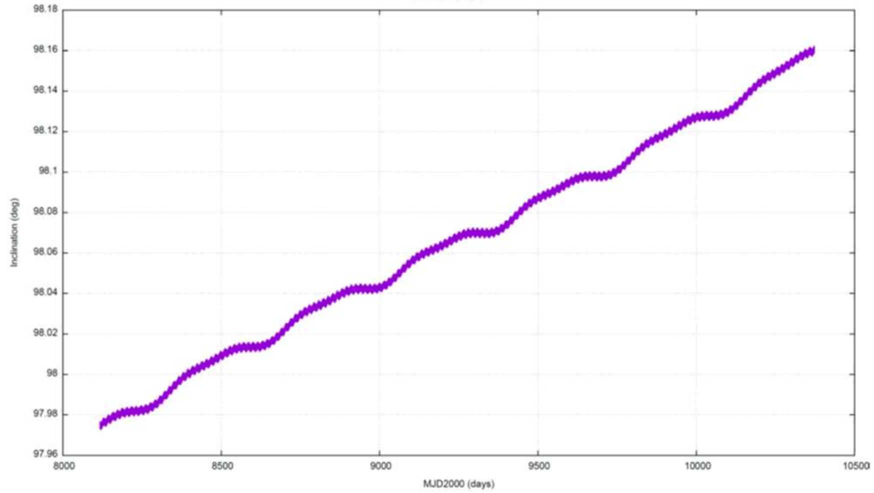


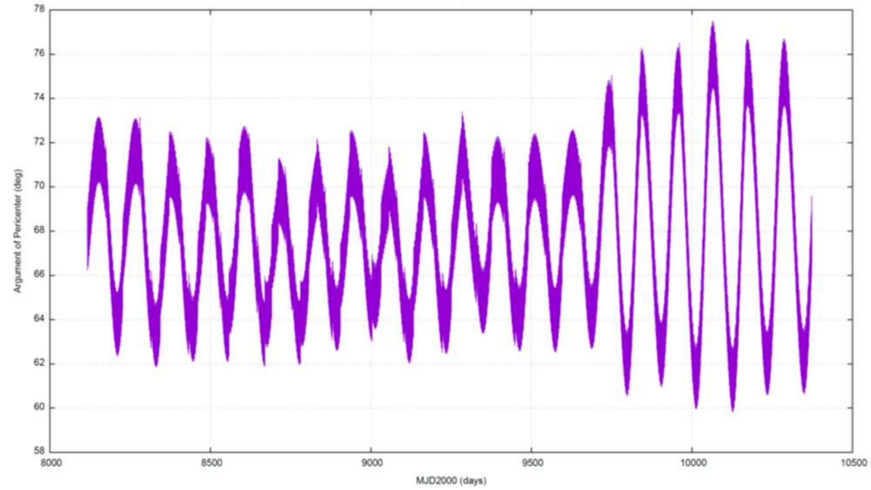


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #3

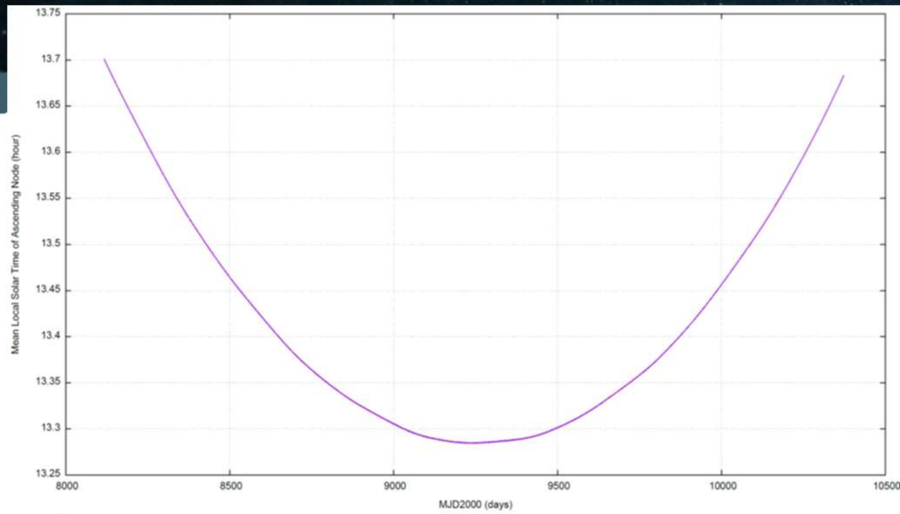


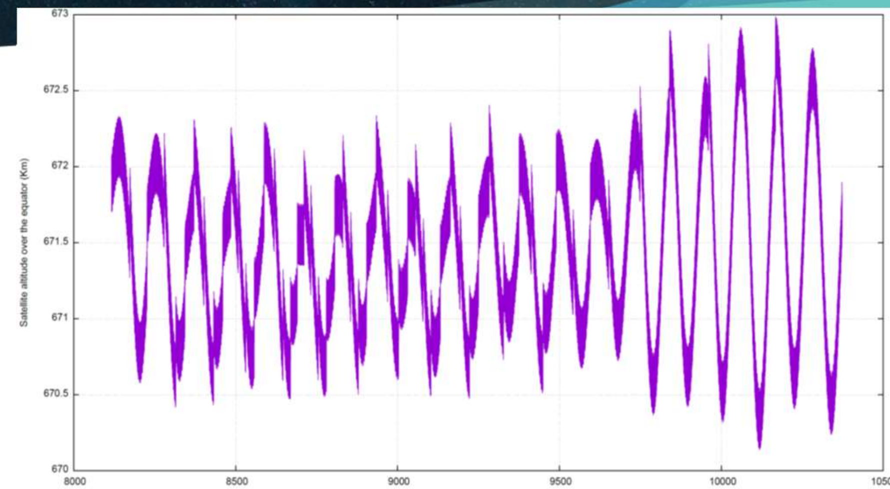


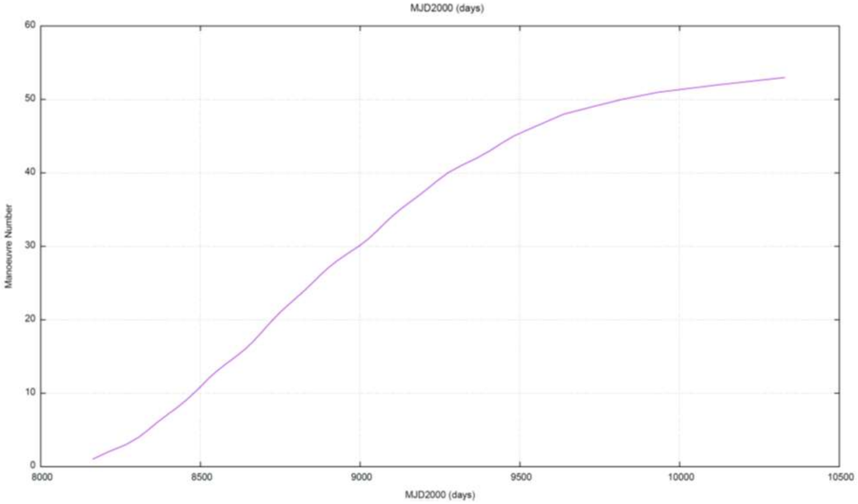


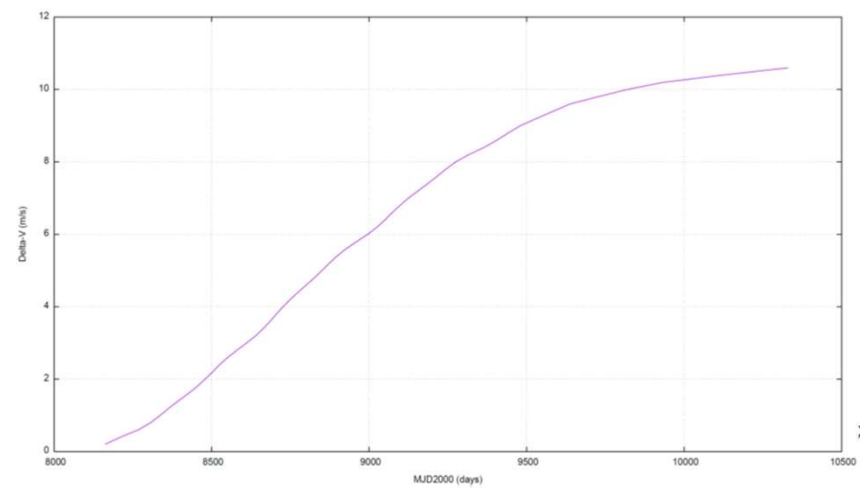


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #3

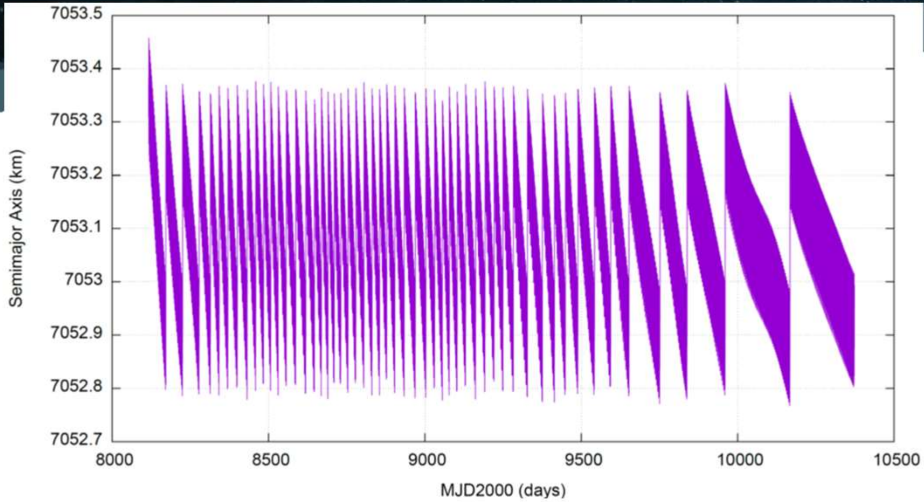


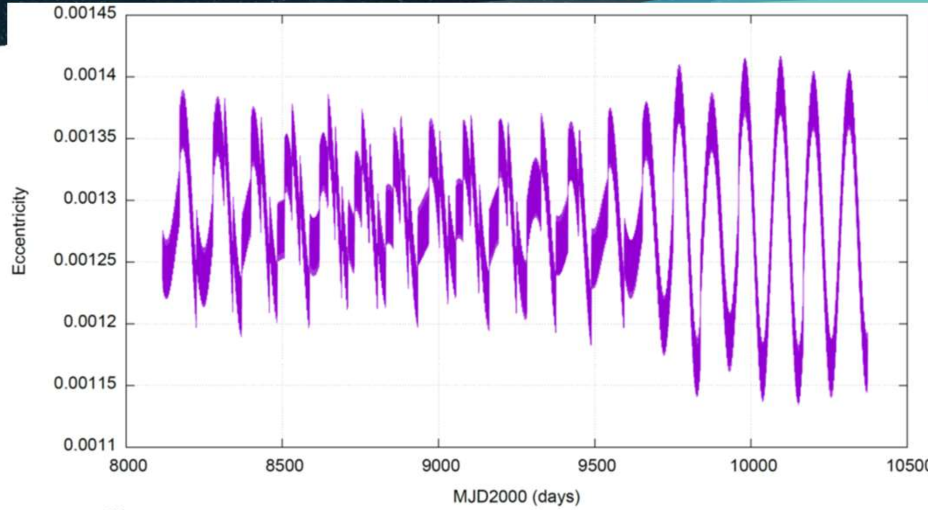


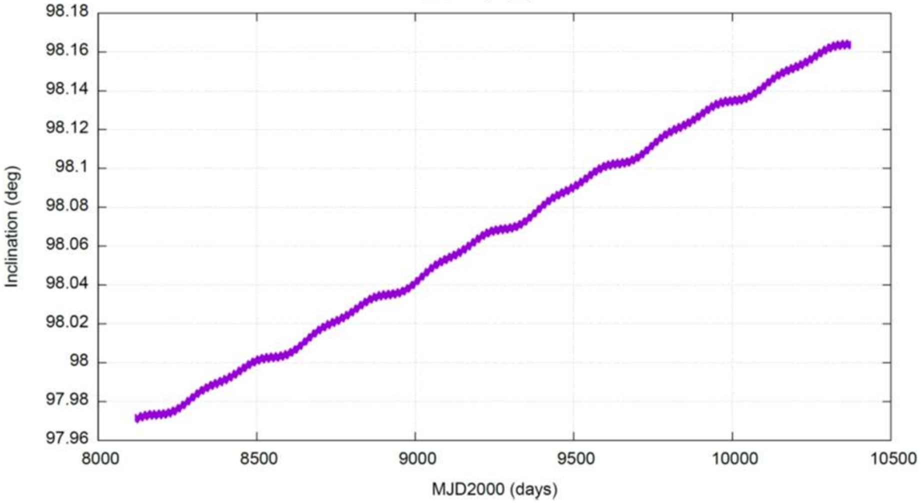


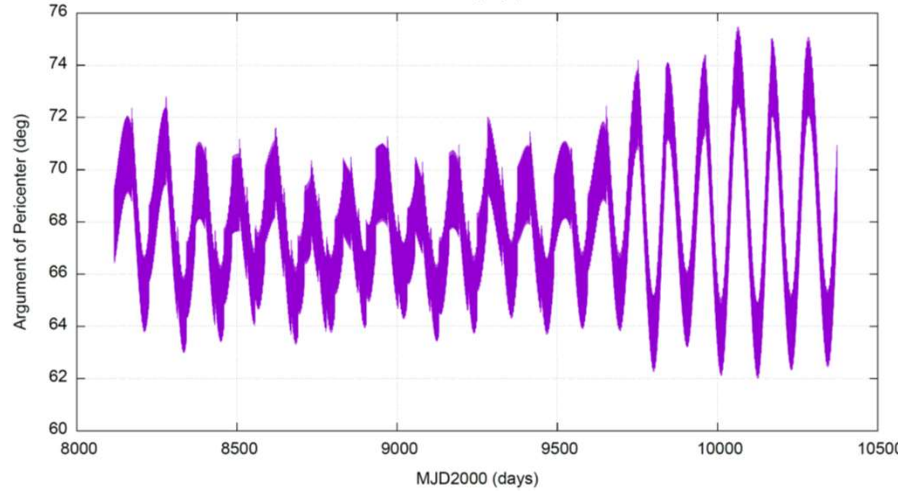


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #4

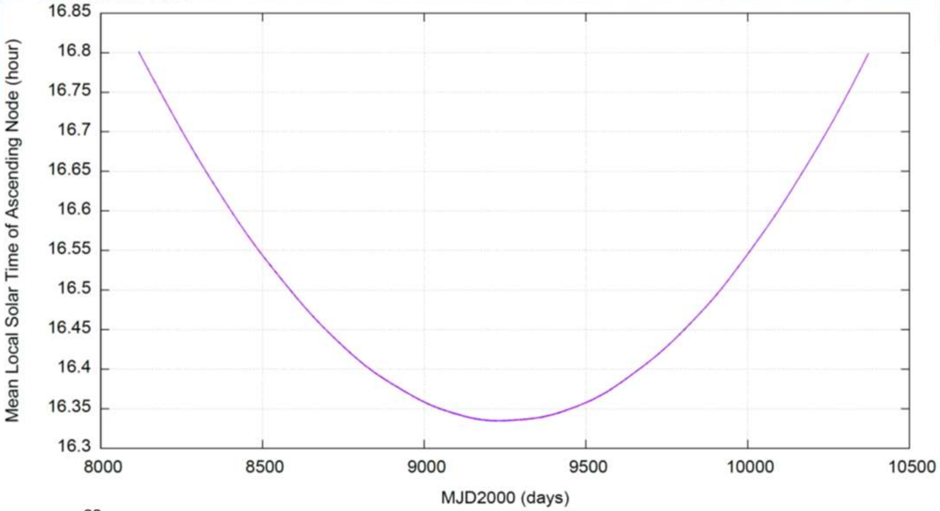


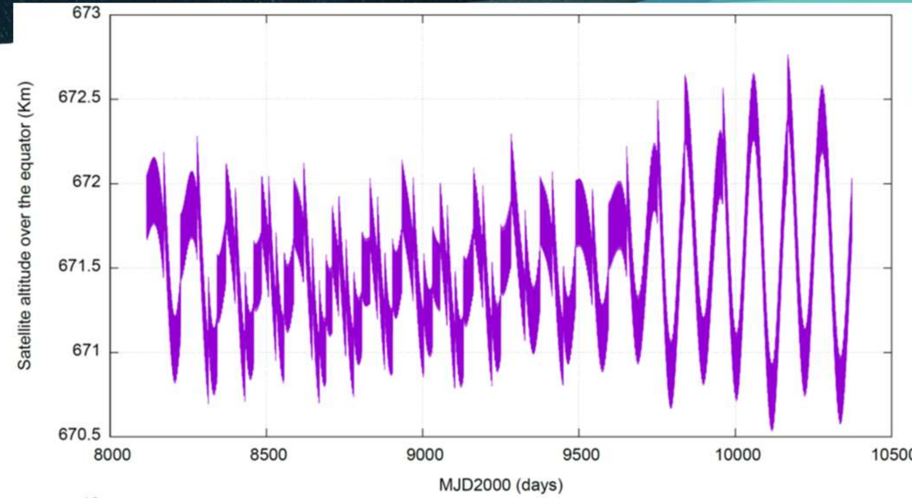


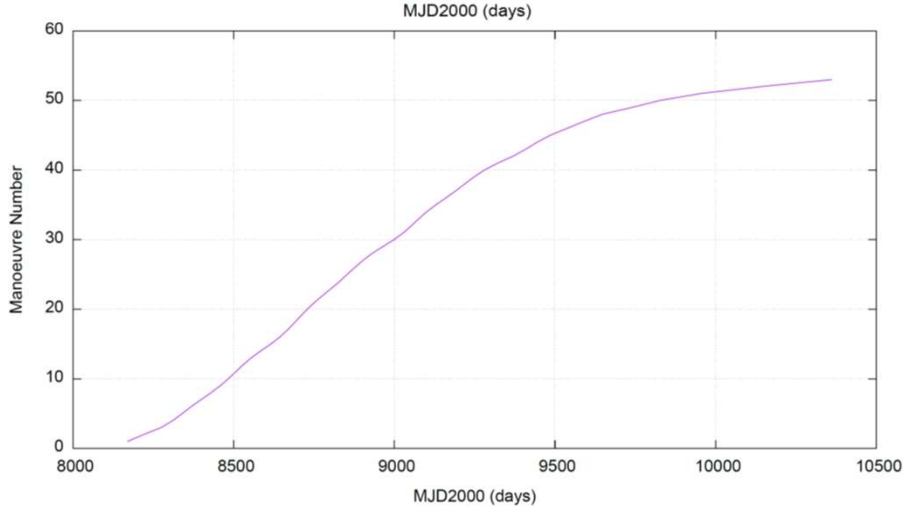


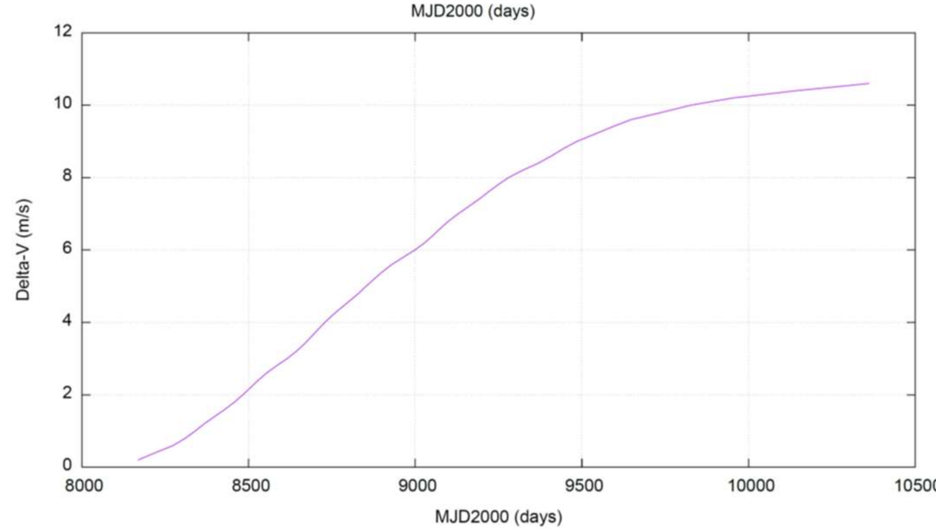


CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL PLANE #4









CONSTELLATION MISSION ANALYSIS: ORBITAL CONTROL CONCLUSIONS

- A successful orbit control strategy has been implemented for all satellites in the constellation:
  - **Altitude control:** an altitude control manoeuvre (300 seconds with 10 mN thrust) is executed at the poles to maintain the nominal semimajor axis, the average time between manoeuvres is 48 days (20 days in peak of solar activity and 180 days in low solar activity), the required total **Delta-V is 10,6 m/s**, it is identical for all satellites in constellation as it was obtained with 95% percentile of solar activity
  - **Passive control of Inclination and MLST:** an effective passive control of the inclination and MLST is achieved by introducing some small variations (biases) in the initial orbital elements described in the table of page 33 such the MLST time moves during 7 years in a band of about +/- 15 minutes around the nominal values. The biases are the following (the new table of initial orbital parameters are in next page):

Bias	Orbital plane # 1	Orbital plane # 2	Orbital plane # 3	Orbital plane # 4
Delta-inclination (deg)	0,12º	0,094º	-0,094º	-0,10º
Delta- right asc. of asc. node	-3.5º	-3º	3º	4.5º

CONSTELLATION DESIGN: ORBITAL ELEMENTS OF ALL SATELLITES corrected by passive orbit control

- Osculating orbital elements in Mean Earth Equator of Day of the 16 satellites of the Atlantic Constellation on March 22st at 12h

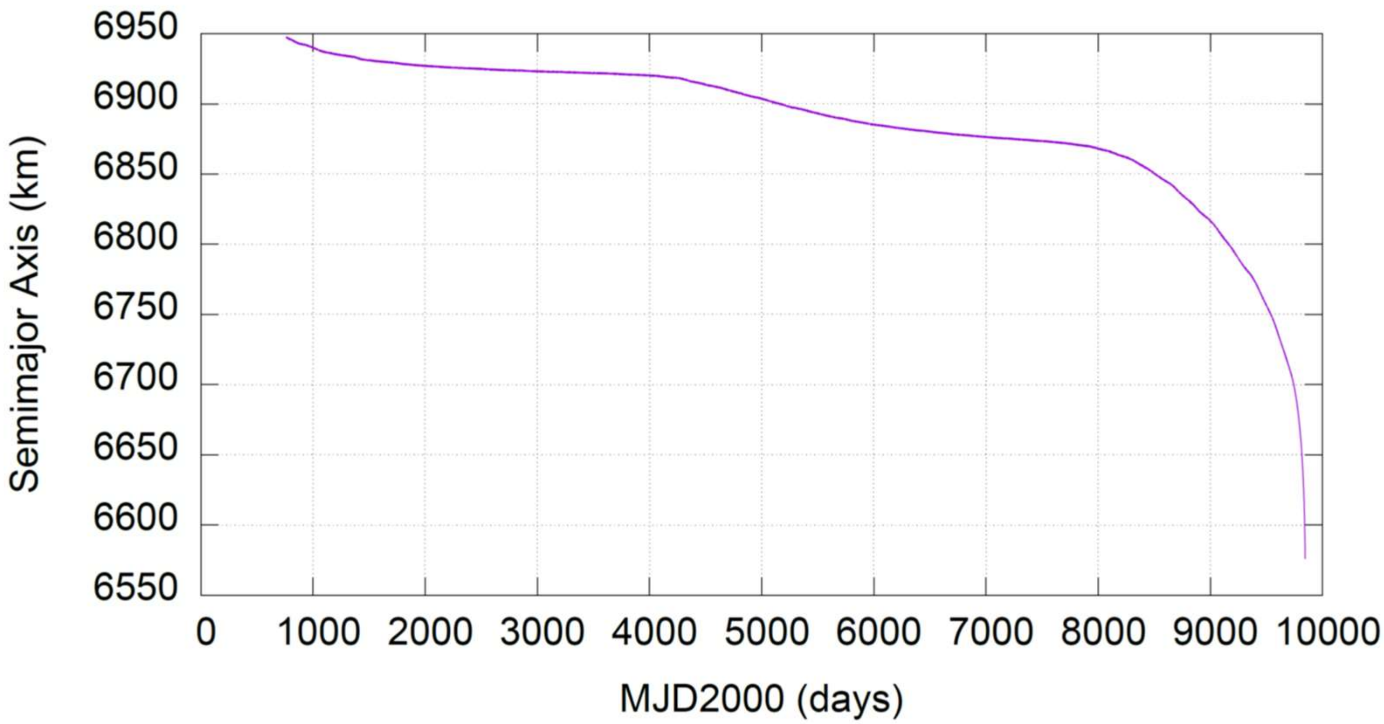
Orbital Plane #1				
	Satellite 1.1	Satellite 1.2	Satellite 1.3	Satellite 1.4
Semimajor axis km	7053.306	7034.919	7053.306	7034.919
Eccentricity	0.0012172	0.0005875	0.0028403	0.0028403
Inclination º	98.18968	98.20029	98.18968	98.20029
R.A. of Asc. Node º	289.0	289.0	289.0	289.0
Arg. Of Perigee º	67.7296	269.99901	112.27146	90.000257
Mean anomaly º	292.2704	180.00099	67.728589	179.99981

Orbital Plane #3				
	Satellite 3.1	Satellite 3.2	Satellite 3.3	Satellite 3.4
Semimajor axis km	7053.306	7034.919	7053.306	7034.919
Eccentricity	0.0012172	0.0005875	0.0028403	0.0028403
Inclination º	97.97568	97.09869	97.97568	97.98629
R.A. of Asc. Node º	25.5	25.5	25.5	25.5
Arg. Of Perigee º	67.7296	269.99901	112.27146	90.000257
Mean anomaly º	292.2704	180.00099	67.728589	179.99981

Orbital Plane #2				
	Satellite 2.1	Satellite 2.2	Satellite 2.3	Satellite 2.4
Semimajor axis km	7044.1176	7044.1128	7044.1126	7044.113
Eccentricity	0.0012435	0.0012432	0.001468	0.001468
Inclination º	98.168981	98.168988	98.168998	98.168985
R.A. of Asc. Node º	334.5	334.5	334.5	334.5
Arg. Of Perigee º	127.15705	52.814007	59.310088	120.69068
Mean anomaly º	277.8834	82.130714	165.74531	194.25423

Orbital Plane #4				
	Satellite 4.1	Satellite 4.2	Satellite 4.3	Satellite 4.4
Semimajor axis km	7044.1176	7044.1128	7044.1126	7044.113
Eccentricity	0.0012435	0.0012432	0.001468	0.001468
Inclination º	97.974981	97.974988	97.974998	97.974985
R.A. of Asc. Node º	72.0	72.0	72.0	72.0
Arg. Of Perigee º	127.15705	52.814007	59.310088	120.69068
Mean anomaly º	277.8834	82.130714	165.74531	194.25423

CONSTELLATION MISSION ANALYSIS: END OF LIFE DISPOSAL



- At the end of life for each satellite, a disposal manoeuvre is performed to reach an orbit that guarantees a maximum of 25 years to re-entry in the atmosphere as stated in the space debris mitigation standards
- A manoeuvre of 52 m/s is needed to reduce the semimajor axis from 7044 km down to 6948 km
- From that orbit, as shown in this plot, the satellite shall decay and enter the atmosphere in 25 years

CONSTELLATION MISSION ANALYSIS: TOTAL DELTA-V MARGIN AND PROPELLANT MASS

- After above analysis the total delta-V budget can be summarized as follows:
  - **Launcher dispersion error correction and constellation deployment:** the required Delta-V depends on the launcher, but for a typical launch (Dnper) this value (with 3 sigma criterion) is **20 m/s**
  - **Altitude control:** as previously seen this value (95% percentile solar activity) is **10,6 m/s**
  - **Collision avoidance manoeuvres**: assuming one maoeuvre every 6 months (14 in total) and a Delta-V of 0,2 m/s, the budget for 7 years is **2,8 m/s**
  - **Final end of life disposal manoeuvre**: the required Delta-V to ensure a re-entry in 25 years is **52 m/s**
- In summary the total required Delta-V at each satellite is **85,4 m/s**
- If we are using a low thrust electric propulsion system with specific impulse of 1000 sec, then the required propellant mass is only **0,13 kg**
- However if we are using a cold gas propulsion system with specific impulse of 100 sec, then the required propellant mass is **1,25 kg**

CONCLUSIONS

- The **Atlantic Constellation** is part of the **Atlantic Pole to Pole Observation System of System (APPOSS)** as a framework where all the different sensors, infrastructures, data, algorithm and models used at the AIR Centre are included
- This document presents a list of **user needs**, the corresponding **measurements** to serve those requirements and the selected list of **instruments** that can provide those measurements taking into account complementarity with Sentinels satellites of Copernicus and the limit of a small satellite platform
- Two set of instruments are selected: optical (MS and HS cameras) and conical (AIS, ADSB) with the corresponding requirements (global mean revisit < 3h, latency<1 h, mean AIS gap<15 min)
- Based on above requirements the Atlantic constellation is designed
- The result is a **16 satellites** (4 satellites in 4 planes) in SSO frozen orbits with 675 km altitude and MLST at ascending node at 7:30, 10:30, 13:30 and 16:30 in a classical Walker Delta Pattern constellation scheme
- A full analysis of coverage, revisit time and AIS gap performance demonstrate the validity of the selected constellation design
- Assuming **12U size** and **15 kg mass**, the ground segment, power analysis, Delta-V budget and orbit control strategies are also considered in this study