The *LUVOIR* Architecture "A" Coronagraph Instrument

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Introduction

In preparation for the Astro 2020 Decadal Survey, NASA has commissioned the study of four flagship missions spanning a wide range of observable wavelengths: the *Origins Space Telescope* (*OST*, formerly the *Far-Infrared Surveyor*), *Lynx* (formerly the *X-ray Surveyor*), the *Large UV/Optical/Infrared Surveyor* (*LUVOIR*) and the *Habitable Exoplanet Imager* (*HabEx*). One of the key scientific objectives of the latter two missions is the detection and characterization of the Earth-like planets around nearby stars using the direct imaging technique (along with a broad range of investigations regarding the architecture of and atmospheric composition of exoplanetary systems). Dedicated exoplanet imaging instruments are being studied for these mission concepts.

Here we present a status update of the coronagraph instrument for the architecture "A" of the *Large Ultra Violet Optical and near Infra Red Surveyor*. The *LUVOIR* STDT (Science and Technology Definition team) has decided to put forth for evaluation two mission architectures that bracket a range of options of varying capability, cost, and risk. Architecture "A" is the larger of these two concepts, with a 15-meter diameter primary mirror that maximizes science yield, while accepting moderate technical and programmatic risk. The *LUVOIR* coronagraph optical, mechanical, thermal, and electrical design was completed in April 2017 by the meticulous GSFC Instrument Design Laboratory team, based on inputs from a community working group that discussed the instrument's basic parameters for over four months. The key technologies featured in this instrument are being matured at the Institute's own Russell B. Makidon Optics laboratory. The optical layout was then disseminated to technologists who optimized coronagraph masks for this architecture. Two of these teams were led by Institute staff.

Exoplanetary science enabled by *LUVOIR* architecture "A"

The *LUVOIR* architecture "A" corresponds to the largest aperture that can be packed into a NASA Space Launch System Block 2 heavy-lift vehicle (SLS: NASA 2015). Because of this large aperture, it is the most ambitious exo-Earth imaging platform studied in detail by NASA to date. The ambitious philosophy underlying architecture "A" is a consequence of and commensurate with the scientific goals for the coronagraphic instrument. Goals are organized around two key science themes: (1) measuring the occurrence rate of biomarkers in the atmosphere of rocky planets orbiting in the Habitable Zone (HZ) of their host stars, and (2) studying the broader diversity of exo-planetary systems (giant planets, circumstellar disks). Note that the first scientific theme is significantly more stressing on the instrument, and is the driver underlying the design decisions for *LUVOIR* architecture "A" coronagraph. As discussed in Stark et al. (2015), any mission aimed at measuring the occurrence rate of biomarkers in the atmosphere of nearby HZ rocky planets, should first be capable of detecting a statically significant ensemble of exo-Earth candidates. This is one of the main drivers of the large aperture for *LUVOIR* Architecture "A" and the instrument concept is developed with the following broad parameters:

- The exo-Earth detection will be carried out at visible wavelengths (the baseline wavelength for detection is 600 nm). At this wavelength, the coronagraphs are designed with starlight suppressions smaller than 10^{-10} in a region that encompasses at least 75% of the HZ real estate for stars within 50 pc of the Sun.
- Under these starlight suppression constraints , the integrated planet light transmissions will be maximized.
- Also wavelength coverage, from the UV to the near IR, will be maximized in order to characterize the detected exoplanets as thoroughly as possible.

The characterization of identified exo-Earth candidates is equally as important as their detection. Figure 1 shows a simulated spectrum of a mature earth, along with an 2 Gyrs old Archean earth, generated with the *LUVOIR* STDT online exoplanet spectrum simulation tool, using the underlying models by Arney et al. (2017) and Robinson (2017). This example illustrates the most salient characteristics of the atmosphere of Earth analogs sought to characterize with great precision and translate into three requirements on the back end spectrograph: (1) Continuous spectral coverage from 200 nm to 2.5μm in order to capture most spectral features associated with carbon- and oxygen-based molecules, (2) resolution of 30 from 200 to 400 nm and of at least 150 (and above 1000 if possible) in the optical and near-IR. Note that because of the telescope operating at ~270K as discussed in Bolcar et al. (2017), spectroscopy of faint exo-Earths beyond 1.6 μm will be limited to the closest target due to thermal background. However, redder spectral coverage will be invaluable for studying in detail the atmosphere of our nearest neighbors (along with characterizing larger planets).

Instrument

The *LUVOIR* architecture "A" coronagraph is a highly complex instrument due to the need for continuous spectral coverage from 200 nm to 2.5μm. In order to accommodate the variety of high reflectivity coatings and detector technologies that span this large a wavelength range, the instrument is split into three channels that cover the following bandpasses: UV (200 to 400 nm), optical (400 nm to 850 nm) and Infra-Red (IR, 850 nm to 2.5 microns). Each channel is equipped with two Deformable Mirrors (DMs) for wavefront control, a suite of coronagraph masks, a low-order wavefront sensor, and separate science imagers and spectrographs. Because wavefront control can only be practically achieved over finite bandpasses as currently demonstrated in the *WFIRST* testbeds (Cady et al. 2016), each channel is split into multiple bandpasses that can be sequentially selected using a filter wheel mechanism. As a consequence, while the three channels can operate in parallel, each channel can only observe in one bandpass at a time. This has an impact on observing efficiency. The detector technologies are specific to each channel and our baseline choices heavily rely on technology that has been used on previous missions or planned in the *WFIRST* baseline instruments.

Spectroscopy is not required at UV wavelengths and the UV imager (field of view 1.4" x 1.4" squared) is the only science detector there. Both an imager and spectrograph are required for the optical and IR channels. The respective fields of view of the imagers are 2.7" x 2.7" and 5.6" x 5.6". These sizes are larger than the angular extent of the HZ for most targets, in order to enable the detection and characterization of outer planets in the exosolar systems detected. For the optical and IR spectrographs, the studies considered the feasibility of both Integral Field Spectrographs (IFSs), such as the ones installed on ground-based instruments and *WFIRST*, and fiber-fed high-resolution spectrographs currently being studied for ground-based instruments. After careful consideration, we chose the latter as the primary spectrograph for the exoplanet imaging of *LUVOIR* architecture "A", which was mostly driven by scientific goals, in spite of its relative technological youth when compared to IFS. Indeed, it was the only design that could obtain both low and high resolution of Earth analogs, along with being able to characterize a wide variety of other type of planets (including outer planets).

Also, a variety of solutions were considered for coronagraph masks and the decision was made to study two of them in depth. A conservative design that is robust to misalignments, stellar angular size, and whose mask technology will be matured by *WFIRST*, is the binary Apodized Pupil Lyot Coronagraph (APLC) (N'Diaye et al. 2016; Zimmerman et al. 2016), along with a more aggressive phase mask design which will improve science performance, but is less robust and mature (Mawet et al. 2009, 2011). The design work for both solutions was spearheaded over the past couple of years at the Institute (N'Diaye et al. 2016; Zimmerman et al. 2016; Pueyo et al. 2013; Mazoyer et al. 2017a,b). Representative masks for these two solutions are shown in Figures 2 and 3. Included are robustness to pupil misalignments: at the 10^{10} contrast the planet transmissivity is of the order of the preliminary solutions presented in N'Diaye et al. (2016). For more aggressive designs, the two DMs that are in the instrument are used for wavefront control purposes to compensate for the discontinuities. However, because this design is very sensitive to stellar angular separation, it will not yield 10^{10} contrast for nearby stars (d < 10 pc); for those, the grayscale apodizer solution will be better suited. The choice of masks drives the overall scientific output of the coronagraph. Because the "Search for Life" objective is the most challenging, it is used as a fiducial to assess the quality of a particular design given a mission lifetime and a survey strategy. Note that the *LUVOIR* Architecture "A" telescope pupil has been circulated to the community: the study team will also assess future contributions to coronagraph design that can be evaluated using a similar procedure.

Finally, the design of a high-yield static coronagraph is a necessary condition to a successful exo-Earth imaging instrument on the *LUVOIR* architecture "A" but it is not sufficient. Indeed, exquisite wavefront stability needs to occur in order for the contrast to remain at the 10^{10} level throughout the duration of the long exposures that are needed for exoplanet detection and characterization. The *LUVOIR* study team has adopted a three-pronged approach to address this problem: build robustness to misalignments within the coronagraph design; use the DMs to shape the static wavefront to reach the adequate contrast, even in the presence of wavefront errors (Shaklan et al. 2006; Pueyo et al. 2007; Trauger et al. 2007; Pueyo et al. 2009); stabilize the wavefront so that high contrast is maintained throughout science exposures, in spite of the presence of time-varying aberrations using a variety of optical and mechanical sensors. However, the system-level complexity remains a challenge of its own: that is exactly what the Institute's High-Contrast Imager for Complex-Aperture Telescopes (HiCAT) testbed will focus on over the next few years, while validating in parallel the actual coronagraph mask technologies for *LUVOIR*.

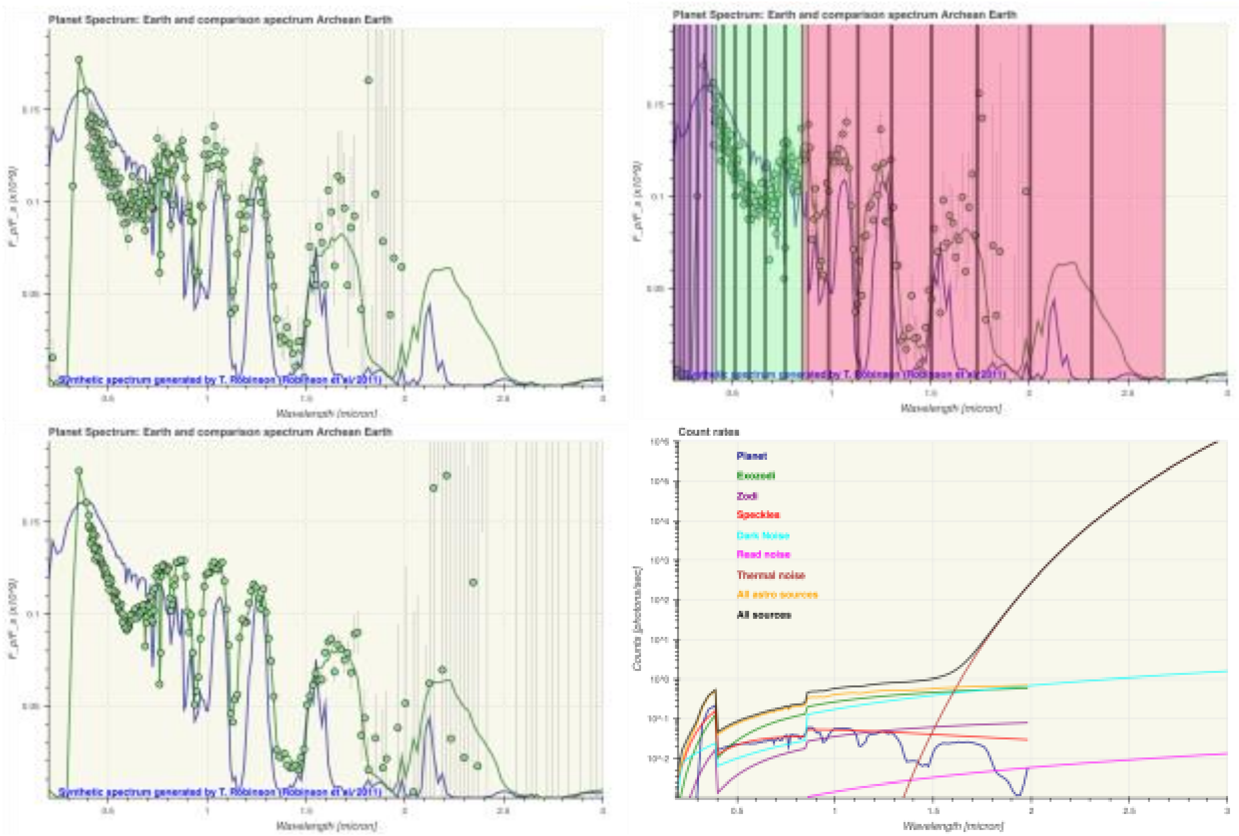

Figure 1: Simulations of the spectrum of an Earth-like planet seen by the *LUVOIR* Architecture "A" coronagraph for an exposure time of 24 hours per bandpass. The green dots with error bars correspond to the simulated data and the green line connecting them are the underlying simulated spectrum. The two spectra displayed correspond to models of a mature and an Archean earth (2 Gyrs), highlighting how the age of the observed eco-solar systems will impact the molecular features detected by *LUVOIR*. *Top Left*: Earth-like planet at 1 AU around a sun at 15 pc. *Bottom Left:* Earth-like planet at 1 AU around a sun at 7 pc. In both cases the data quality is sufficient to identify molecular absorptions that are able to ambiguously discriminate a mature earth from and Archean earth. *Top Right*: The bandpasses in each channel of the LUVOIR coronagraph are overlayed to the spectrum. UV, optical and IR channels can operate in parallel, however the bandpasses in each channel can only be operated sequentially. Thus, the observing time to obtain this spectrum would be on the order of a week. *Bottom Right:* wavelength-dependent noise budget associated with the 15 pc simulation. Longward of 1.6 μm the field thermal noise overwhelms the planet signal. These calculations were carried out with the *LUVOIR* exoplanet spectrum online tool.

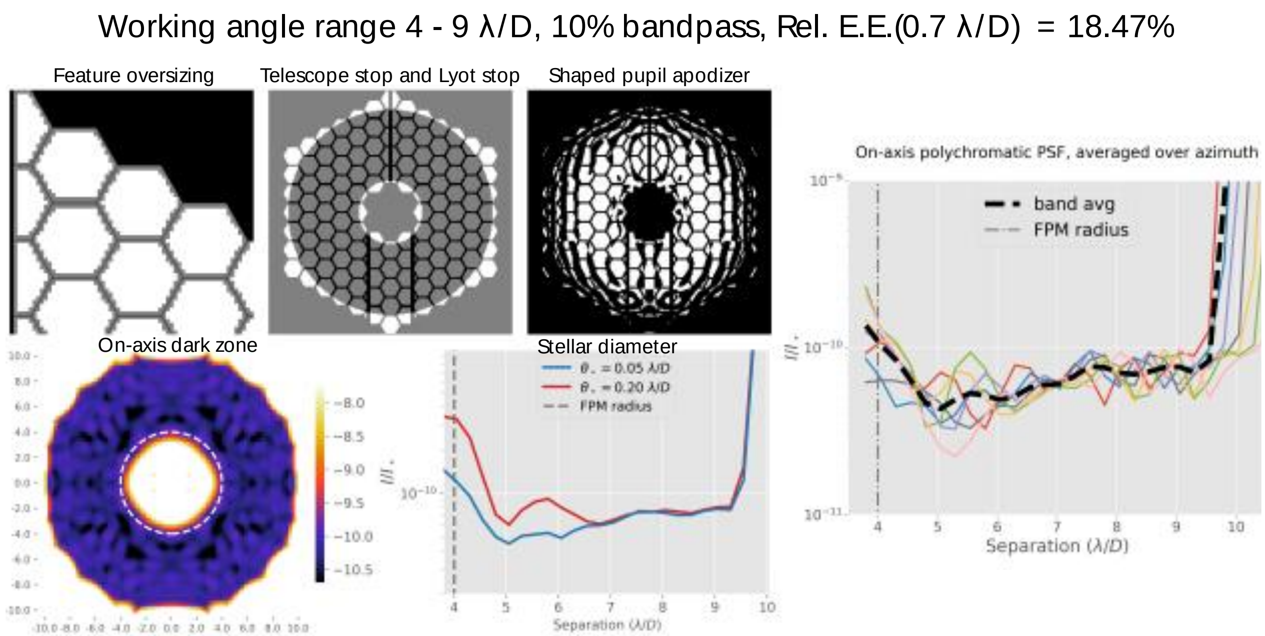

Figure 2: Coronagraph design for the *LUVOIR* Architecture "A" based on a hard edge focal plane mask and a binary apodizer. This coronagraph concept has been pioneered by Remi Soummer and his group and is currently being tested in the Institute's Makkidon Laboratory. This specific focal plane mask geometry would be used to search for exo-Earths in the optical around the most nearby stars. The top row describes in detail the assumptions of the telescope geometry that went into the coronagraph design. *Top, First Left:* the gaps between segment are oversized to account for potential misalignments between the telescope aperture and the coronagraph mask, *Top, Second from Left:* the field stop (also called Lyot Stop) where the coronagraph spans the circle inscribed in the segmented aperture, *Top, Third from Left*: aperture mask resulting from the coronagraph optimizations process, portions of the aperture are zeroed out in order to mitigate the impact of diffraction from the secondary, its support structures, and the segment gaps. The bottom row shows the resulting on-sky response of our design. *Bottom Left*: two-dimensional response featuring a Dark Zone where the starlight is rejected by ten orders of magnitude; in this area of the focal plane an exo-Earth can be identified orbiting its host star. *Bottom Second from Left*: azimuthal profile of this response for varying stellar angular size (with a 15 meter aperture, nearby stars are resolved and appear as disks instead of point sources). Even if our coronagraph was designed assuming that the host star is a point source, this shows that the results from our optimization is robust for resolving nearby stars. Finally, the *rightmost* panel shows the response of our design as a function of wavelength, demonstrating that this instrument can be used to characterize the spectrum of an exo-Earth over the bandpasses defined on Figure 1. Courtesy of N. Zimmerman.

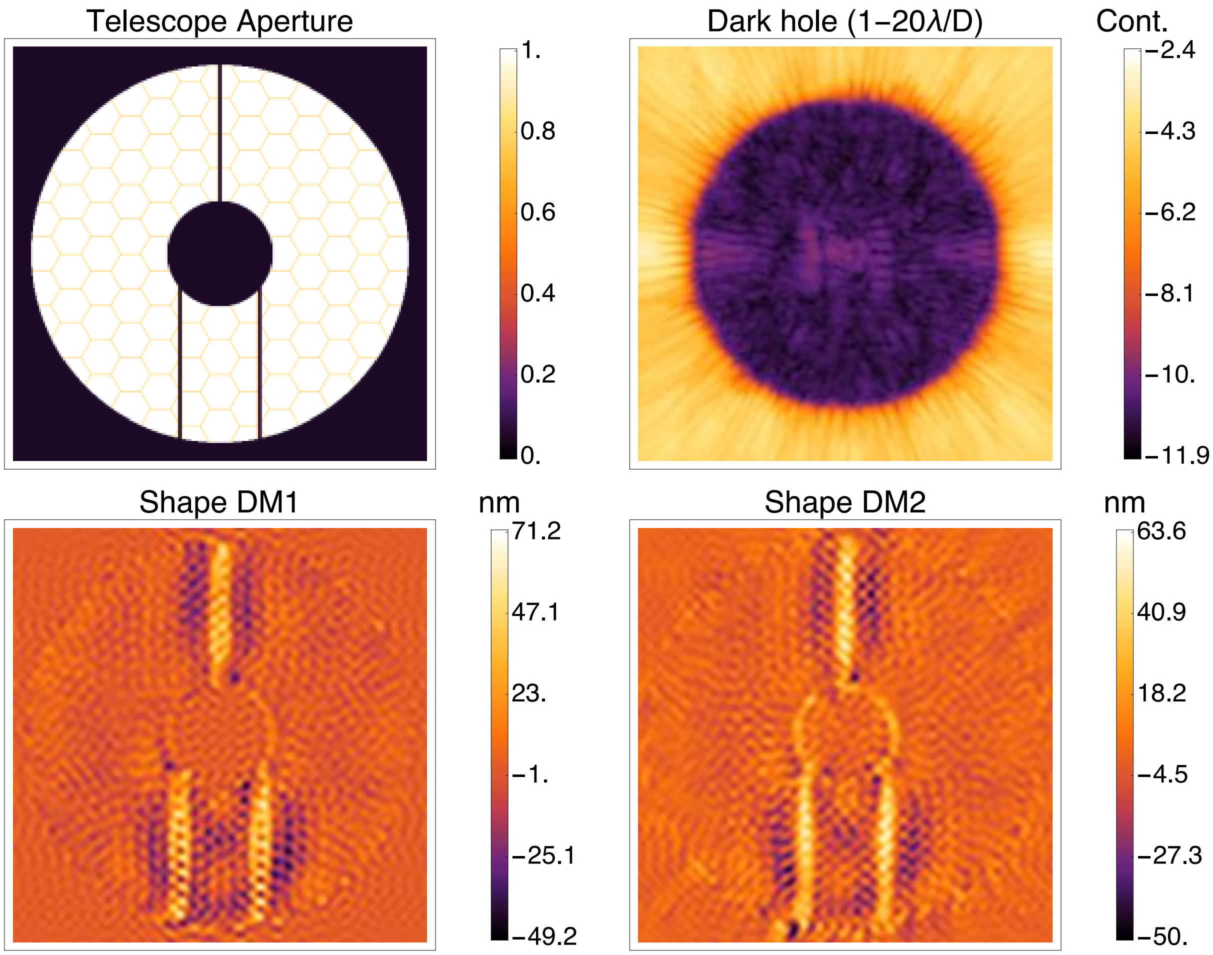

Figure 3: Coronagraph design for the *LUVOIR* Architecture "A" based on a Vector Vortex focal plane mask and using the ACAD-OSM technique to control the DMs. Courtesy of J. Mazoyer.

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