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Event: SPIE Optical Engineering + Applications, 2022, San Diego, California, United States

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ABSTRACT

We describe progress on the Nautilus Space Observatory concept that is enabled by novel, very large (8.5m-diameter), ultralight-weight, multi-order diffractive lenses that can be cost-effectively replicated. The scientific goal of Nautilus is the rigorous statistical exploration of one thousand potentially life-bearing planets and the assessment of the diversity of exo-earths. Here we review the science requirements and key design features of Nautilus. The new optical technology (MODE lenses) at the heart of the Nautilus telescopes also poses exciting new optical fabrication and metrology challenges. We will summarize these challenges and provide an overview of emerging solutions.

Keywords: Diffractive optics, space telescope, extrasolar planet, astrobiology, ultralight optics, MODE lens

1. INTRODUCTION

Recent advances in detector technology and computational capabilities exceeded important thresholds and the discovery and characterization of extrasolar planets became possible [e.g., 1]. Powerful surveys using ground- and space-based telescopes discovered thousands of new planets [e.g., 2]. Although finding Earth-sized planets remains very challenging, the emerging statistics strongly suggests that such planets are common. Even more excitingly, it appears that many ($5-30\%$, e.g., 3, 4) of single stars may harbor Earth-sized planets in their habitable zones, i.e., on orbits that would allow Earth to remain habitable. These discoveries, thus, make the characterization of these planets and the search for life on them compelling. Recently, the US National Academies of Science's Astronomy 2020 Decadal Survey – as well as the corresponding Planetary Science and Astrobiology Decadal Survey – identified the *search for life* among the most important scientific goals of the next decades [5].

Search for Life in Other Worlds: It has been long proposed that alien ecosystems – just like Earth's – may have a long-term, cumulative impact on their home planet, strong enough to thoroughly transform it. In the case of our own world, oxygenic photosynthesis – using Photosystems I and II – have pumped enough free molecular (O_2) oxygen to the atmosphere to change our planet's redox state from reduced to oxidized [e.g., 6]. It is thought that, once the planet's reduced lithosphere and reduced ocean have saturated with oxygen, the ongoing photosynthesis led to the accumulation of massive amounts of free oxygen in our atmosphere. This powerful

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Optical Manufacturing and Testing XIV, edited by Daewook Kim, Heejoo Choi,
Heidi Ottevaere, Proc. of SPIE Vol. 12221, 122210C · © 2022 SPIE
0277-786X · doi: 10.1117/12.2633184

change likely altered the planet's visible appearance (from orange to blue, e.g. 7) and transformed the chemical environment in which Earth life could exist and evolve (also enabling the rise of complex organisms). Therefore, Earth represents an example where the biosphere's impact thoroughly transformed the planet's properties: From its chemical state through its atmospheric composition to its climate.

It is such transformed worlds that are expected to be detectable and identifiable life-bearing planets. The co-existence of free oxygen (or ozone, its proxy) with free methane (a pair that would not co-exist in chemical equilibrium), is widely accepted as a clue for the existence of life: a "biosignature" (e.g., [8]). It is important to stress that, although Earth's example is very encouraging – no biosignature, as of now, has been identified that could in itself, unambiguously indicate the existence of life. In other words, we do not posses the ability to detect "life" itself. Rather, we will search for life by collecting and interpreting the clues in a planetary context [e.g., 9]. The general approaches to the observations and interpretation of biosignatures have been reviewed elsewhere [e.g., 10–12] and we focus here on the optical requirements such searches represent.

A Scientific and Technological Challenge: The search for life on other worlds is, however, a perhaps uniquely formidable scientific and technological challenge: The scientific community simultaneously needs telescopes of unprecedented capabilities, an understanding of the diversity and complexity of other worlds, and a quantitative, universal framework for planetary-scale ecosystems.

The success of the James Webb Space Telescope (JWST) motivates the approach to build a next-generation life-finder space telescopes as a high-contrast imaging facility capable of surveying nearby stars (within 25 pc) for potentially habitable worlds. Building on the heritage of JWST helps inform the design of the telescope and lowers risks. It also has, however, important disadvantages: (1) High-contrast imaging at the levels capable of directly detecting Earth analogs is still at very low technology readiness levels. (2) The inner working angle of even the most capable direct imaging facilities is comparable to their diffraction-limited resolution, i.e., $\phi \propto \frac{\lambda}{D}$ (where λ is the wavelength and D is the telescope diameter). At the same time, the angle ϕ_{target} subtended by the habitable zone (the target of the observations) is inversely proportional to the distance ($\phi_{target} \propto \frac{1}{d}$). Therefore, for any given high-contrast imaging telescope there will be a maximum distance at which it is capable of resolving potentially habitable planets from their host stars. For even the most ambitious high-contrast imaging systems envisioned, this distance remains modest (ca. $25-40$ pc). The limited volume that can be probed also means that the number of planets that can be studied is relatively small. With high-contrast imaging techniques the size of the sample of potentially habitable planets remains small (<25), which is problematic, as explained below.

The Importance of Large Samples: Due to the lack of unambiguous biosignatures, the interpretation of signals that may indicate life relies on understanding highly complex and strongly coupled systems (host star, planetary atmosphere, planetary interior, oceans/continents, as well as the potential ecosystems). A robust interpretation of these complex systems will likely require large sample sizes [e.g., 9, 13]. It is only in such large samples that trends, clusters, and outliers can be robust identified, and thus the underlying causal connections can be established firmly. However, direct imaging surveys – where the sample sizes are directly limited by the diffraction limit of the telescope – are not expected to be capable of probing large samples of potentially Earth-like planets. It follows that an approach that allows studying exoplanet atmospheres without the limitations imposed by spatially resolving the planetary systems is much better suited for statistical exploration of habitable planets. It will also provide a much more robust basis for interpreting potential biosignatures.

Planetary Transits – The Key to Large Samples: As of now, the vast majority of extrasolar planets have been discovered not via direct imaging but through the observations of temperal modulations of the host star's brightness. Specifically, in events when a planet passes in front of its host star (as seen from Earth), a small part of the host star's disk is occulted. These *planetary transits* allow an efficient detection of even small planets. Because planetary atmospheres are not opaque, a fraction of the star's light will pass through the atmospheres, providing an opportunity for absorption spectroscopic study of its composition. This is a powerful method for the search of biosignatures because: (1) It is highly sensitive to atmospheric absorbers; (2) Does not rely on spatially resolving the planet and the star, therefore insensitive to the diffraction limit of the telescope; (3) For the same reasons, it is also relatively insensitive to the optical image quality formed by the telescope.

Therefore, absorption spectroscopy during planetary transits provides a method to search for atmospheric biosignatures at great distances, thus allowing large samples to be studied. At the same time, planetary transits are relatively short events (in this case, typically 4–10 hours), which limits the time for collecting the signal. Furthermore, as the light intensity from a star weakens with the square of the distance, the studies of faraway systems does require larger light-collecting area. However, the light from this larger light-collecting area does not need to be coherently combined, thereby allowing for more favorable scalability than single-aperture, coherent telescopes [e.g., 14]. Comprehensive modeling shows that the light-collecting power of an approximately 50m telescope will allow the search for biosignatures in the atmospheres of 1,000 potentially Earth-like exoplanets [14].

At the intersection of the scientific need for larger light-collecting area and the new opportunities offered by the transformation of the space launch industry, we identified an important opportunity for a novel approach to build space telescopes.

2. SPACE 2.0 OPPORTUNITIES FOR ASTROPHYSICS AND ASTROBIOLOGY

Since the 1960s, space launch costs decreased only very slowly. However, over the past fifteen years, this changed and launch costs dropped dramatically. Projections suggest that SpaceX's Starship will allow launching a kg mass to low Earth orbit (LEO) for less than $200 – a cost that exceeded $20,000 in the early 2000's. This nearly 100-times efficiency increase has already transformed spacecraft design, fabrication, and operations in the commercial satellite industry. It also opens exciting new possibilities for scientific instrumentation. Most prominently, the architectures – and design approaches – for the largest space telescopes could be reconsidered.

In the commercial communication satellite industry, a massive transition is underway: A small number of very large (multiple tons), very expensive (>1B), long-lived (decades), geostationary telecommunication satellites are being replaced by satellite constellations: tens of thousands of identical, low-cost, relatively small and short-lived LEO satellites (Starlink, OneWeb, Galileo).

These satellite constellations offer a multitude of advantages: Networks consisting of such units are easily scalable, highly resilient (costs/risks are distributed and units can be easily replaced), and are easier to maintain and upgrade. The satellite constellations are bringing the economy of scale to space.

These examples – and the revolution in rocketry that enabled them – also has the potential to transform space telescopes. The current paradigm is to build single, highly capable, and unique prototypes (e.g., Hubble Space Telescope, Spitzer Space Telescope, James Webb Space Telescopes). This approach, necessarily, concentrates risks and costs into single, unique observatories. Given the costs and project timelines, these observatories are *highly intolerant* to risks: Any of the possible 347 single point failures of JWST would have rendered the entire project a disaster. With the high launch costs of the past, this approach was considered to be the optimal strategy.

The lower launch costs of the 2020's and beyond, however, enable a radically different approach: Space telescope constellations that distribute risks, costs, and provide scalable, resilient, and easy-to-upgrade, yet highly capable technological solutions. Realizing the benefits of this transformation, however, requires a paradigm change in how telescopes are designed, fabricated, and operated. This publication focuses on a key optical technology that enables space telescope constellations: A scalable and relatively low-cost solution to collect light and form images.

3. NAUTILUS SPACE OBSERVATORY CONCEPT

The *Nautilus Space Observatory* is a highly resilient, robust, highly sensitive, and relatively low-cost space telescope concept under development at The University of Arizona. The *Nautilus Space Observatory*'s science goals are to (1) Study the diversity of habitable planets; (2) Search for life on habitable worlds. Although a few other space mission concepts are being developed around similar science goals, *Nautilus Space Observatory* is unique in that it aims to study a sample as large as 1,000 habitable planets. This large sample is necessary, as explained in § 1 to develop a robust understanding of the habitable planet population and to reliably interpret potential atmospheric signatures of alien ecosystems.

The *Nautilus Space Observatory* and its potential precursor, the Nautilus Probe, were described in detail in previous publications [14, 15]. Here, we provide only a general overview of the key properties of the mission to set the context for the discussion of its optical system.

A Space Telescope Constellation: The *Nautilus Space Observatory* aims to achieve these goals through a paradigm new to large space telescopes: satellite constellations. Through the launch of 35 unit telescopes, a constellation with a light-collecting power equivalent to that of a 50m-diameter space telescope is deployed. This observatory will represent almost two orders of magnitude gain in the light-collecting power of space telescopes. For reference, a comparison of the collecting area of the world's largest existing and planned telescopes – including Nautilus – is shown in Figure 4.

Launch Vehicles and Deployment: The *Nautilus Space Observatory* system will use the SpaceX Starship or the NASA Space Launch System (SLS) B2 configuration, to combine large fairing volumes (for maximum unit telescope diameters) with large mass-to-orbit capacity (>100 metric tons per launch to LEO). The fairing capacity of Starship, for example, will enable launching ∼15 unit telescopes (see Figure 1). Depending on the fairing configuration, NASA SLS B2 may be able to launch as many as 20-24 unit telescopes. After reaching their target orbits, the unit telescopes are deployed, using a simple and robust inflatable spacecraft element, deploy their primary optics, an 8.5m-diameter MODE lens. Upon deployment, the lens' position is fixed by lock-in struts. Fine alignment, including focusing, is carried out through the positional adjustment of the science instrument. Unit telescopes will be identical, distributing costs and risks within the constellation, providing a highly resilient architecture.

Orbit: The science goals of the *Nautilus Space Observatory* require high-precision differential measurements (in time) to obtain the atmospheric transmission spectra of the targeted approximately Earth-sized planets. The required sub-ppm-level precision (after post-processing and de-trending) requires an orbit that provides high thermal stability and continuous target visibility (∼20 hours). We identified two such candidate orbits: One is the Sun–Earth 2^{nd} Lagrange point (L2), which places *Nautilus Space Observatory* on a stable, long-period orbit around the Sun. *Nautilus Space Observatory* would share this orbit with JWST and other experiments (without any realistic chance of collision). Alternatively, *Nautilus Space Observatory* could also be placed on a TESS-like orbit [16]: A highly elliptical orbit around the Earth, in 2:1 resonance with the Moon. This orbit is also stable on decade timescales and provides the required long visibility windows and possibility of Sun and Earth avoidance. Both of these options are viable and, as the *Nautilus Space Observatory* approaches its final definition stage, trades will be studied to identify the orbit that is better suited for the mission.

Power source: The *Nautilus Space Observatory* units will be powered by lightweight, flexible, film-based solar cell panels (TRL9, already successfully used by Venus Express). The large surface area of the unit telescopes provides ample area to generate the required power: Our estimates – considering solar cell efficiency and spacecraft illumination fractions – show that solar cells covering only 7% of the spacecraft's body would suffice to generate an 1.5 kW power [14], the expected level of power consumption. Therefore, existing and high-TRL solar cell technology can already cover, by a large margin, the power requirements of the spacecrafts.

Instrument package and its alignment: *Nautilus Space Observatory* will use an axially centered instrument package, positioned between the geometric center and the outer edge of the inflatable spacecraft component. The exact location will be determined in the final mission definition stage. With the currently envisioned spacecraft dimensions and shapes, the lens-instrument package distance range is compatible with focal ratios between 1.0–2.5. As the front lens is deployed via the inflation of the shroud, the mechanically attached instrument package also deploys and struts that provide crude alignment lock in place (see Figure 5). With the struts locked in, even complete loss of pressure from the inflatable shroud would not impact the optical alignment of the telescope assembly. After deployment, the instrument within the instrument package will be moved (three axes) and tip-tilted (two axes) to focus and align the instrument.

The NAVIIS Instrument: The science requirements of *Nautilus Space Observatory* call for intermediate-resolution (R∼200) transmission spectra over a very broad wavelength range, with high throughput. As the *Nautilus Space Observatory* mission is still in early conceptual state, there is no detailed instrument design yet. The current instrument concept is the Nautilus Visible Infrared Imaging Spectrograph (NAVIIS, see 17), which builds on the optical layout and design of the Hubble Space Telescope's Wide Field Camera 3 [18]. This instrument includes a visible and near-infrared arm, each equipped with its own detectors and filter wheels. The filter wheels include grisms, which provide low-resolution slitless spectroscopic capabilities. In addition to the grisms, the filter wheels host a multitude of narrow-, intermediate-, and broad-band filters that provide deep, multi-band imaging with high throughput. HST's WFC3 is a highly successful workhorse instrument that is

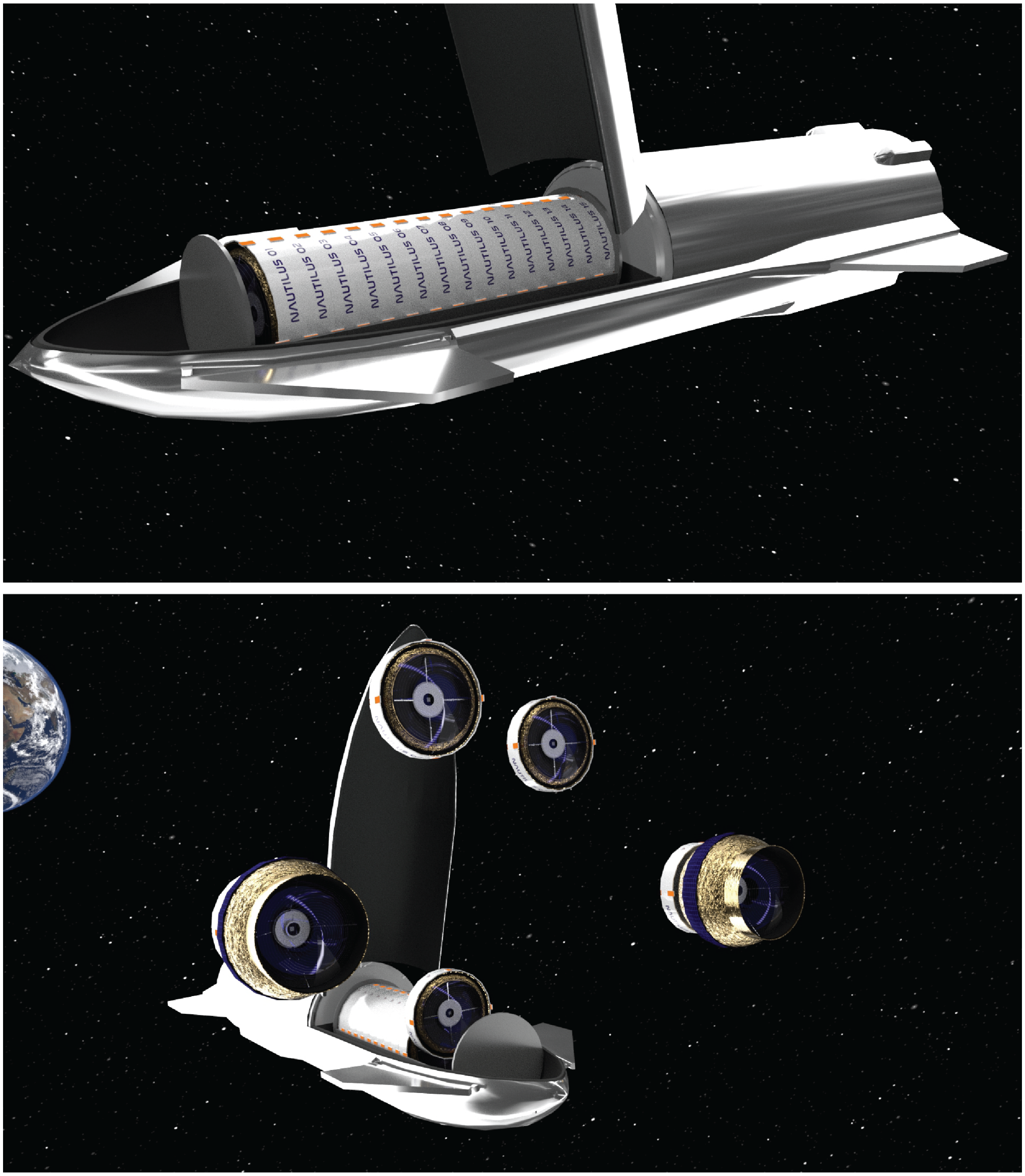

Figure 1. The *Nautilus Space Observatory* will be launched with SpaceX Starship or NASA SLS B2 launch vehicles. These launch vehicles allow placing 10-15 unit telescopes on orbit (top panel). The constellation consists of identical telescope units, which are launched in a compact configuration and unfold on orbit after deployment (bottom panel). The telescope will use 8.5m-diameter MODE lenses to collect light.

responsible for about 1/3 of the HST observations. Although primarily envisioned to be an instrument for large-area cosmology surveys, WFC3 also proved to be the arguably most powerful exoplanet instrument on Hubble. *Nautilus Space Observatory*' NAVIIS instrument is currently envisioned to replicate the key capabilities of WFC3, but with a dichroic instead of a tilt mirror between its visible and near-infrared arms. This change provides simultaneous operational capabilities for the two arms, thereby allowing Nautilus to acquire a very broad band spectra, meeting its science requirements. As the *Nautilus Space Observatory* concept matures and the MODE technology is demonstrated on meter-sized scales, our team will study and define the NAVIIS instrument's design.

Relaxed telescope pointing constraints and no formation flying: The *Nautilus Space Observatory* will operate as an incoherent telescope array (see Figure 2). In other words, intensity measurements will be co-added digitally, without phase information. Therefore, the relative positions of the telescopes (and phase differences) is of no importance, alleviating the need for formation flying and high-precision metrology to establish and monitor relative spacecraft positions. The only considerations for the positions of the spacecrafts within the Nautilus array are as follows: (1) Each telescope must be able to observe the target during the entirety of the observing window, i.e., mutual occultations must be avoided. This criteria is easily met simply by positioning the spacecrafts far from each other (where distances between any two spacecraft are orders of magnitude greater than the diameter of any unit). (2) The targets must be visible within the celestial regions that are not denied to the spacecraft by bright object avoidance criteria (i.e., Sun, Earth, Moon, and other planets). (3) The spacecraft positions and orientations must be maintained such to provide a stable thermal environment with periodic communication windows to the Deep Space Network. None of these pointing considerations are particularly limiting and most are typical to space telescopes. Therefore, it is not expected that these constraints would represent design or operational challenges to the *Nautilus Space Observatory*.

Sub-Array operations: Although the key strength of *Nautilus Space Observatory* will be its ability to obtain images and spectra with an extreme sensitivity — exceeding the state-of-the-art by about two orders of magnitude – it will also be capable of operating in a sub-array or even single-unit mode. That is, an arbitrary number of *Nautilus Space Observatory* units could turn toward the same target and combine their data digitally. For example, large-area surveys may utilize 35 Nautilus units individually, yielding a 35× increase in the field of view over that of a single unit. Alternatively, a sub-array of twenty Nautilus telescopes could provide *immediate* spectroscopic follow-up to characterize transient objects (supernovae, hypernovae, gravitational wave counterparts) discovered as a survey is being carried out by fifteen independently-targeting Nautilus units. As proposed in [17], the *Nautilus Space Observatory* would be transformational not only for the studies of Earth-sized exoplanets but equally for studies of faint objects (Kuiper-belt objects, tiny asteroids and natural satellites of Solar System planets, high-red shift galaxies, distant and old brown dwarfs, etc.), as well as time-domain astronomy (optical transients, stellar explosions, tidal disruption events, gravitational wave counterparts).

4. KEY REQUIREMENTS FOR THE OPTICAL SYSTEM

We performed comprehensive sets of simulations to explore the type and quality of information required to search for biosignatures and to interpret these correctly. Specifically, we simulated transits of 14 of Earth-sized planets in the habitable zones of Sun-like stars (main sequence G dwarfs), and lower-mass stars (K dwarfs and M dwarfs). We considered published exoplanet occurrence rates to calculate the range of distances to which these transiting planets need to be probed to allow for a study of 1,000 such planets at the signal-to-noise ratio required to probe for key molecular absorbers. We considered scenarios when the survey would be limited to Sun–Earth-like systems; or only red (M) dwarf host stars; or to the closest 1,000 transiting planets regardless of the host star's properties. In a separate study, we explored the science requirements for testing fundamental hypotheses about potential Earth-like planets [19]. One such study explored the requirements for the observational test of the existence of the "habitable zone" around other stars. The second such study explored whether the hypothesis that "a significant fraction of Earth-like planets undergo an atmospheric evolution similar to that of Earth" could be observationally tested.

From these studies and the science goals of *Nautilus Space Observatory*, we derive the following mission requirements: Intermediate signal-to-noise ratio (SNR 5−25) atmospheric transmission spectroscopy of 1,000 approximately Earth-sized ($\sim 0.8 - 1.4 R_\oplus$ (Earth radius), habitable zone planets. We tentatively set the wavelength range to 0.24–1.7 μm: In the near-UV, the wavelength choice is driven by the Hartley band (O_3 ozone absorption), while in the red end, the 1.7 mum target is driven by access to water absorption bands and less sensitivity to potential atmospheric hazes. The intermediate SNR is driven by the need to probe molecular absorption bands (H_2O, O_2, O_3). More detailed discussion of these choices and their impact on the science scope of the mission are provided in [14, 19]. The most challenging requirement is, of course, the light-collecting

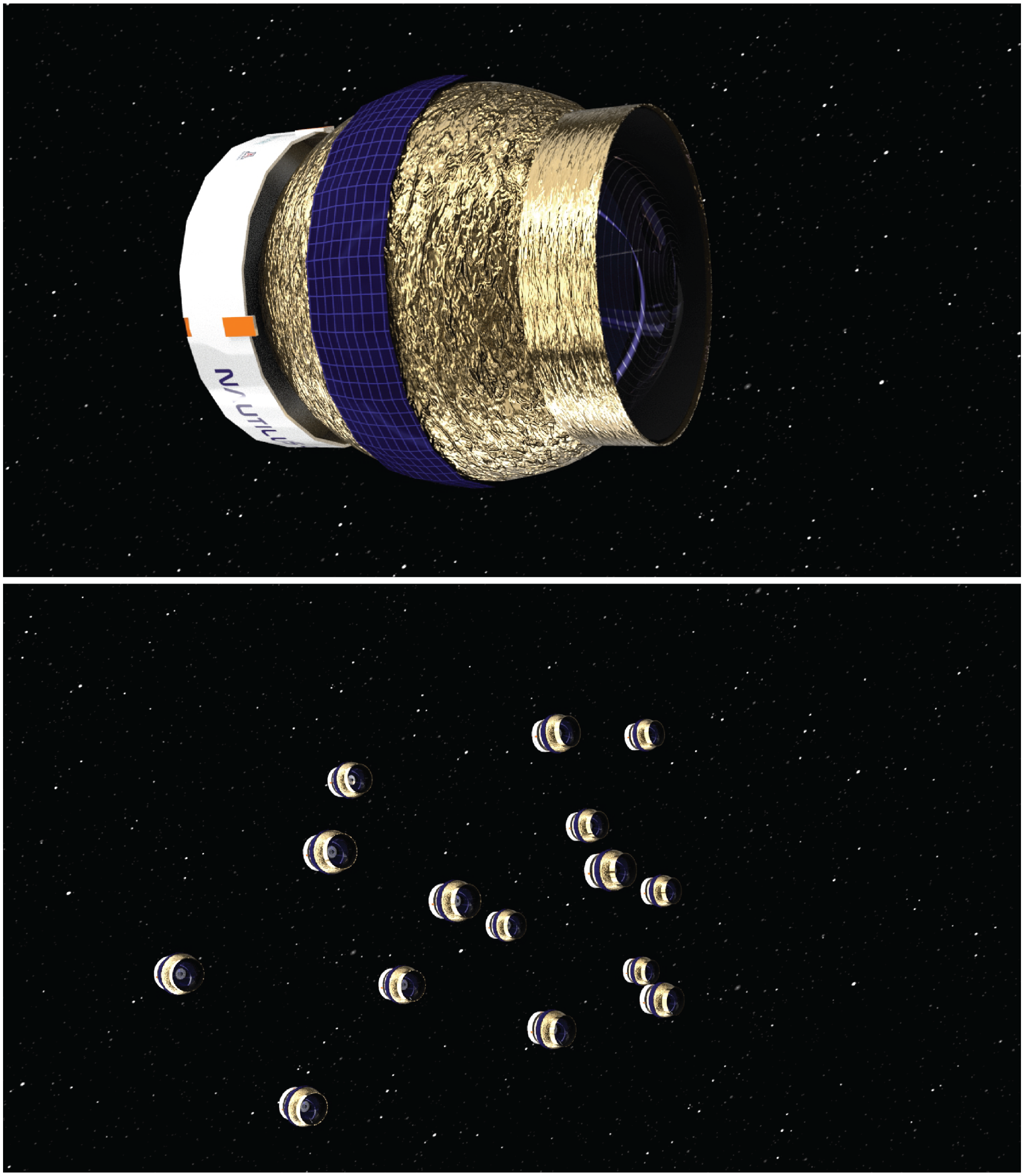

Figure 2. Top: In the current design, unit telescopes use a simple inflatable system for the front-lens deployment (although other solutions are also possible). MODE lenses have much more relaxed alignment requirements than reflective optics, allowing for simpler and more robust deployment. Bottom: The telescopes can operate as individual observatories or, when more light is needed, will function telescopes as an incoherent array (i.e., intensity signal collected by the telescopes is co-added digitally). Their relative positions are not important, as long as they can observe the same target, i.e., no formation flying or metrology is required.

power. Our studies show that a light-collecting power of an approximately 50m-diameter telescope is necessary to achieve the science goals identified for *Nautilus Space Observatory*.

5. THE IMPORTANCE OF THE MODE TECHNOLOGY

As described in § 2, space telescope constellations offer resilient, relatively low-cost, low-risk, and scalable technological solutions to extending the capabilities of future astrophysics, planetary science, and astrobiology missions. The space launch infrastructure is developing rapidly and are expected to be in place well before the first powerful space telescope constellations could be built.

This is, in large part, due to the lack of scalable, low-cost, large-aperture optical imaging systems. As discussed previously [14], primary mirrors, which collect and focus light in most space telescope, remain very expensive to fabricate, align, and test. Furthermore, they carry hidden costs: The stringent alignment requirements of these reflective systems translate into stringent downstream structural stability requirements on the spacecraft itself.

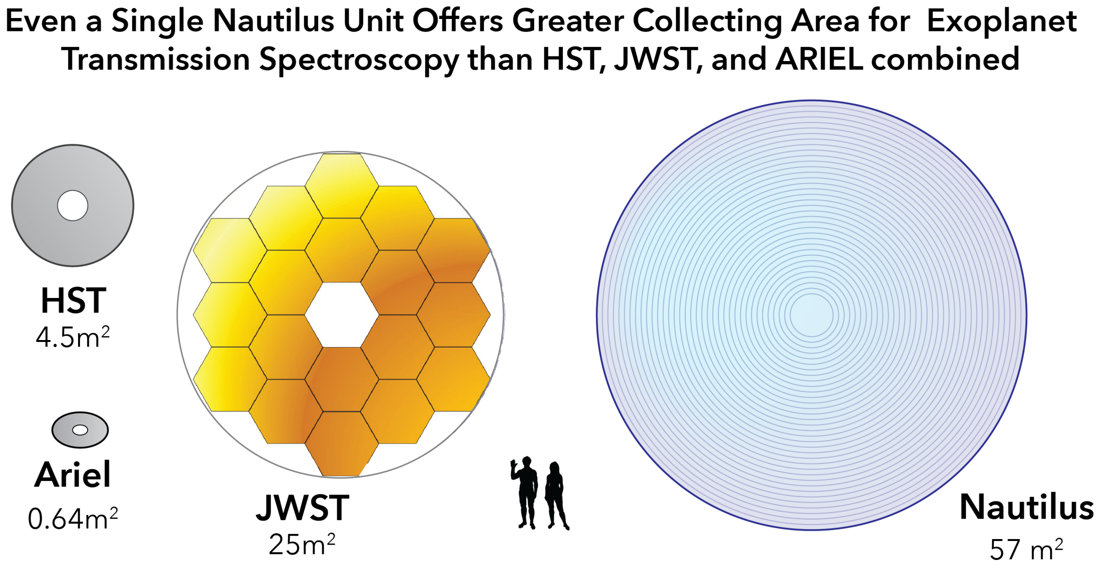

Figure 3. Comparison of the relative aperture sizes of ESA's ARIEL mission, the Hubble Space Telescope, the James Webb Space Telescope, and a single Nautilus unit telescope. Even a single Nautilus unit telescope has more light-collecting power than that of ARIEL, HST, and JWST *combined*.

Our *Nautilus Space Observatory* team has, over the past seven years, developed a comprehensive technological solution to design, fabricate, and align ultralight, relatively low-cost, high-performance space optics that are intrinsically scalable – allowing, in the near future, diameters up to 10 m.

Multi-order diffractive engineered material (MODE) lenses are novel optical elements that combine diffraction and refraction to provide high quality imaging over intermediate wavelength bands (∼300 nm) [20, 21]. With co-designed small-aperture color corrector system [22–25], MODE-lens based telescopes can provide very broad band (∼0.3–1.7μm), essentially diffraction-limited imaging performance [26, 27].

As envisioned, MODE lenses provide the following important advantages over conventional primary mirrors:

1. Lens thickness does not scale with lens diameter
2. 100-1,000 times lower areal density
3. ∼100 times lower sensitivity to misalignments
4. Fabricated through a finely controlled process (∼ 10 nm footprint) in contrast to large-footprint grinding and polishing
5. Suitable to cost-effective and rapid replication via optical molding

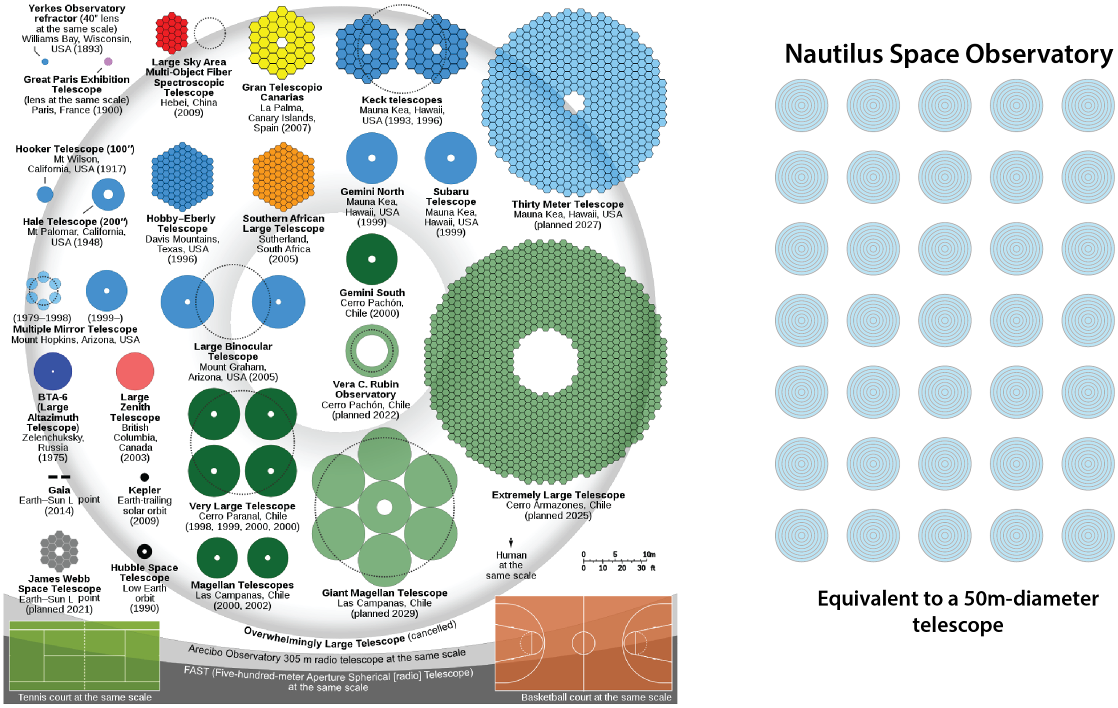

Figure 4. Comparison of the relative aperture sizes of the world's largest ground- and space-based telescopes. Modified from Wikipedia, original figure covered by Creative Commons License.

6. If desired, a simple instrument can be integrated into the multiple diffractive surfaces

MODE technology is still in its infancy, but rapid progress is maturing and scaling this technology: Our research group at The University of Arizona's James Wyant College of Optical Science – supported by domestic and international partners – are developing the technological capabilities and know-how required to design [20,26], fabricate [28], replicate, align [29], and test MODE-lens-based optical systems, including systems optimized for wide field of view or broad wavelength coverage. Our team has passed multiple major milestones in this development effort, bringing large-scale MODE lens systems closer to deployment.

In the twin sessions *Nautilus Space Telescope I and II* of the 2022 SPIE conference *Optical Manufacturing and Testing XIV*, we present updates on the optical design, fabrication, and alignment of MODE telescope systems. Specifically, our results include the study of Type 2 longitudinal chromatic aberration from a high-harmonic MODE lens and a corresponding color corrector [24], and the fabrication, assembly and testing of a color corrector [25]. Our results also include initial optical tests of a MODE lens telescope [27], with specific, in-depth stray light analysis and testing [30]. On the optical fabrication side, we present new results on precision glass molding specifically for MODE-lens-based telescopes [31]. Finally, we present new studies and results on autonomous closed-loop control for multi-segmented optic aligning and assembly [32]. Complementing this study is our work on automatic alignment of multi-order diffractive engineered (MODE) lens segments using the kinematically-engaged yoke system (KEYS) for optical performance testing [33].

6. SUMMARY

The *Nautilus Space Observatory* is a concept proposed to meet the emerging scientific opportunity of remote characterization of extrasolar habitable worlds by exploiting the emerging technological opportunities offered by the transformation of the space launch industry. Specifically, *Nautilus Space Observatory* is a constellation of very large-diameter, relatively low-cost space telescopes that, with its combined light-gathering power, will be as sensitive as a 50 m-diameter space telescope. This nearly two orders-of-magnitude increase in sensitivity is

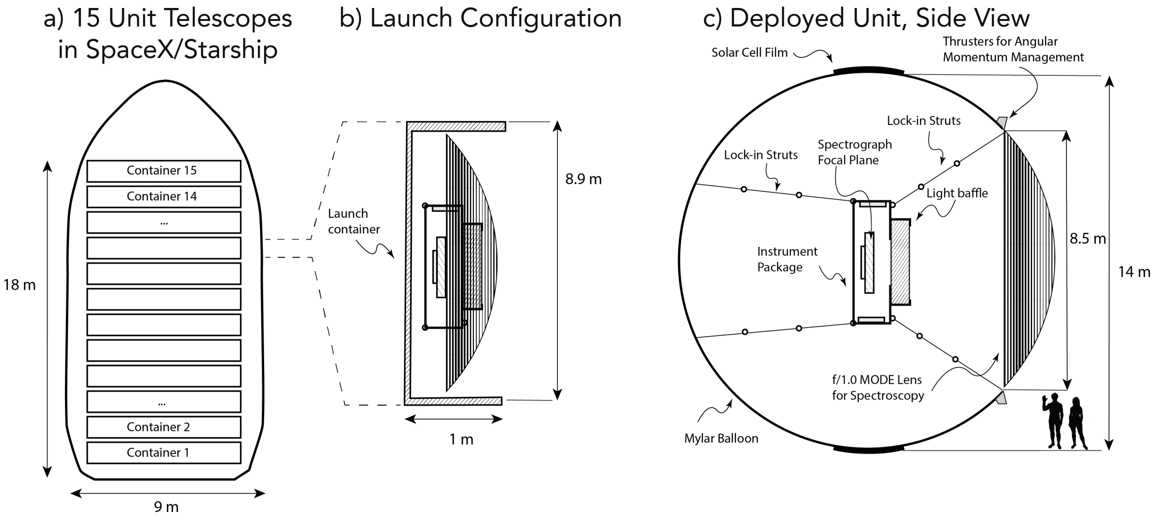

Figure 5. Nautilus unit telescopes will be launched in their compact configuration in launch vehicles that can accommodate 10–24 units. Each unit telescope is equipped with an 8.5m-diameter MODE lens, which focuses light into the instrument package. The deployments of the instrument package and MODE lens are executed by an inflatable spacecraft component, but positional stability is provided by lock-in struts.

required to search for atmospheric biosignatures in a large sample of habitable worlds, which is likely going to be key to correctly interpret these indirect indications of extraterrestrial life.

In this Invited Review, we introduced the technological changes in space launch capabilities, the scientific opportunities, and the mission requirements that motivate *Nautilus Space Observatory.* We summarized the properties of MODE lenses, a revolutionary optical technology that is being developed to enable effectively replicated, powerful, low-cost, very large-aperture imaging systems.

ACKNOWLEDGMENTS

We are indebted to the Gordon and Betty Moore Foundation for their support of the Nautilus project (Grant number 7728). We acknowledge and thank the University of Arizona, its Steward Observatory, and the University of Arizona Space Institute for their support. We thank Katie Yung for her visualization of the Nautilus Space Observatory's launch, deployment, and operations. This material is based upon work supported by the National Aeronautics and Space Administration under Agreement No. 80NSSC21K0593 for the program "Alien Earths". The results reported herein benefitted from collaborations and/or information exchange within NASA's Nexus for Exoplanet System Science (NExSS) research coordination network sponsored by NASA's Science Mission Directorate.

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