Journal of
Astronomical Telescopes,
Instruments, and Systems

AstronomicalTelescopes.SPIEDigitalLibrary.org

Innovative telescope architectures for future large space observatories

Ronald S. Polidan
James B. Breckinridge
Charles F. Lillie
Howard A. MacEwen
Martin R. Flannery
Dean R. Dailey

SPIE.

Ronald S. Polidan, James B. Breckinridge, Charles F. Lillie, Howard A. MacEwen, Martin R. Flannery, Dean R. Dailey, "Innovative telescope architectures for future large space observatories," *J. Astron. Telesc. Instrum. Syst.* **2**(4), 041211 (2016), doi: 10.1117/1.JATIS.2.4.041211.

Innovative telescope architectures for future large space observatories

Ronald S. Polidan,[a,b,*] James B. Breckinridge,[c] Charles F. Lillie,[d] Howard A. MacEwen,[e] Martin R. Flannery,[a] and Dean R. Dailey[a]
[a]Northrop Grumman Aerospace Systems, One Space Park Drive, Redondo Beach, California 90278, United States
[b]Polidan Science Systems and Technologies, LLC, 888 Southwest Evergreen Avenue, Redmond, Oregon 97756, United States
[c]Breckinridge Associates, LLC, 985 East California Boulevard, Pasadena, California 91106, United States
[d]Lillie Consulting LLC, 6202 Vista del Mar, Playa del Rey, California 90293, United States
[e]Reviresco LLC, 4901 Loosestrife Court, Annandale, Virginia 22003, United States

Abstract. Over the past few years, we have developed a concept for an evolvable space telescope (EST) that is assembled on orbit in three stages, growing from a 4×12-m telescope in Stage 1, to a 12-m filled aperture in Stage 2, and then to a 20-m filled aperture in Stage 3. Stage 1 is launched as a fully functional telescope and begins gathering science data immediately after checkout on orbit. This observatory is then periodically augmented in space with additional mirror segments, structures, and newer instruments to evolve the telescope over the years to a 20-m space telescope. We discuss the EST architecture, the motivation for this approach, and the benefits it provides over current approaches to building and maintaining large space observatories. [DOI: 10.1117/1.JATIS.2.4.041211]

Keywords: space telescopes; innovative architectures; segmented telescopes; in-space assembly and servicing.

Paper 16007SSP received Feb. 3, 2016; accepted for publication Jul. 22, 2016; published online Aug. 17, 2016.

1 Introduction

The scientific case for very large space telescopes has been very well established by various studies over the past decade (as discussed by Thronson et al.[1]), most recently and particularly well by the Association of Universities for Research in Astronomy (AURA) in its "From Cosmic Birth to Living Earths" study,[2] which presents a concept for a high definition space telescope (HDST). These observatory concepts all featured a single launch of a large telescope on a heavy lift launch vehicle (ranging up to an Space Launch System (SLS) Block 2), even though numerous authors[3–5] have discussed the advantages and feasibility of in-space assembly of large space telescopes. Perhaps the most detailed study of in-space telescope assembly was conducted by the NASA Satellite Servicing Capabilities Office (SSCO) and reported in 2010.[6] This study included an option for a large space telescope to be launched in a single 600-day launch campaign along with a human/robotic assembly system: the campaign would feature four launches on Delta IV-H and three on SLS. While the concentration of acquisition, fabrication, and launch at the early stages of these programs has been a common feature of all of these studies, scientific observations would not be possible until completion of this single deployment stage.

Building any one of these observatories in the current and likely future cost-constrained environment will be a challenge. Space telescope costing studies, e.g., Ref. 7, have developed empirical relationships that indicate that the costs of large astronomical telescopes will greatly challenge the existing NASA astrophysics budget. These costing studies have most generally addressed minimizing the total system cost, which, combined with the noted programmatic concentration over a short period of years, has led to a sharp cost peak in the implementation stage of the programs. This can adversely affect the affordability of other programs in the overall budget, or completely prevent acquisition of the space telescope system itself.

We argue that shifting cost emphasis to a strategy that maintains a lower annual cost profile even at a somewhat higher total program cost spread over more years would prove more affordable in this current flat-budget era. This assembly-in-space strategy may also lead to an earlier scientific observation start coupled with a staged increase to the full scientific capability while enabling much greater insight into what is needed to create this capability. An evolvable space telescope (EST) concept that builds the observatory in stages utilizing in-space robotic assembly and servicing to keep annual costs relatively low and predictable can enable early science return and produce a very long-lived observatory that evolves to take advantage of advancing technology and adopt new science questions and technology improvements as they arise. A detailed high-priority study of this assembly-in-space strategy is essential to provide well-founded and convincing results concerning the performance and cost of the underlying concept. A similar phased approach to building a large complex science mission, although not assembled in space, has been adopted by the NASA Mars Sample Return Program, whose architecture has three independent missions performing the necessary tasks over a large number of years to achieve the sample return goal (see Ref. 8 for a concise summary of the Mars Sample Program).

The ability to launch an EST in multiple stages on a few lower-cost medium launch vehicles rather than a single very heavy (and costly) launch vehicle is key to managing affordability. While historically the cost of the launch vehicle is covered at the agency level rather than the division level, it is still a cost

*Address all correspondence to: Ronald S. Polidan, E-mail: ron.polidan@psstconsulting.com

2329-4124/2016/$25.00 © 2016 SPIE

factor, and if a lower-cost option were possible [such as James Webb Space Telescope (JWST) using an European Space Agency (ESA) launch vehicle], the agency would utilize that option. Moreover, continuing development of reusability in the medium launch vehicle class, e.g., Space-X′s current effort to develop a reusable Falcon 9 first stage, and the response by legacy launch vehicle providers, raises the possibility of much lower costs in the near future, further enhancing the cost dynamics of multiple launches and robotic assembly over an extended period in contrast to a single launch and deployment of a preassembled telescope. The staged launch strategy would also complement and assist the development of technology in critical areas, notably coronagraphs, starshades, ultrastable large aperture telescope systems, detectors, and mirror coatings, specifically enabling a staged introduction of appropriate technologies as they mature. These technologies have been identified as critical in both Advanced Technology Large-Aperture Space Telescope (ATLAST) and HDST studies, and are discussed in detail by Bolcar et al.[9] elsewhere in this issue.

We recommend examining alternative telescope architectures that reduce annual cost, expand performance, and take advantage of new or pending technologies and the developing space infrastructure to maintain a steady development cadence while not being locked into traditional approaches. This is the foundation of our EST: it was first presented in 2014 and 2015 (see Refs. 10 and 11), but its flexibility and serviceability have a long history traceable directly to the Hubble Space Telescope (HST) and the International Space Station (ISS) programs. The purpose of this paper is to present an initial technical architecture that could serve as a starting point for such an alternative approach study.

2 Future Telescope Science Goals

The science goals for future large space observatories will only very briefly be discussed in this paper, since they have been outlined in great detail in the AURA "From Cosmic Birth to Living Earths" study[2] of the HDST. As noted elsewhere in this issue (see Refs. 1 and 12), the HDST design concept is consistent with science ranging from the detection of biomarkers in candidate Earth-like worlds to that of a powerful general-purpose astronomical flagship. The top-level science goals will likely be:

- characterize exoplanets and, ideally, discover signatures of life (specifically spectral biomarkers) for a statistically significant number of planets outside the solar system; and
- expand our understanding of the nature, origin, and evolution of the universe, including star and planet formation and galaxy assembly.

Of course, there is a wide range of additional science that would be enabled by these future observatories, but for this paper, we will adopt these goals as illustrative of the top-level science needs for future observatories, while recognizing that the detailed design of the EST will have to be sufficiently adaptable to accommodate each of their performance requirements.

3 Evolvable Space Telescope Concept

In 2014 and 2015 (see Refs. 10 and 11), we presented the baseline EST concept. Three characteristics particularly distinguish the EST mission concept from other approaches: evolvability, adaptability, and serviceability.

- *Evolvability.* This, of course, is the core of the EST concept, and directly implies that there will be several configurations of EST as it evolves in several "stages" over the observatory's lifetime. These stages will be separated from each other by several years (nominally five) and will provide substantial performance advances based upon the evolution of the science drivers and/or available technologies. The Stage 1 EST will be launched as a fully functional observatory designed to produce compelling science. Subsequent stages increase the telescope collecting area, add new instruments, and/or upgrade telescope or spacecraft subsystems. Stage 1 will be designed to provide significant capability to address the science drivers currently being used to define HDST, and it will form the core of future even larger telescopes, beginning with the collecting area of an equivalent ∼7-m telescope and evolving to a 16- to 20-m aperture telescope at Stage 3.
- *Adaptability.* Evolvability will not occur in a static environment, and EST will respond with versatility to changed conditions that will generally be outside control of the program itself. Many external effects are quite obvious; the following list in no way exhausts the possibilities, and almost all will be reflected in the program schedule:
    - Budgetary changes themselves, either negative or positive, affecting either the entire NASA budget or priorities within that budget, and political changes, such as the addition or subtraction of sponsors or stakeholders, can be a significant source of schedule changes.
    - Science priority changes that occur during telescope and instrument development.
    - Technical advances in areas such as detectors/instruments, optical systems and coatings, structural materials, disturbance control, robotic servicing, and other important areas.
- *Serviceability.* This capability is essential to each of the preceding two, since it directly addresses the program's ability to maintain performance against failures or wear and tear, major or minor, and the ability to enhance or upgrade systems, again including minor enhancements or stage changes. It is also directly related to the continued performance of the EST over many decades, lasting perhaps as long as 50 or more years with periodic robotic and/or crewed servicing, and is thoroughly addressed in another paper in this journal.[13] The value of serviceability has, of course, been quite effectively established by HST, and will be an even more pervasive characteristic of the EST program.

The baseline EST is designed to be a Sun–Earth L_2 (SEL2) observatory. It begins with an initial development and launch of a "core" fully functional and productive telescope with instruments. Specifically, this first stage is a three-segment off-axis telescope. Subsequently, this observatory is augmented with additional mirror segments, new instruments, spacecraft subsystem replacements/upgrades, and other needed infrastructure elements to build a filled aperture telescope. Follow-on augmentations would add additional mirror segments and instruments along with any needed spacecraft and infrastructure

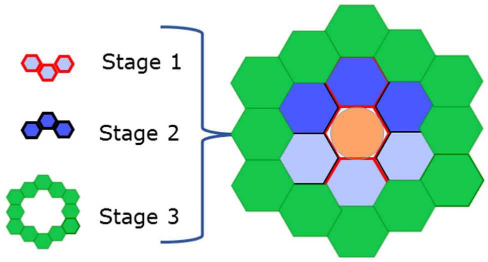

Fig. 1 Pictorial configuration for EST Stages 1, 2, and 3.

replacements/upgrades to build an even larger filled aperture observatory.

For simplicity for this study, we have adopted a fixed mirror element size of ∼4 m flat-to-flat with a 60-m radius of curvature to produce at Stage 2 an f/2.5 12-m aperture, although these dimensions are purely illustrative. We believe that each stage of a telescope of this size can be launched using existing launch vehicles and, since it will be designed for the UVOIR wavelengths, it can produce compelling science both as a more capable follow-on to HST and as a complement to JWST. There is nothing in the architecture that requires a specific size for each mirror element. In fact, each mirror element can be a single mirror segment (the baseline for this study) or composed of smaller mirror segments that are built up into the basic mirror element. The EST approach can be implemented with any segment size, with the telescope size and total collecting area scaling with the mirror element size, the EST architecture functions equally well with smaller or larger mirror segments.

This nominal evolution of the EST primary mirror assembly (PMA) is described below and shown pictorially in Fig. 1. Illustrations of the full observatory in each of its three stages are presented in Fig. 2.

- EST Stage 1 is indicated in Fig. 1 by the three gray hexagons and the central circle (changed from the 2014 two-element "bow-tie" Stage 1 to improve performance). The hexagons form the initial PMA, and will typically be formed to the master prescription. The central circle represents the secondary mirror, and will be designed to serve the same role throughout Stages 1, 2, and 3. These elements will all be orbited and assembled using the first EST launch, providing an off-axis aperture on the order of 12 m × 4.5 m with a prime-focus instrument suite. Stage 1 in particular is designed to be an exceptional UV astrophysics observatory with its large collecting area, low scattered light off-axis configuration, and high transmittance to the prime-focus instruments. It could also accommodate a Vis–IR coronagraph and wide-field camera.
- Stage 2. At the chosen time (about half a decade following Stage 1 deployment), three additional segments (shown in dark blue) will be launched, along with other components (e.g., new instruments and additional tensegrity truss structural elements) to form the Stage 2 EST: a 12-m filled aperture, with a prime-focus and/or a Cassegrain or three-mirror anastigmatic (TMA) configuration.
- Stage 3. Again, approximately a half-decade after the preceding launch, the next stage of telescope evolution will occur, in this case, adding 12 mirror segments (in green) to form a 20-m aperture for the telescope in a Cassegrain configuration. In this case, since the size of the PMA will be significantly increased, the upgrade will include modification or replacement of the sunshield, and structural modifications and servicing if and as needed.
- Stage 4+. Later stages of the EST remain possibilities for examination in the future, but are not considered in this paper.

With this architecture and the two top-level science goals, we can specify the top-level requirements for the EST, which are enumerated in Table 1. These system requirements and stretch goals for the EST are based on the goals summarized in Dalcanton et al.[2] (a product of multiple NASA and NRC studies and reports, previous large observatory studies, and input from members of the science and engineering communities) and on this paper's authors experience designing, developing, and operating space telescopes for previous NASA missions. Large mirror segments are specified to maximize the telescope aperture while minimizing the number of gaps between the segments that diffract the incident light and increase the thermal background. The operating temperature of the primary mirror (PM) will be determined by the science drivers and engineering trades and analyses during the formulation phase of the EST mission, considering a variety of criteria including the mirror material, thermal design, system performance, manufacturing cost and complexity, and integration and test approach. A low PM

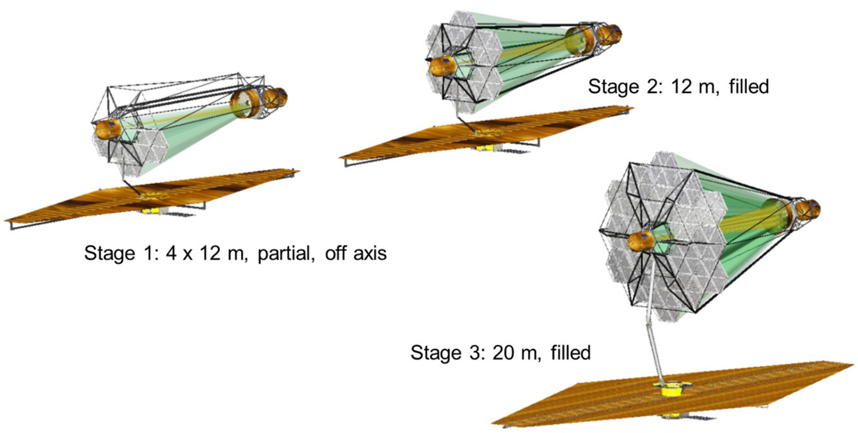

Fig. 2 Illustrative representations of the full EST observatory Stages 1, 2, and 3.

Table 1 EST design reference concept top-level requirement.

Parameter	Requirement	Goal	Traceability/notes
Telescope aperture	≥10 m	≥16 m	Sized from ATLAST, HDST studies
Stage 1	Off-axis, three segments	4 × 12 m	Three hexagonal segments
Stage 2	Filled aperture	12 m	Six hexagonal segments
Stage 3	Filled aperture	20 m	Eighteen hexagonal segments
Wavelength range	100 to 3000 nm	90 to 8000 nm	Science drivers outlined in HDST study and Rioux[8]
Field of view	4 to 8 arc min	6 arc min	Maximum survey power (area × FOV)
Primary segment size	2 to 3 m	4 m	Provide adequate collecting area for Stage 1 Four meters is the largest segment that can fit un a 5-m fairing
PM temperature	≤ 200 K	~100 K	Minimize heater power, enable mid-IR observations
Design lifetime	15 years	≥30 years	Extended lifetime from on-orbit assembly and servicing

temperature has been specified in Table 1 to enhance the observatory's NIR and MIR performance and reduce the heater power requirements and electrical power system costs. However, this would require a strong scientific justification, e.g., the need to measure MIR exoplanet atmospheric absorption features, to balance added cost/complexity.

3.1 *EST Optical System*

3.1.1 *Introduction*

The EST concept is versatile and flexible to respond to the continuously evolving needs of a diverse astronomical community in the presence of budgetary and technical constraints. By launching the telescope in parts and assembling it in space, we have the opportunity to replace aging hardware with more capable hardware without the expense and waste of discarding the expensive core telescope and instruments, as will happen to the multibillion-dollar JWST. Affordable cutting-edge space-astrophysics will be achieved by reusing our investment in space hardware to the maximum extent possible. The HST's success is in large part because of our ability to swap out instruments in response to new science priorities and technology evolution and reuse the very expensive 2.4-m telescope. The EST concept is to robotically add to or replace instruments and segments as needed, in a manner similar to that pioneered by the AAReST[14] project at Caltech.

The EST design approach has been to reduce recurring engineering cost by using a modular architecture. For example, Stage 1 and Stage 2 are almost identical optical telescopes. EST Stage 1 has rotational symmetry about the optical axis, and the nonrecurring engineering costs of Stage 1 are fully applicable to Stage 2. In fact, one can build two identical Stage 1 PMAs, launch the Stage 1 tri-hex system, and observe with this off-axis large telescope. Then, when sufficient funds are available, launch the second unit, rotate it around the telescope axis, and dock it to the Stage 1 system to create the 12-m Stage 2 on-axis, filled aperture telescope. Figure 3 shows a concept for the EST PM and metering structure. Light, shown as a broken line, enters the system from right to left, reflects from the concave PM, and converges to a focus near the right end of the metering structure. At the right end of the metering structure is a flange for docking either a Cassegrain secondary or a prime-focus instrument assembly (PFIA). The decision between prime-focus instruments and instruments behind the primary depends on the then current science measurement priorities.

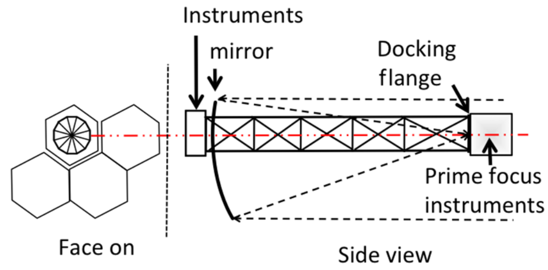

Fig. 3 The EST Stage-1 core structure is shown in a schematic. It is an off-axis unobscured segmented aperture. Light enters the system from the right, reflects from the three-segment PM, and converges to the prime focus or a secondary. Left is a face-on view of the three segments. Right is a side view showing a notional deployable optical metrology structure separating the primary from the docking flange. Prime-focus instruments or a secondary mirror will be docked at the right end of the metering structure depending on the then-current science priorities.

The optical figure on the primary will be designed to be consistent with using the telescope as a Cassegrain or prime-focus or TMA telescope. Correctors downstream in the optical path from the primary will correct the optical figure and optimize it for each instrument. Designs for similar correctors were developed by Meinel[15] and for the HST.[16,17]

3.1.2 *Classical Cassegrain or TMA*

A concept for the EST with a classical Cassegrain secondary mirror assembly or prime-focus instrument package docked to the right end of the metering structure is also shown in Fig. 3. The prime-focus instrument package can be undocked and removed in space and replaced with other modules such as a secondary mirror with an optical figure optimized for a TMA wide-field system, depending on the science measurement priorities.

The science and engineering case for locating an instrument package behind the primary is well established since HST, Spitzer, and JWST telescopes locate their science instruments at the back of the primary. A prime-focus system (as shown in Fig. 3) has several advantages for space telescopes, and these are examined in the next section.

3.1.3 *Prime focus*

In this section, we introduce the concept of a prime-focus EST. An instrument at prime focus enables us to minimize scattered light, eliminate a structurally sensitive optical element (the secondary), minimize polarization aberrations, reduce thermal disturbances, and maximize transmittance for observing extremely faint objects in the visible and the UV.

For many years, before the dawn of the age of space telescopes, ground-based astronomers used the Cassegrain configuration for their telescopes. This design approach was chosen to minimize telescope dome structures and place the instruments behind the PM, where there was a large volume available. The mass of the instrument was also near the heavy PM and easy to reach by an astronomer peering through the telescope eyepiece. Ground telescopes are constrained to operate at atmospheric temperature, within the Earth's atmosphere and gravitational field. For space telescopes, some of these ground-based constraints are missing, and a prime-focus space telescope system may be less expensive to build.

Using a prime-focus system instead of a Cassegrain saves one reflection or ~4% absorption in the visible. In the UV, where reflectances are much lower, the savings are greater. However, if one takes a systems perspective, the advantages of the prime focus may lie elsewhere, such as controls and pointing, adaptive optics, optical metrology, and optical bench stability.

Several ground-based telescopes (Mayall 4-m, Blanco 4-m, Subaru 8-m, SALT 10-m) use low-mass wide-field cameras at their prime focus. For ground telescopes, it is necessary to build more massive instruments such as integral-field spectrometers and imaging spectra-polarimeters at the Cassegrain or Coude foci. Space observatories do not face this mass limitation. Some of these ground-based telescopes (e.g., the Mayall and Blanco telescopes) have the capability to switch between prime focus and Cassegrain focus to optimize scientific return.

The cost of a telescope depends to a large extent on the number of large optical elements that need to be controlled (passively or actively) to nanometer tolerances. The EST gives us an opportunity to conduct trades and analyses and explore the feasibility of a new, possibly more cost-effective, large space telescope optical configuration.

Figure 4 shows a sketch of a notional prime-focus telescope system designed for wide-field and coronagraphic imaging by the Stages 1 and 2 EST. Light passes from the right to the left to reflect from the 12-m, $F/\# = 2.5$, EST Stage 2 segmented PM. The box shown just to the right of the prime focus is the

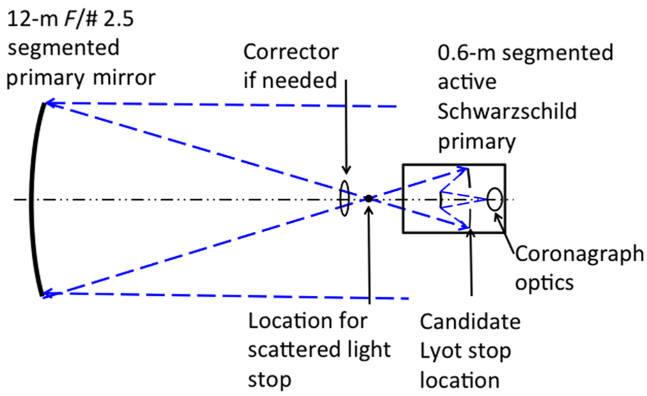

Fig. 4 Prime-focus schematic concept for the EST system. A PFIA is shown docked at the right end of the metering structure, 30 m from the vertex of the PM that separates the primary from the PFIA. (Illustrative—not to scale.)

PFIA, whose diameter is 3 to 4 m and length is a few meters to hold prime-focus instruments such as UV spectrometers, imagers, coronagraphs, and wide-field cameras. The focal plane is shared (such as HST and JWST) with several instruments contained within the PFIA. A free-flying spacecraft can be attached to the PFIA for unlatching and precision docking of the PFIA from the end of the metering structure for replacement of the entire instrument assembly. The PFIA can then be returned to Earth for instrument refurbishment. Following one of the HST system architecture features, the EST is designed for instrument and mirror upgrades based on new detector developments, A/O systems, mirror technology, and improved optical designs to accommodate evolving scientific measurement objectives during the 50-year anticipated lifetime of the PMA.

We select two example instruments for discussion here. In our first notional design, the prime focus is 30 m (12-m diameter and $F/\# = 2.5$) from the vertex of the primary. Light passes through a field lens and expands to fill the primary of an inverse Schwarzschild.[18,19] This reimaging system is mounted just beyond the prime focus. The field lens relays an image of each segment of the primary onto the 0.6-m diameter active segmented first reflecting surface of the Schwarzschild. PM wavefront errors (tilt, piston, and surface) caused by fabrication and time-dependent thermal, dynamics, and structural effects are compensated for at the 60-cm diameter segmented active Schwarzschild PM. Light reflects to the convex tertiary and then to the focal plane indicated by the circle or to a dispersive element if a spectrometer is chosen. The convex curvature on the tertiary combines with concave powered mirrors 1 and 2 to provide a flat field at the focus. Adjusting the design of the Schwarzschild relay controls the detector sampling frequency. For small fields of view such as those needed for exoplanet coronagraphy and high-contrast imaging of stellar neighborhoods, the transparent field lens could be swung out of the way and replaced by a complex mask for unprecedented direct control of unwanted radiation after the first reflection. There are no fold mirrors in the system, which will minimize polarization aberrations and their deleterious effect on the point spread function (PSF).[20]

The second system is a UV imaging system. We have shown near-diffraction-limited performance down to 150 nm for a 10-m $F/\# = 2.2$ single PM over a 40-arc sec field-of-view (FOV) using a doublet corrector of CaF2 and LiF derived from the Wynne corrector design on the 4-m Mayall telescope. The design work shows promise to give a wider FOV.

Alternatively, the doublet could be moved out of the light path, allowing the beam to go directly to the concave holographically ruled diffraction gratings of a Rowland circle spectrometer with a ~4-arc sec FOV, covering the 90- to 320-nm spectral region with resolutions of 1500 to 30,000. This instrument, similar to the Cosmic Origins Spectrometer on the HST, would provide very high sensitivity for ultraviolet spectroscopy of faint, compact objects.

3.1.4 *Exoplanet applications*

The characterization of terrestrial exoplanets at the extreme 10^{-11} raw contrast level requires the coronagraph instrument designer to minimize polarization aberrations.

The vector electromagnetic (EM) field $\vec{U}(x_3, y_3)$ at the image plane x_3, y_3 is given by[21,22]

$$\vec{U}_3(x_3, y_3) = \mathrm{K} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [\vec{U}_2^-(\xi_2, \eta_2)] \cdot \vec{\tau}_2(\xi_2, \eta_2) \cdot \exp\left[-j \frac{2\pi}{\lambda f}(x_3\xi_2 + y_3\eta_2)\right] \mathrm{d}\xi \mathrm{d}\eta, \quad (1)$$

where $\vec{U}_2^-(\xi_2, \eta_2)$ is the complex field directly in front of the exit pupil and $\vec{\tau}_2(\xi_2, \eta_2)$ is the vector complex transmittance of the exit pupil. For over 30 years, scalar approximations to the vector EM field have been used to model exoplanet coronagraphs.[23] Today, coronagraphs are still optimized using the intensity PSF that is given by the scalar relationship

$$\mathrm{PSF} = |U_3(x_3, y_3)|^2$$

rather than the PSF given by the physical optics properties of the optical system, which require vector representation. The intensity PSF is the convolution of the four PSFs needed to represent the complete transfer function of the optical system

$$\mathrm{PSF} = \left[\mathrm{PSF}_{\|<=\|} \otimes \mathrm{PSF}_{\perp<=\perp}\right] \otimes \left[\mathrm{PSF}_{\|<=\perp} \otimes \mathrm{PSF}_{\perp<=\|}\right],$$

where $\mathrm{PSF}_{\|<=\|}$ is the end-to-end optical system point spread function one obtains from parallel-polarized light in and analyzing the parallel-polarized light out. $\mathrm{PSF}_{\perp<=\perp}$ is the end-to-end optical system point spread function one obtains from perpendicular-polarized light in and analyzing the perpendicular-polarized light out. $\mathrm{PSF}_{\|<=\perp}$ is the end-to-end optical system point spread function one obtains from perpendicular-polarized light in and analyzing the parallel-polarized light out. $\mathrm{PSF}_{\perp<=\|}$ is the end-to-end optical system point spread function one obtains from parallel-polarized light in and analyzing the perpendicular-polarized light out. The two cross-product terms $[\mathrm{PSF}_{\|<=\perp} \otimes \mathrm{PSF}_{\perp<=\|}]$ are highly distorted and typically of low value.[24–27]

However, their magnitude and spatial extent across the image plane depends on the number of high incidence angle reflections in the system, the orientation of those reflections, and the magnitude of the angles. To minimize these cross-product terms, EST minimizes the incidence angles on mirror surfaces.

The point spread function from EST Stage 1 is not rotationally symmetric, but rather approximates that from a rectangular exit pupil 12×4 m in size. This presents the need for additional data processing. Some scientific measurement objectives do require a perfect axially symmetric exit pupil, but since the 1960s, radio astronomers have used nonrotationally symmetric PSFs in all of their interferometric imaging systems. Example systems requiring additional data processing are: the very large array (VLA), Atacama Large Millimeter Array (ALMA), and the very long base line interferometer. Instruments and data analysis methods to process optical images from an asymmetric exit pupil have also been extensively and successfully used by the European Southern Observatory Very Large Telescope Interferometer, the Keck Interferometer, and the CHARA interferometer on Mt. Wilson.

As far as using EST Stage 1 for exoplanet characterization, the Wide-Field InfraRed Survey Telescope Coronagraphic Instrument mission and other space- and ground-based research will have established detailed orbital elements, including on-sky position angle (PA) as a function of time for candidate objects, long before the launch of EST Stage 1. The option remains for the telescope to be rotated about its pointing axis to give the highest angular resolution at the PA of the planet, and multiple images taken at different rotation angles could be combined to cover the entire field of view with the resolution of a 12-m filled aperture. A study is needed to quantitatively assess and trade off the merits of distributing the EST PM over a circular area compared to an irregular-shaped aperture telescope such as EST Stage 1 within the photon-starved regime of exoplanet discovery. Considering the limiting magnitude achievable by an aperture of this area, some exoplanets will be discovered by EST, and these will require additional processing.

The signal-to-noise ratio as a function of the sparseness of the aperture is discussed in detail in Ref. 28. Coronagraphs optimized for exoplanet characterization are in development by several groups.[29,30]

The first stage of the EST will use three 4-m class segments oriented as shown in Fig. 1. With an effective light gathering area of 40 m^2 and a maximum aperture base line of 12 m, this Stage 1 system will be a very capable and productive first stage for EST. Redesign of the instruments, in particular the location and shape of the telescope pupil, will be necessary for the 12-m 6-Hex Stage 2 and the eventual 20-m 18-Hex Stage 3.

Several coronagraph architectures are candidates for application to EST Stage 1. The apodized pupil Lyot coronagraph is a candidate to examine further. N′Diaye et al.[31] show by analysis that an arbitrary aperture can be used for coronagraphy.

3.1.5 *Wide field of view*

Wide-field imaging is available by placing an array of charge coupled devices or equivalent at the prime focus as imaged through a two- or four-element refractive corrector. Wynne[32] designed prime-focus field correctors for the Blanco 4-m telescope at Cerro Tololo (parabolic) and correctors. Near-diffraction-limited fields of view up to 40 arc min have been achieved at a 4-m telescope $F/\# = 2.7$.[33] The dominant aberrations are coma and astigmatism, both of which affect the symmetry of the PSF. If we use the structural aberration coefficients developed by Gardner[34] and Sasian[35] used by Breckinridge,[36] we find that coma increases linearly with the product of diameter times field angle and that astigmatism increases linearly with diameter times the square of the field angle. At wide fields, astigmatism will dominate. Scaling, we find that a 12-m should have diffraction-limited performance over a 5-arc min FOV. The 12-m EST diffraction spot size of 8 mas at 400 nm gives $>10^9$ independent Nyquist sampled resolution elements across the 5-arc min FOV object space. Additional research into innovative optical designs specifically focused on increasing this FOV may double it.

Radiation damage to glasses was extensively studied by the Kepler project, which uses a Schmidt transparent lens corrector. Glass types with the correct dispersion and index properties that also survive long durations in space have been studied,[37,38] but additional work is needed.

3.1.6 *Design advantages*

Large-aperture space telescopes that use a Cassegrain or TMA configuration have been studied and flight hardware built for over 40 years at a total NASA investment $>10 \times 10^9$ dollars. On the other hand, no NASA resources have been expended investigating possible advantages of an innovative approach using a prime-focus configuration. Investigating innovative prime-focus configurations may ultimately provide the science community with a more productive telescope. That remains to be determined.

The advantages of the EST and the PFIA are:

1. There are only three reflections from powered optical elements and no reflections from fold mirrors before the focal plane. The refractive correctors needed for wide-field applications[14] have low curvature. This will minimize reflection losses and system Fresnel polarization aberrations to maximize system transmittance for imaging objects at the threshold of detection and UV spectroscopy.

2. For exoplanet coronagraphy, since the polarization aberrations are minimal, there will probably be an insignificant difference between the aberrations in the two orthogonal polarizations and no need to polarization-divide the pupil-image for optimal adaptive optics correction. This will avoid a 50% loss in system transmittance.

3. In a classical Cassegrain system such as HST and a TMA such as JWST, the telescope optical path passes twice along the metering structure separating the primary and secondary. Length errors caused by thermal changes and structural dynamics of this metering structure are doubled in a Cassegrain configuration compared to a prime-focus system.

4. Because the PFIA looks directly at the PM, the prime focus requires less baffling than a system that locates the instruments behind the primary. This saves mass and reduces system complexity to reduce cost and eliminate sources of unwanted radiation, which create background noise on the detector.

Further investigation is needed to explore other possible advantages of the prime focus such as free-form optics—the diffraction-limited FOV achievable with the inverse Schwarzschild in the presence of the radiation-hard apochromatic prime-focus aspheric correctors will be better optimized using modern free-form optimization.[39] Polarization aberration balancing will be needed to optimize the coronagraph contrast. Telescope dynamics also improve due to the advantages of the two-body dynamics of the prime focus (primary and instruments) compared to the three-body (primary, secondary, instruments) dynamics if the instruments are behind the primary.

3.1.7 *Metering structure*

The metering structure selected for the EST is an adaption of the "deployable optical bench using a tensegrity structure" that was developed by Northrop Grumman for the International X-ray Observer (IXO) mission.[40] The tensegrity truss structure produces a high level of stability once fully deployed, with structural stability provided by deployable telescoping booms and a tension line system. The dimensional stability of the fully deployed structure can best be visualized by understanding the preloading system. The tension truss lines are multisegment telescoping tubes (thin-walled Carbon fiber reinforced polymer (CFRP), developed by Astro Aerospace),[41] each with low CTE metallic end collars structurally bonded to the tube walls. When deployed, the extended tubes preload conical seats in the metallic end collars together without latching; the ends of the tension truss lines are rigidly connected to the base anchor struts and secondary mirror system (SMS) truss points. A compliance feature is mounted in line with the booms, which takes them out of the deployed stiffness path and stabilizes preload levels in the booms. The deployed stiffness of the statically determinate (hexapod) truss tower is provided by the tension truss lines and hex base, whereas the booms provide compressive preload and carry mass. Dimensional changes in the SMS position caused by factors such as stress changes, outgassing, thermal effects, and so on, are compensated by linear actuators connecting the tension truss lines to the secondary mirror truss structure. Tension truss line adjustment is via stepper drives, which are activated only if a PM segment hexapod mount is reaching the end of its design travel—tension line adjustment recenters the PM segment hexapod travel. The PM hexapods in turn adjust only in response to an SMS mirror segment positioner reaching the end of its travel limit. It is expected that the active PM and SMS hexapod adjustments would easily handle the temperature-driven length variations caused by telescope pointing slews. The tension line stepper-driven linear actuators would be sized with enough travel to provide at least 10× (or more) of the predicted lifetime adjustment requirement. The preloading clock spring travel limits are sized to be similar to the tension line actuator travel limits (and could also be adjustable if desired).

3.2 *Infrastructure for Launch, Assembly, and Servicing*

3.2.1 *Launch vehicles*

An essential element of an affordable EST development is an adequate launch vehicle. To remain on the required conservative cost curve, the EST will need to employ lower-cost launch systems that are available when it is ready to enter the operational stage, and it must avoid any launch system that is a special development or that creates a single critical path and/or failure mode. Fortunately, there are several launch families that either are or will be available to provide sufficient lift mass within 5 m outside diameter fairings when the EST is ready. These include the SpaceX Falcons, the Atlas and Delta vehicles from the United Launch Alliance (ULA), and the ESA Ariane 5, as detailed by Rioux et al.[12] There is also a considerable effort by the developers to reduce the costs of their vehicles and to develop more capable and less costly future systems.

3.2.2 *Assembly and servicing*

The existence of a mature in-space assembly and servicing infrastructure, either purely telerobotic, purely crewed, or most likely a combination of telerobotic and crewed, is essential to the EST concept (as to most others). The foundation for in-space assembly and servicing methods and infrastructure is now being laid, principally in the NASA SSCO at Goddard SFC, which is currently conducting the Restore-L program to develop the technology for limited servicing of low Earth orbit (LEO) satellites and make it available for commercial use under standard conditions for government-developed technologies. In addition, Defense Advanced Research Projects Agency is conducting a similar program, Robotic Servicing of Geosynchronous Satellites (RSGS) that will be used for geosynchronous altitude satellites and will also make servicing technologies available to commercial entities. While concepts and technologies from both of these programs will be applicable to the assembly and servicing of the EST, they are not being conducted fully in the public domain, and details are not available for this paper. However, based on the earlier work by Lillie and MacEwen,[42] the needs and some of the approaches for EST servicing are discussed in another paper in this journal (MacEwen and Lillie[13]).

4 Summary

In this paper, we have discussed the analyses we have conducted of an alternative architecture for future large astronomical observatories. A primary goal of this effort is to demonstrate to NASA and the science community the need to explore alternative architectures to mitigate cost issues, adapt to new technologies, and better integrate into future in-space assembly and servicing. The space observatory environment has changed substantially over the past decades, both positively, such as in advanced mirror and wavefront control technologies, the high probability of lower-cost access to space, and a growing in-space operations capability; and negatively, in observatory costs growing faster than can be easily accommodated by flat budgets. The alternative architecture approach discussed in this paper is highly viable and can address all the currently foreseeable future science goals. We believe that we should not constrain ourselves to a future of rebuilding our grandfather's space telescope.

The EST concept focuses on how to build a large space telescope in a flat science budget era by mitigating big cost peaks and by encouraging and embracing the development of in-space assembly and servicing infrastructure. The EST starts with a modest-size off-axis telescope (equivalent to a ∼7-m filled aperture telescope) that is launched as a fully functional telescope with instruments (EST Stage 1) performing first-rank science. After the passage of time (∼5 years), an augmentation mission is sent to the observatory with additional mirror segments, instruments, and other needed hardware to grow it in space to a ∼12-m filled aperture observatory (EST Stage 2). Future augmentations would again increase its size and add new instruments and support hardware to create a ∼20-m filled aperture observatory (EST Stage 3). After EST Stage 3, additional augmentations are also possible, either to maintain or upgrade the 20-m telescope for decades or to grow it to even larger sizes with added mirror elements.

Again, we encourage NASA and the astrophysics community not to be constrained only to traditional space telescope approaches, but rather to fully explore and evaluate alternative architectures for these space telescopes. The technologies that enable these different approaches are either mature or maturing rapidly, so the risk levels are very manageable. They do, however, require a culture change. These alternative approaches can offer cost savings and performance enhancements over traditional methods and can enable a more capable astrophysical observatory earlier in time than the traditional approach.

Acknowledgments

The authors would like to acknowledge strong support and internal funding from Northrop Grumman Aerospace Systems and very helpful comments, suggestions, and criticisms from a variety of people, including Jonathan Arenberg, Suzanne Casement, Alberto Conti, Marc Postman, Ken Sembach, Wes Traub, and Harley Thronson.

References

1. H. Thronson et al., "The path to a UV/optical/IR flagship: ATLAST and its predecessors," *J. Astron. Telesc. Instrum. Syst.* **2**(4), 041210 (2016).
2. J. Dalcanton et al., *From Cosmic Birth to Living Earths: The Future of UVOIR Astronomy*, Association of Universities for Research in Astronomy (AURA), Washington, DC (2015).
3. D. Miller et al., "Assembly of a large modular optical telescope (ALMOST)," *Proc. SPIE* **7010**, 70102H (2008).
4. L. Feinberg et al., "Modular assembled space telescope," *Opt. Eng.* **52**(9), 091802 (2013).
5. W. Oegerle et al., "Concept for a large scalable space telescope: in-space assembly," *Proc. SPIE* **6265**, 62652C (2006).
6. National Aeronautics and Space Administration, Goddard Space Flight Center, "On-Orbit Satellite Servicing Study Project Report," NASA GSFC SSCP-RPT-000144 (2010) http://ssco.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf (May 2016).
7. H. P. Stahl et al., "Update to single-variable parametric cost models for space telescopes," *Opt. Eng.* **52**(9), 091805 (2013).
8. A. Witze, "NASA plans Mars sample-return rover," *Nature* **509**, 272 (2014).
9. M. R. Bolcar et al., "A technology development plan for a future large-aperture ultraviolet-optical-infrared space telescope," *J. Astron. Telesc. Instrum. Syst.* **2**(4), 041209 (2016).
10. R. S. Polidan et al., "An evolvable space telescope for future astronomical missions," *Proc. SPIE* **9143**, 914319 (2014).
11. R. S. Polidan et al., "An evolvable space telescope for future astronomical missions 2015 update," *Proc. SPIE* **9602**, 960207 (2015).
12. N. Rioux et al., "A future large aperture UVOIR space observatory: reference design," *Proc. SPIE* **9602**, 960205 (2015).
13. H. MacEwen and C. Lillie, "Infrastructure for large space telescopes," *J. Astron. Telesc. Instrum. Syst.* **2**(4), 041208 (2016).
14. C. Underwood et al., "Autonomous assembly of a reconfigurable space telescope (AAReST)—A cubesat based technology demonstrator," in *27th-Annual AIAA/USU Conf. on Small Satellites* (2013).
15. A. B. Meinel and M. P. Meinel, "Two-stage optics: high acuity performance from low-acuity optical systems," *Opt. Eng.* **31**, 2271–2281 (1992).
16. J. B. Breckinridge and H. J. Wood, "HST optics," *Appl. Opt.* **32**, 1677 (1993).
17. J. R. Fienup et al., "Hubble space telescope characterized by using phase retrieval algorithms," *Appl. Opt.* **32**, 1747–1767 (1993).
18. W. B. Wetherell and M. P. Rimmer, "General analysis of Aplanatic Cassegrain, Gregorian, and Schwarzschild telescopes," *Appl. Opt.* **11**, 2817–2832 (1972).
19. A. Budano, F. Flora, and L. Mezi, "Analytical design method for a modified Schwarzschild optics," *Appl. Opt.* **45**, 4254–4262 (2006).
20. J. B. Breckinridge and B. Oppenheimer, "Polarization effects in reflecting coronagraphs for white light applications in astronomy," *Astrophys. J.* **600**, 1091–1098 (2004).
21. J. W. Goodman, *Introduction to Fourier Optics*, Roberts & Co. Publishers, Greenwood Village, Colorado (2005).
22. J. B. Breckinridge, T. Lam, and R. Chipman, "Polarization aberrations in astronomical telescopes: the point spread function," *Publ. Astron. Soc. Pac.* **127**, 445–468 (2015).
23. J. B. Breckinridge, T. G. Kuper, and R. V. Shack, "Space telescope low scattered light camera: a model," *Opt. Eng.* **23**, 816–820 (1984).
24. J. B. Breckinridge, W. S. T. Lam, and R. A. Chipman, "Polarization aberrations in astronomical telescopes: the point spread function," *Publ. Astron. Soc. Pac.* **127**, 445–468 (2015).
25. R. A. Chipman, W. S. T. Lam, and J. B. Breckinridge, "Polarization aberration in astronomical telescopes," *Proc. SPIE* **9613**, 96130H (2015).
26. J. B. Breckinridge, "Self induced polarization anisoplanatism," *Proc. SPIE* **8860**, 886012 (2013).
27. J. B. Breckinridge and B. Oppenheimer, "Polarization effects in reflecting coronagraphs for white light applications in astronomy," *Astrophys. J.* **600**, 1091–1098 (2004).
28. J. Breckinridge, N. Bryant, and J. Lorre, "Innovative pupil topographies for sparse aperture telescopes and SNR," *Proc. SPIE* **7013**, 70133E (2008).
29. O. Guyon et al., "High-contrast imaging and wavefront control with PIAA coronagraph: Laboratory system validation,"*Publ. Astron. Soc. Pac.* **122**, 71–84 (2010).

30. N. T. Zimmerman et al., "Shaped pupil Lyot coronagraphs: high-contrast solutions for restricted focal planes," *J. Astron. Telesc. Instrum. Syst.* **2**(1), 011012 (2016).
31. M. N′Diaye, L. Pueyo, and R. Soummer, "Apodized pupil Lyot coronagraphs for arbitrary apertures IV: reduced inner working angle and increased robustness to low-order aberrations," *Astrophys. J.* **799**, 225 (2015).
32. C. G. Wynne, "Field correction for very large telescopes," *Mon. Not. R. Astron. Soc* **273**, L45–L46 (1995).
33. C. G. Wynne, "Wide field imaging," *Mon. Not. R. Astron. Soc.* **236**, 47–50 (1989).
34. I. C. Gardner, "Applications of the algebraic aberration equations to optical design," scientific papers for the National Bureau of Standards 22, US Government Printing Office, pp 73–202 (1927).
35. J. Sasian, *Introduction to Aberrations in Optical Imaging Systems*, Cambridge University Press, Ch. 11, pp. 147–162 (2013).
36. J. B. Breckinridge, *Basic Optics for the Astronomical Sciences*, pp. 84–99, SPIE Press, Bellingham, Washington (2012).
37. H. Liu et al., "Effects of space environment factors on optical materials," *J. Spacecr. Rockets* **42**(6), 1066–1069 (2005).
38. G. Naletto et al., "Effects of proton irradiation on glass filter substrates for the Rosetta mission," *Appl. Opt.* **42**, 3970–3980 (2003).
39. K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "Theory of aberration fields for general optical systems with free-form optical surfaces," *Opt. Express* **22**, 26585–26606 (2014).
40. R. Danner et al., "Enhancing the International X-ray Observatory," *Proc. SPIE* **7732**, 77323V (2010).
41. "Deployable structures for space applications," in *Northrop Grumman Astro Aerospace Products* (2016) http://www.northropgrumman.com/BusinessVentures/AstroAerospace/Products/Pages/TelescopicTubeMasts.aspx (May 2016).
42. C. Lillie and H. MacEwen, *Flexible Servicing in Deep Space—MiniServ*, AIAA SPACE, San Diego, California (2014).

Ronald S. Polidan is an astrophysicist with an extensive background in technology development. His career spans over 35 years, in academia (12 years), at NASA (14 years), and at Northrop Grumman Aerospace Systems (12 years). Since 1998, his work has been mostly in technology and mission concept development areas. His past positions include chief technologist for GSFC and chief architect for civil systems at Northrop Grumman. Now, he runs a small science and technology consulting company.

James B. Breckinridge spent 33 years building optical instruments at NASA/JPL and 12 years in solar physics at KPNO. He studied under Shack and Meinel to earn the PhD in optical science from the University of Arizona. In 2010, he left JPL to establish a consultancy and join academia at Caltech and the College of Optical Sciences. He holds 5 patents, published 120 papers and 1 book and teaches with active research in coronagraphy and telescope architectures.

Charles F. Lillie is an astrophysicist and systems engineer with more than 50 years experience in government, industry, and academia. He retired from Northrop Grumman Aerospace Systems (formerly TRW Space and Defense) in 2011, after 32 years as a program manager and SME for space science and mission design. Before joining TRW, he was an associate professor at the University of Colorado and a fellow of LASP. Currently, he is a consultant to the aerospace industry.

Howard A. MacEwen has spent over 45 years identifying, evaluating, and advocating new technologies and concepts for space systems, specifically optical systems for intelligence, defense, and astronomy, detectors and sensor system assemblies for space telescopes, materials and components for telescope primary mirrors and other elements of complete optical assemblies, wavefront sensing and control, manufacturing, testing, and metrology infrastructures, system integration, and needs and requirements for concepts enabled by these technologies.

Martin R. Flannery received his BS in physics from Caltech in 1968 and a PhD in electronics and physics from USC in 1979. He worked for Xonics from 1976 to 1978, joined Hughes Aircraft in 1979 and TRW in 1982, continuing with Northrop Grumman since 2002. At TRW, he worked on high power lasers, later on astronomical telescopes, hyperspectral earth imagers and high power fiber laser systems. He is an optical designer and optical and materials physicist.

Dean R. Dailey (BSME from CSULB in 1982) is a retired aerospace engineer with 33 years of experience with Northrop Grumman/TRW Space Division. He specialized in spacecraft and space-based payload architecture and structures and mechanisms mechanical design and analysis. Proficiency in solid modeling (Catia), finite element modeling and analysis (Femap), dynamic modeling and analysis (ADAMS), visual basic analysis (Excel), preliminary orbital dynamics/modeling (STK)—mechanical systems engineering/architecture through detailed mechanical design, and analysis for fabrication.