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Future Capabilities in Space Servicing and Assembly: Opportunities for Future Major Astrophysics Missions

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The performance of astronomical observatories – sensitivity, signal-to-noise ratio, angular resolution – depends upon a high power of the telescope aperture, which has for centuries been the compelling motivation for the enormous effort put into ever-increasing telescope size. Although ground-based telescopes seem at present to be limited in aperture only to available technologies and budget, space-based observatories must also confront, in addition, limited capabilities of available launch vehicles. Since the launch of the first successful space observatory, OAO-2, 50 years ago, astronomers have endeavored to use every kilogram and cubic meter made available to them by existing launch vehicles of the era. As new capabilities were developed, astronomers were quick to adapt them to the next generation of space observatories. Perhaps the most iconic example of this has been NASA's Hubble Space Telescope (HST), which not only adapted technologies developed for space optical systems designed for national security, but also was designed to be launched by the Space Shuttle and, memorably, upgraded by astronauts in five subsequent servicing missions. More recently, with priority science goals for the early 21st century requiring apertures greater in diameter than the largest launch vehicle fairing, engineers and technologists designed the James Webb Space Telescope (JWST) with its segmented 6.5-

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meter mirror to be self-deployed once in space and on the way to its operating venue, the second Sun-Earth libration point (SE L2). Significantly for this report, JWST is not likely to remain the largest space observatory desired by astronomers: early self-deployed concepts being developed for the upcoming National Academies' Decadal Survey in Astronomy and Astrophysics have approached the limit enabled by the largest version of the future NASA Space Launch System (SLS). What capabilities will be required when even larger apertures are required? We will discuss the technical and engineering merits and challenges of in-space servicing and assembly, including issues of launching telescopes and instruments in parts, assembly in space, and repair and replacement of instruments and systems. Possible future space infrastructure that may make on-orbit assembly and servicing feasible will also be discussed. Precursors and demonstration activities will be presented, as well as early candidate missions for in-space upgrade and servicing.

I. Introduction and Background

For centuries astronomers have recognized the criticality of designing and building increasingly larger-aperture telescopes, which has driven the search for technologies that will allow affordable – that is, feasible – observatories over a wide range of wavelengths. Over the past century or so, for example, the largest ground-based individual apertures have gone from one or two meters in diameter to today's very common ten-meter-class facilities, often as part of a multi-telescope observatory. Even larger telescopes will become available on the ground in coming decades. The increase in capabilities of instrumentation has been at least equally impressive. The motivation for this growth in aperture size is easy to understand, given that the signal-to-noise of an observation of an astronomical source in a given time increases as a strong power of the aperture (D), ~$D^{2 \text{ to } 4}$, depending upon the nature of the source and its environment. Of course, an increase in the signal-to-noise of an observation translates into a reduction in integration times, increasing usable spectral resolution, and/or allowing more areas on the sky to be mapped.

These considerations apply equally to space observatories, which, due to operating in a hostile environment often far from Earth, face greater technological and engineering hurdles than do ground-based observatories. As space observatories have been operated successfully for decades, for the purposes of this paper, however, the most significant engineering challenge is the limitation imposed by the requirement to be contained within the launch vehicle upper stage fairing. Over many wavelengths, detector performance has approached theoretical limits. Thus, further scientific advancement now generally requires larger apertures, substantially larger today than the inner diameter of available launch vehicles. At present, the redoubtable James Webb Space Telescope (JWST) design is expected within a few years to demonstrate one obvious solution to the limit of fairing sizes: remote self-deployment of a segmented optical system folded to fit into the fairing of its Ariane 5 launch vehicle.

As successful, albeit extremely challenging, as self-deployment by JWST is intended to be, eventually a proposed telescope aperture will be reached that can no longer rely solely on remote self-deployment to achieve its operating aperture. Over the past decade, increasingly detailed concepts have been described for future observatories ranging in aperture up to ~15 meters [1,2,3], which seems to be the maximum that can be self-deployed from the largest fairing proposed for the "super heavy-lift" Space Launch System (SLS) Block 2 Cargo, a vehicle being designed for future human missions to Mars. A 15-meter space observatory will truly be an impressive scientific instrument, even in the era of 40+ meter ground-based observatories. For example, at present, the faintest galaxies that have been imaged (via the 23-day exposure of the Hubble eXtreme Deep Field [HXDF]) are around one-ten billionth of the faintest objects that the human eye can detect. Including the advances in detector performance over the many years since imaging instruments were last installed on the Hubble Space Telescope (HST), a telescope aperture 6 times greater in diameter would be a profound advance in capability.

Even larger space observatories will require alternatives to self-deployment. The obvious alternative is in-space assembly (iSA), which may take advantage of current and near-future technological capabilities unavailable to JWST-style self-deployment:

- lower-cost medium-lift launch vehicles to carry observatory elements into space for subsequent assembly,
- increasingly capable space robotics, and
- on-site astronauts at a Gateway-type habitation and operations site or other assembly venues

Moreover, assembly in space may permit more innovative optical designs that perhaps would evolve over time, as well as lighter-weight materials able to be launched for assembly in packaging not possible for "all-up" concepts deployed as a single unit.

II. The Science Case for Very Large Apertures

The science justification for space observatory apertures greater than that of JWST, which in turn justifies assessment of in-space assembly, is impressive.

Since at least the mid-1980s, long before the HST became an iconic scientific instrument, astronomers advocated priority science goals possible only with apertures at ultraviolet, visual, and near-infrared (UVOIR) wavelengths five times that of HST and at least twice that of JWST. Remarkably, many of the basic design requirements and some priority scientific objectives of those ambitious concepts of three decades ago, which were advocated as the natural eventual successors to HST, are just as compelling today.

For historical interest, probably the earliest substantive identification of a large UVOIR space observatory specifically intended to follow HST was the National Research Council Space Science Board (SSB) report, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 – 2015* (begun in 1984 and published in 1988; see summary by Field [4]). Volume II of this report presciently observed, “A large-aperture space telescope for the [UVOIR] regions has immense scientific potential. The need for such a telescope will be very high after 10 to 20 years of use of HST . . . Even now we see that some of the most fundamental of all astronomical questions will require the power of a filled-aperture telescope of **8- to 16-m diameter** designed to cover a wavelength range of 912 Å to 30 μm, with ambient cooling to 100 K to maximize infrared performance.” [Emphasis added.]

Not long after the SSB report, in his overview of the influential 1989 Space Telescope Science Institute (STScI) community workshop report, *The Next Generation Space Telescope*, Illingworth [5] urged the participants to “look beyond, to the missions that will succeed the Great Observatories.” Illingworth summarized the basic parameters of the notional mission concept embraced at the workshop: again, a 10 – 16 meter-class telescope operating from ~0.1 μm to “beyond 10 μm” thanks to passive cooling to 100 K.

In the proceedings of the STScI workshop, Illingworth summarized a selection of some of the most exciting science that a large post-HST observatory would be capable of, including revealing important structures in cosmologically distant galaxies observable throughout the Universe with scale sizes of 100 – 1000 pc. Recent and more sophisticated modeling reinforces the importance of high-resolution observations of very distant – hence, very young – galaxies [3].

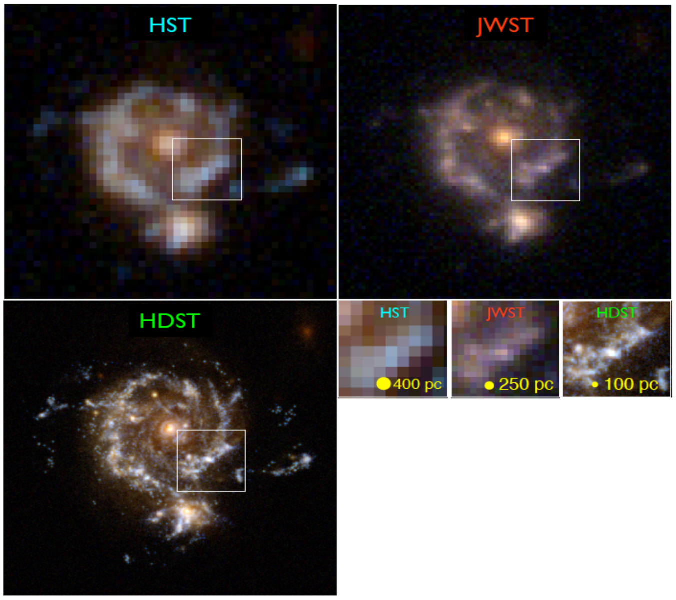


Fig. 1 Simulated galaxy at an age of the Universe of about 3 Gyr as imaged by space telescopes of different apertures: HST (2.4 m), JWST (6.5 m), and the High-Definition Space Telescope (12 m) [2].

In the same 1989 conference summary, Illingworth also pointed out the exciting prospect of such a mission being able to detect Earth-like planets orbiting stars within 10 pc of the Sun. In the same proceedings, Angel observed that the search for Earth-like planets “was in large measure the original rationale for such a large telescope" in the SSB report published in 1988. His article, which emphasized the daunting engineering challenges to such a mission, included discussion of the required performance of an observatory able to search for biomarkers in hypothetical Earth-like planets and discussed those biomarkers considered at the time to be most revealing. Figure 2 shows a UVOIR spectrum of a well-known life-bearing planet.

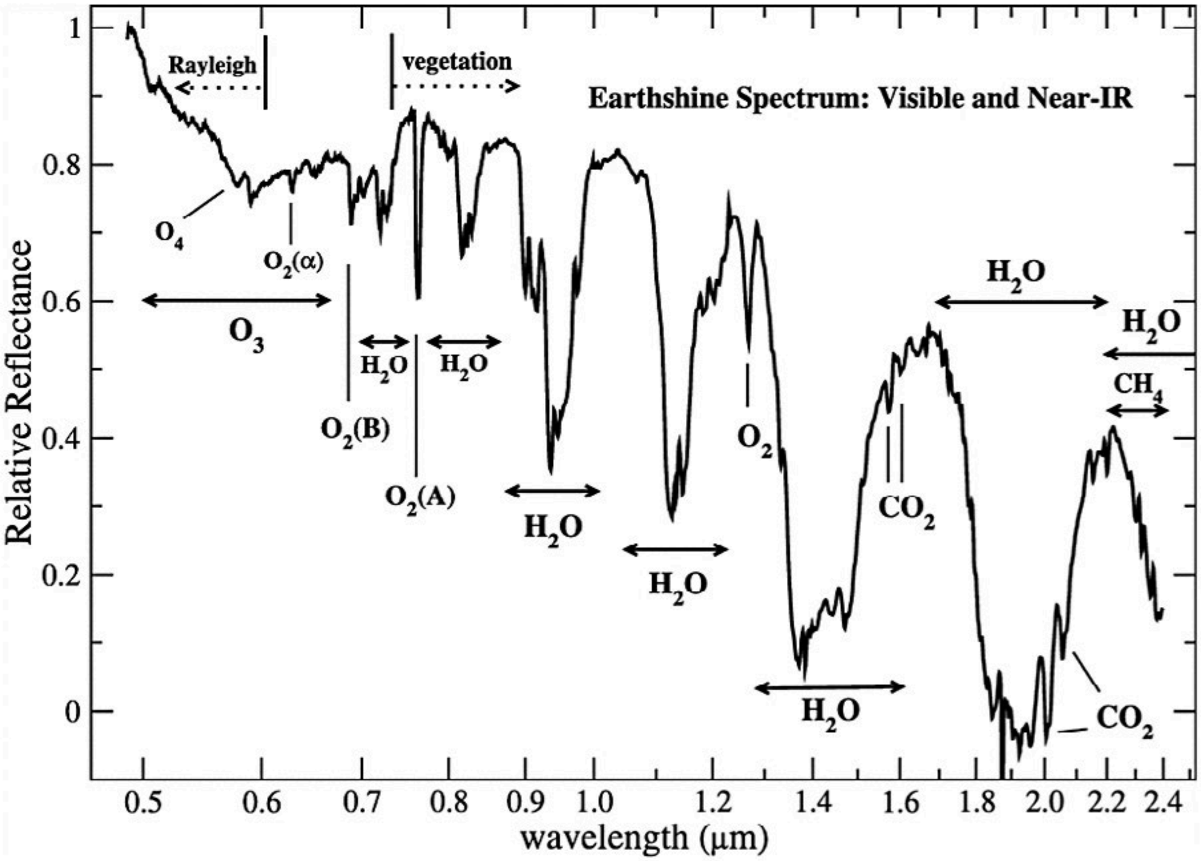


Fig. 2 Spectra of the Earth, a known life-bearing planet [6].

III. What In-Space Assembly Enables and Enhances

Although in-space assembly (iSA) was considered as an option to enable space observatories as soon as required apertures were larger than the inner diameter of plausible launch vehicles, until recently its necessity was considered to be far in the future. However, with concepts for post-JWST space telescopes at or exceeding the available volume of launch vehicle fairings undergoing advanced concept development, the impetus is growing for a sustained examination of options for iSA.

Consider what is enabled or enhanced by having the capability to assemble large structures in space, either with robots and/or astronauts:

- Telescope designs that are not encumbered by the constrains of a single launch vehicle fairing, for example
  - Monolithic apertures greater than the current limit of ~15 meters for self-deployed telescopes requires a launch vehicle developed for the human exploration of Mars
  - Spatial interferometers or starshades that are extremely challenging to self-deploy no matter what their size
  - Alternative telescope architectures that improve science return, but would have had difficulties with an autonomous deployment approach can be considered.
- Telescope apertures that may be able to grow over time as budgets and technology developments permit.

- Extension of an observatory's operational life by replacing and upgrading instruments and subsystems that wear out or whose performance is exceeded by newer technologies.
- Observatories made up of a much lighter structure thanks to the elimination of the launch loads of a fully assembled, self-deployed design.
- Lower-cost, "standard" medium-lift launch vehicles may be adopted.
- Reduction in the need for new ground test facilities that have a single, unique purpose.
- Reduction in overall risk

Furthermore iSA may reduce overall mission cost by moving away from "craft-built" space observatories toward some aspects of "assembly line" or modularized construction where greater commonality with previous systems may be possible. For example, individual observatory modules may be tested in parallel, rather than in a fully assembled mission. In addition, cross-cutting capabilities may be able to be employed, thus spreading the cost across multiple participating programs.

In addition, integration and testing of the components of a telescope to be assembled in space is likely to be substantially less expensive than would be the case for an equivalent-aperture system tested "all up" on the ground. Smaller and less-expensive ground test facilities would likely involve a substantially reduced "standing army," a major driver of total mission cost.

We hasten to add, of course, that as of this writing lowering the cost of a future larger-aperture telescope is educated speculation. Although space assembly has been proposed for consideration for decades, in-depth trade studies have rarely been undertaken, so there are a large number of unknowns to a program of space assembly. Consequently, our team has a proposed trade study under consideration by NASA to explore this critical issue in greater detail in the coming year.

IV. The Future Assembly/Servicing Study Team (FASST) Workshop Series

Our assessment activity of options, technologies, telescope designs, robotic systems, assembly by astronauts, and capabilities to achieve major science goals was initiated in a rump session at the 229th meeting of the American Astronomical Society in January, 2017. About a dozen astronomers and technologists together discussed the growing realization that early concepts for post-JWST UVOIR space observatories, if self-deployed, would require the largest SLS vehicles under consideration for human exploration of Mars. Unless there was a major change in the current convention for mission development and management, such a mission could also consume a larger fraction of NASA's astrophysics budget for a decade.

Consequently, this small group agreed to undertake formal engineering assessments of options for assembly in space of a ~15+ meter UVOIR observatory with the near-term goal of a 2019 report to the NASA Headquarters Astrophysics Division and the National Academies' 2020 Decadal Survey of Astronomy and Astrophysics. The results of these assessments, including professional presentations, summaries of the trade studies, and design concepts, will be found as they are produced at https://exoplanets.nasa.gov/exep/technology/in-space-assembly/

A. The First Workshop

Our first iSA Technical Interchange Meeting (TIM) was held at Goddard Space Flight Center on November 1-3, 2017. The goal of the meeting was to engage for the first time professionals from three major communities associated with space assembly of large telescopes: astronomers to provide scientific drivers and telescope design and definition; developers of future space robotics systems to establish a current context and an assessment of likely future robotic capabilities; and NASA- and industry-led designers of a cis-lunar habitat to supply a vision of the in-space infrastructure that may exist to help in the assembly of future large telescopes. This TIM was attended by over 70 participants spanning all the desired communities and who were asked to address a series of top-level questions regarding in-space assembly of telescopes:

- What is changing in the engineering and technological environment to better enable in-space assembly of telescopes?
- How would iSA enable innovative instrument and telescope designs?
- How would iSA reduce cost and risk, both technical and programmatic?
- How will future large observatories be serviced?
- What are possible precursor demonstration activities?

A detailed summary package containing the meeting agenda, a list of attendees, excerpts from presentations, a complete list of findings and suggestions/recommendations made to NASA can be found on our iSA web site (above).

A few of the findings from this TIM as reported to NASA Headquarters Astrophysics Division (APD) were:

- iSA is an important and enabling capability that has clear applications to near-term NASA Astrophysics Division objectives, including concepts being developed for post-JWST missions.
- The current paradigm of telescope design (deployed or monolithic) does not contribute to the design of subsequent large-aperture space telescopes. Hence, the cost model for large telescopes is unlikely to change unless there is a paradigm shift.
- There is a revolution in the TRL of robotics on the ground and, for example, DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) and NASA Goddard Space Flight Center's Restore-L missions are embodiments of this for space operations.
- The "serviceability" of future telescopes is ambiguous as there is recognition that there are no ready servicers. Consideration ought to be given on how to leverage existing servicer work (e.g., RSGS, Restore-L), including the opportunities enabled by a cis-lunar human-occupied operations and habitation facility (usually referred to as the Gateway).
- A completed NASA Gateway infrastructure potentially offers a unique facility in which APD may be able to leverage the iSA of future large telescopes.
- Industry has very strong interest in iSA and can play an important role.

In addition, the GSFC TIM developed a set of suggestions and recommendations that were forwarded to NASA APD for consideration. Key among these were:

1. Commission a design study, with industry and academia participation, to understand how large-aperture telescopes could be assembled and serviced in space in time for initial results to be available to Gateway and robotics designers within 2018, but certainly before the end of 2019.
2. Consider initiating an iSA coordination group among the three NASA HQ Mission Directorates, perhaps with international space agencies as well.
3. Consider providing input to the 2020 Decadal Survey about iSA as a potential implementation approach for future large apertures.

NASA APD accepted the 1st and 3rd recommendations and a funded iSA design study was chartered with a second technical workshop held in June 2018 to begin a technical assessment of many of ideas, concepts, and issues raised during the first workshop.

B. The Second Workshop

NASA's Exoplanet Exploration Program Office, based at JPL, organized and hosted our second workshop and first trade study, at the Keck Institute for Space Studies (KISS), June 5 – 7, 2018. The emphasis was on designing and analyzing a modularized – that is, able to be assembled – space telescope. Included in this goal was to advance the variety of selection criteria for an eventual final design while building a broad community of experts in space assembly. The ground rules for the concept assessment included

- The basic telescope design:
  - A 20-meter, off-axis, filled-aperture segmented design operating at UVOIR wavelengths, and
  - Operating at the Sun-Earth L2 venue.
- The instrument suite includes a high-performance coronagraph to search for exo-Earths.
- Astronaut- and robot-enabled assembly would be available.
- The launch vehicle of choice uses a widely available 5-meter fairing.

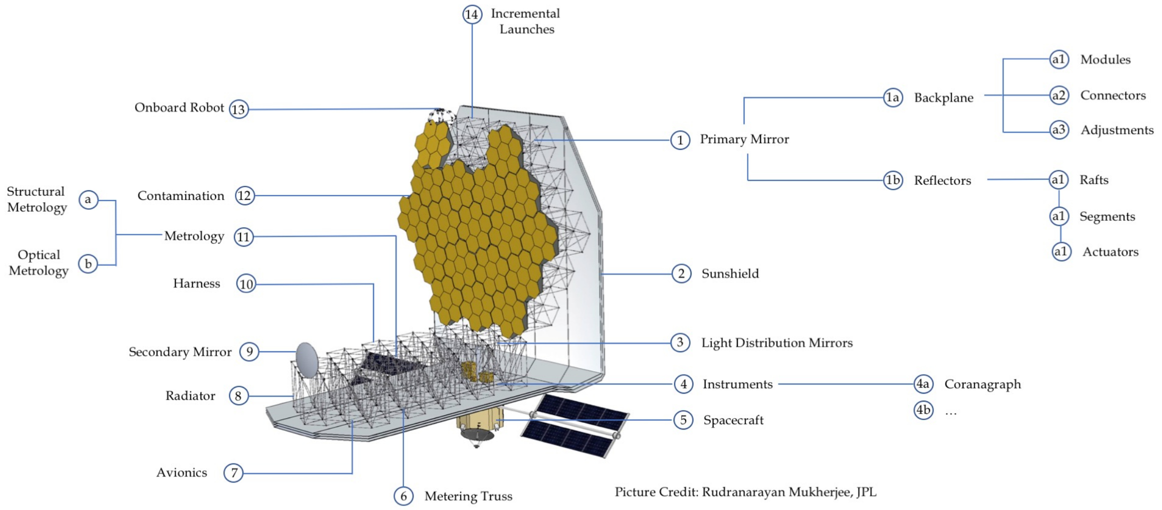
The aperture size was chosen to be significantly larger than current concepts for future self-deployed UVOIR space observatories. Consequently, a successful assembled observatory of this design would be a major increase in scientific capabilities.

Breakout teams at the workshop undertook an initial modularization of the primary mirror, its backplane, and telescope system, as well as an assessment of a program of integration and test, both on the ground and in space. The modularization trade space for the observatory was very open in the workshop and included

- Number of modules,
- Mirror segment size, segment carriers, and sunshade,
- Backplane architecture,
- Power, latching, and harnessing, and

- Instrument carriers and thermal management.

Figure 3 shows the basic observatory design that we adopted for our trade study and telescope elements that were discussed. We hasten to add that our workshop dealt with these elements and the issues of modularization and assembly in a preliminary manner, recognizing the significant amount of work yet to come and that this particular design is being evaluated as a proof-of-concept of the value of iSA.



Picture Credit: Rudranarayan Mukherjee, JPL

Fig. 3 The concept adopted for consideration by this activity, including major observatory elements adopted for modularization.

Our workshop concluded that the 20-meter off-axis design would serve well as a reference design for further work and there were no obvious technical or engineering barriers or "show stoppers." Most significantly, the consensus of the several dozen workshop professionals was that assembling the reference design in space was feasible with current and anticipated capabilities and processes.Three analyses will be undertaken to follow up on the workshop:

- Primary mirror truss height and structure
- Stray light analysis
- Sunshade architectural concept

B. The Third Workshop

Colleagues at NASA LaRC will host our third workshop and second trade study during 2 – 4 October 2018. The focus of this study will be on assembly, testing, robotics, assembly platforms, and launch vehicles.

IV. Summary of Next Steps

With the successful conclusion of the second workshop and overall satisfaction with the workshop outcomes, there was unanimous agreement to pursue a more detailed engineering assessment effort. Detailed summaries of the workshop discussions and conclusions were generated and distributed to the attendees. A series of telecons are being carried out to further discuss and assimilate the results from the second workshop and to begin the process of defining our third technical workshop to continue to advance the telescope modularization activity associated with in-space assembly. This next iSA engineering workshop will focus upon the topic of assembling and testing the modularized reference telescope.

Assuming that a few end-to-end architecture concepts produced by this third workshop survive with the promise to achieve the needed science capabilities and reduction of cost and risk with respect to traditional approaches, an in-depth engineering study of in-space assembly of very large astronomical telescopes will commence in FY 2019. Information on the schedule, scope, and opportunities for community involvement in this investigation will be posted on our iSA web site (https://exoplanets.nasa.gov/exep/technology/in-space-assembly).

Although the near-term goal of our study is to supply usable engineering design detail to NASA's Astrophysics Division, as well as the upcoming National Academies' Decadal Survey, our results and processes are being shared for consideration by the NASA-funded major design teams as they develop their largest concepts. In parallel, our design activities also include representatives of developers of robotic systems so that they may incorporate our scenarios as they consider future directions for development of space robotic systems.

Acknowledgments

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