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Science Enabled by the Ares V: A Large Monolithic Telescope Placed at the Second Sun-Earth Lagrange Point

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The payload mass and volume capabilities of the planned Ares V launch vehicle provide the science community with unprecedented opportunities to place large science payloads into low earth orbit and beyond. One example, the outcome of a recent study conducted at the NASA Marshall Space Flight Center, is a large, monolithic telescope with a primary mirror diameter of 6.2 meters placed into a halo orbit about the second Sun-Earth Lagrange point, or L2, approximately 1.5 million km beyond Earth's orbit. Operating in the visible and ultraviolet regions of the electromagnetic spectrum, such a large telescope would allow astronomers to detect bio-signatures and characterize the atmospheres of transiting exo-planets, provide high resolution imaging three or more times better than the Hubble Space Telescope and the James Webb Space Telescope, and observe the ultraviolet light from warm baryonic matter.

Nomenclature

AR&D = Autonomous Rendezvous and Docking
AU = Astronomical Unit, the mean distance between Earth and the sun
C3 = Twice the orbital energy
HST = Hubble Space Telescope
HTXS = High Throughput X-ray Spectroscopy
IR = Infrared electromagnetic radiation
JWST = James Webb Space Telescope
L2, SEL2 = Sun-Earth Lagrange Point collinear with the Sun-Earth line but outside Earth's orbit
LEO = Low Earth Orbit
mT = metric ton
OD = Outer Diameter
OTE = Optical Tube Enclosure
PD = Payload Dynamic Envelope
SIB = Spacecraft/Instrument Bus
UV = Ultraviolet electromagnetic radiation
VLT = Very Large Telescope

I. Introduction

Our fascination with our natural history, and our future, seems to only increase with each scientific discovery. The Hubble Space Telescope (HST), launched in 1990, has yielded incredible insight into the structure and natural history of the universe. Orbiting the earth at an altitude of more than 500 km, the HST is well out of reach of the atmosphere's optical effects, allowing stunning images and access to wavelengths of radiation that are normally attenuated by the atmosphere. With a single 2.4-meter-diameter primary mirror, the HST is relatively small when compared with today's largest monolithic ground-based optical telescopes, which have primary mirror diameters of up to 8 meters or more. Since the diameter of the primary mirror largely determines the light gathering capability of

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a telescope, one can imagine the incredible discoveries that will be enabled by placing the equivalent of a large ground-based observatory into space.

Few scientists would dispute the scientific benefit and incredible discoveries resulting from the Hubble Space Telescope. The advantages of a space-based telescope, out of reach of the Earth's atmosphere, are clear. Most large terrestrial telescopes strive to optimize the balance between accessibility and minimal atmospheric interference. The Palomar observatories, home of the 200-inch Hale reflector, sits at an altitude of approximately 5500 feet, in a region of the country noted for dry, clear air at the time of the telescope's construction. The suite of telescopes at Kitt Peak National Observatory near Tucson, Arizona, sit in very dry, clear air at an altitude of nearly 7000 feet above sea level. And the 8-meter-class Subaru and Gemini telescopes both sit atop Mauna Kea in Hawaii at an elevation of more than 13000 feet, placing them above 40% of Earth's atmosphere. While high altitudes and dry, clear climates can help minimize the atmosphere's effect, placing a large telescope into space deletes the atmosphere's effect entirely, allowing the sharpest possible images and minimal light loss. Just as importantly, a space-based telescope can see more of the electromagnetic spectrum. The atmosphere blocks much of the deep ultraviolet and mid-infrared spectrum, so ground based telescopes are somewhat blind to these wavelengths. A space-based telescope affords astronomers access to objects emitting radiation at these wavelengths.

The location of the telescope in space is also important. A telescope in low earth orbit (LEO) lives in a constantly changing thermal environment, passing from full sun to shade during each revolution, unless it is placed in a sun-synchronous orbit. During the orbit, Earth may also temporarily block the section of sky being observed. And the thin, almost negligible atmosphere at those altitudes slowly causes the telescope to spiral closer to Earth, requiring periodic orbit corrections, such as those provided to the HST by the Space Shuttle. One benefit of LEO, however, is that the telescope can be serviced by astronauts. Another possible orbit is a halo orbit about the Sun-Earth second Lagrange point, or L2. The L2 point, located on a line connecting the sun and Earth, and approximately 0.1AU beyond Earth's orbit, is an excellent location for astronomical observation. By placing a space-based telescope into a halo orbit about L2, the occluding effects of the earth and moon are largely eliminated. And since the L2 point is always in the same location relative to the Sun-Earth line, the telescope, utilizing a small station-keeping budget, will remain in the vicinity of Earth.

The proposed telescope,[1] described below, is a large optical telescope with a target lifetime of at least 30 years and operating in the UV/visible range. The 6.2 m monolithic primary mirror will be created from an existing 8 m Zerodur blank available from the Very Large Telescope (VLT). The telescope is actually composed of two separate spacecraft: a telescope bus which houses the optical tube enclosure (OTE), and a replaceable spacecraft/instrument bus (SIB) which houses the science instruments and subsystems necessary to communicate with and control the telescope. The telescope will be launched aboard the Ares V cargo launch vehicle, which will place the telescope into roughly a geostationary transfer orbit (energy, or C3, of $-2.60\ km^2/s^2$). The propulsion system on the SIB then performs a lunar swingby and places the telescope into a halo orbit about the Sun-Earth L2 point. Using autonomous rendezvous and docking (AR&D) technology, servicing and science instrument replacement will occur every five years when a new SIB arrives to replace the existing unit.

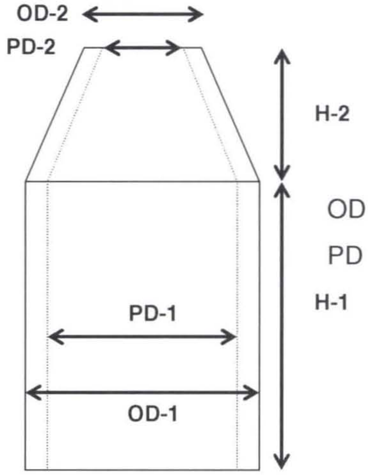
II. The Science Case for a Large, Space-based Telescope

For millennia, humans have looked up to the night sky and wondered about our place in the universe. Starting with Galileo, each generation of astrophysicists has relied on advanced optical telescope technology to answer some questions while posing new questions. The same has held true for the HST and Chandra X-Ray Telescope, and the same will hold true for the James Webb Space Telescope (JWST). For example, while the HST has allowed astronomers to successfully determine the age of the universe to be approximately 13.8 billion years old, it has also provided data that suggests the universe is not expanding at a constant rate, but that the rate of expansion is increasing. The reason for the accelerating expansion is not clear - but astrophysicists think it is related to dark matter and dark energy, the study of which requires a large aperture space telescope capable of operating in the ultraviolet/visible spectrum. As another example, astronomers have detected nearly 200 exo-solar (mostly Jupiter class) planets. Yet, we know not the frequency of exo-solar terrestrial class planets which might harbor life. The search for extra-terrestrial life in the universe is clearly one of humankind's most compelling questions and requires a large aperture visible/near-infrared space telescope. Furthermore, Chandra has shown compelling evidence for the existence of black holes. But what happens at the event horizon of a super massive black hole? The answer requires a new generation large aperture X-ray telescopes. Finally, JWST will detect the first illuminating objects and galaxies of the universe. But to study the detailed evolution of these galaxies as well as proto-planetary systems requires an even larger aperture far-infrared telescope which can individually distinguish these galaxies in the early universe. In all these examples, the search for answers to humankind's most compelling astrophysics questions requires new classes of very large telescopes - telescopes which are enabled by the massive payload capacities of a launch vehicle like the Ares V.

III. Benefits and Capabilities of the Ares V Launch Vehicle

The primary benefits of using the Ares V launch vehicle in delivering a telescope to the Sun-Earth L2 point are its payload mass and payload volume capabilities. Space-based telescopes that have been or will be launched on current launch vehicles are constrained by both mass and volume, requiring expensive and complex solutions for packaging. One example is the James Webb Space Telescope (JWST), which must fit within the confines of the 4.57 m diameter Ariane 5 ECA shroud. In order to achieve the desired 6.5m diameter reflective surface and overcome the confines of the relatively small payload bay, a series of complex and expensive mechanisms must unfold and position the telescope components before the science mission can begin. Another example is the Hubble Space Telescope (HST), a simpler design in that the primary mirror is a single piece of glass, but constrained to a maximum spacecraft diameter of 4.6 m due to the payload bay of the Space Shuttle.

Figure 1 shows the shroud dimensions and payload capacity used in this design study. The authors should stress that the Ares V shroud dimensions and weights are currently being assessed by NASA and could change. Yet, even when considering that fact, one can see that the Ares V greatly increases the available payload volume and mass over that offered by current launch vehicles. With a payload dynamic envelope of 7.5 m, and a maximum payload mass of slightly over 60 mT to a geostationary transfer orbit, the Ares V can enable the placement of a very large monolithic telescope into a halo orbit about the Sun-Earth L2 point. The baseline shroud payload dynamic envelope restricts the primary mirror diameter, which must be enclosed in the optical tube, to a diameter of approximately 6.2 m, with an optically clear diameter of 6 meters. This mirror, with a light gathering area more than six times that of the HST, compares well with today's large, monolithic, *terrestrial* telescopes. Yet the Ares V allows the science community to place the equivalent of a large terrestrial telescope into space, away from the effects of Earth's atmosphere and light pollution.



OD = outer diameter

PD = payload dynamic envelope

Shroud Outer Diameter	8.4 **m**
Shroud Mass	5.9 **mT**
OD-1	8.4 **m**
PD-1	7.5 **m**
H-1	12.0 **m**
OD-2	4.8 **m**
PD-2	3.9 **m**
H-2	6.3 **m**
Total Height (H-1 + H-2)	18.3 **m**
Payload to C3 = -2.60 km^2/s^2	60.1 **mT**

Figure 1. Ares V preliminary shroud dimensions and payload mass capability. Although the Ares V is an evolving vehicle, the telescope design team used the above dimensions as upper limits on the telescope size and weight. Please note that these are preliminary values and may not match the latest Ares V shroud dimensions and payload capability.

IV. The Proposed 6-meter Telescope

As stated above, the telescope, illustrated in Fig. 2, is actually composed of two separate spacecraft: the telescope bus which houses the optical tube enclosure (OTE), and a replaceable spacecraft/instrument bus (SIB).

The initial telescope optical system was an f/15 Ritchey-Chretién design, chosen for its excellent on- and off-axis image quality, compact size, and versatility. Also, since it is the optical system mainly used by today's large telescopes, its use should reduce the cost and risk of acquiring scientific instruments. The optical design used to size the telescope and spacecraft subsystems is shown in Fig. 3(a). This telescope has a 1 arc minute field of view. To achieve the desired wide field performance, a refractive corrector is used in the scientific instrument suite. A two element design was selected to maximize broadband multi-spectral throughput, but the refractive corrector limits spectral range and introduces additional losses. A multi-spectral wide field system can be achieved, with lower throughput, via a three mirror anastigmatic design, shown in Fig. 3(b). This configuration has a field of view of 8.4 by 12 arc minutes. Although time constrains prohibited the design team from sizing the telescope subsystems for the second optical configuration, the impact of the additional two mirrors on the subsystems should be small. To lower costs, the primary mirror will use an existing 8.2 meter Zerodur blank ground down to a 6.2 meter diameter, with a usable viewing diameter of 6 meters. At an estimated mass of 18 mT (with the mirror mass estimated at 11 mT), the primary mirror assembly is by far the heaviest single element of the proposed 34 mT telescope.

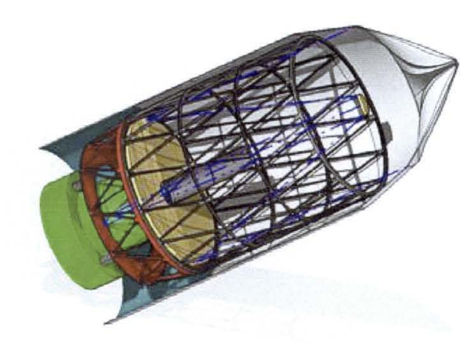


Figure 2. Cutaway of the telescope integrated within the Ares V baseline shroud. The green object at the rear of the telescope is the replaceable SIB.

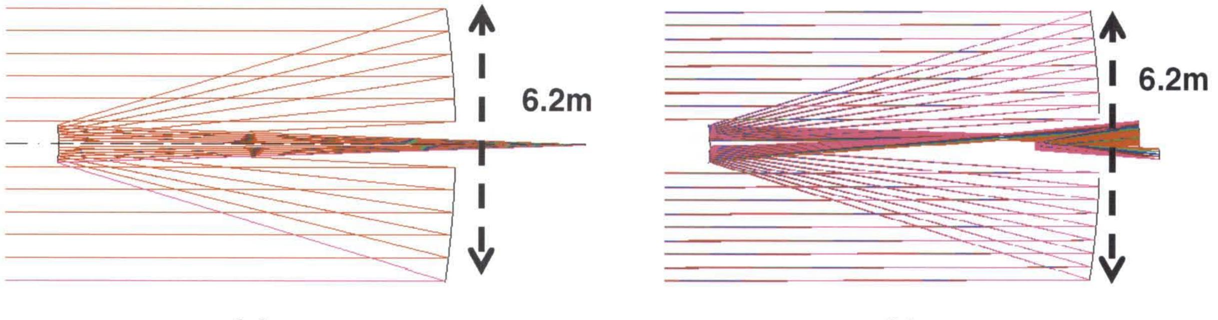


Figure 3. The telescope optical path. The original optical configuration (a) was used to size the telescope subsystems and develop the mass budget. The revised optical configuration (b) results in a viewing area more than 80 times greater than the original

To extend the life of the telescope to a target value of 30 years or more, the science instruments and as many subsystem components as possible should be replaced at periodic intervals. Therefore, the design team placed these instruments and components onto the SIB, shown in Fig. 4. When required, the SIB is replaced as a single unit, maybe every five years, using autonomous rendezvous and docking (AR&D) technology. This approach simultaneously maximizes the telescope investment and reduces the cost of the subsystems. Instruments and components which only need to withstand 5 years of the harsh environment of space cost less than those that must withstand 10 or more years. To facilitate AR&D, a few subsystems remain on the telescope, such as a small propulsion system and basic avionics, these are primarily used

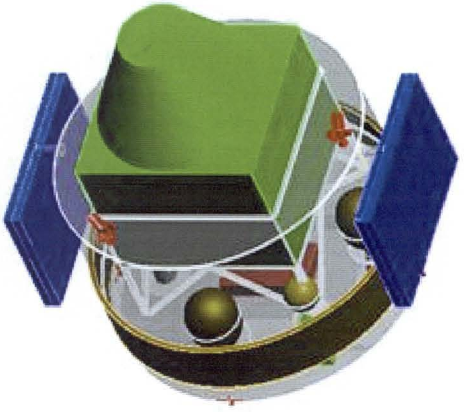


Figure 4. The Spacecraft/Instrument Bus (SIB), with the science instrument shown in green, and the retracted solar panels in blue.

only when the current SIB undocks and a replacement SIB approaches. The primary subsystems for pointing, communications, power, guidance, propulsion, as well as the science instrument package and fine guidance sensor, are located on the SIB. One notable exception is the thermal control for the primary mirror, which must be placed on the telescope bus.

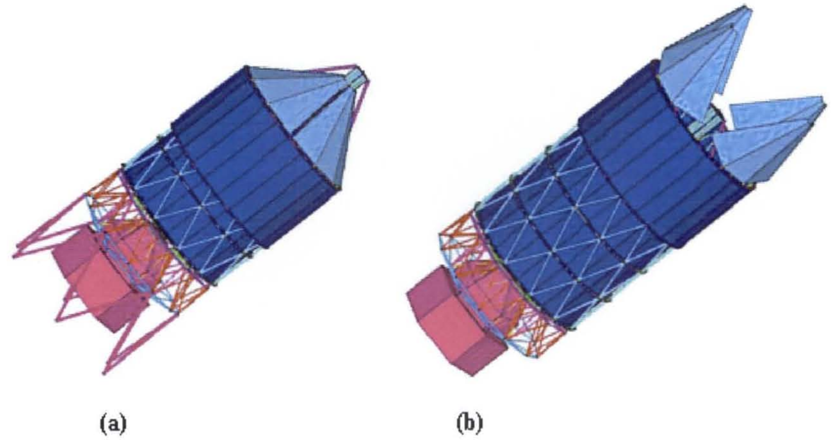
The mass budget for the telescope bus and the SIB is listed in Table 1. The total mass rollup of nearly 34 mT does not include any mass margin. Instead, the margin is kept as the difference between the payload mass capability of the Ares V and the mass of the telescope. Therefore, the Ares V affords a payload mass margin of approximately 26 mT. This shows that the payload bay diameter, and not the payload mass capability, is the limiting factor in the size of the telescope. A larger shroud, perhaps 10- or even 12 meters, might allow for an 8-meter-class telescope.

Table 1. Mass budget for the telescope OTE and SIB. Please note that the masses for the docking system and payload adapter are rough estimates.

	Mass (Kg)
Total mass = OTE W / Bus + Spacecraft and Science Inst	33,849
OTE W / Bus mass	25,619
Primary mirror assembly	17750
Secondary mirror assembly	671
Telescope enclosure	3,600
Avionics Subsystems	153
Power Subsystems	381
Thermal Management System	1,091
Structures	917
Propulsion	16
Propellant	40
Docking station	1,000
Spacecraft and Science Instrument	6,230
Science Instrument Package	1500
Avionics Subsystems	334
Power Subsystems	377
Thermal Management System	481
Structures	755
Propulsion	248
Propellant	1,536
Docking station	1,000
Launch Adapter	2,000

The target orbit, which is based on the orbit chosen for the High Throughput X-Ray Spectroscopy (HTXS) Mission,[2] is a halo orbit about the Sun-Earth L2 point, with a semimajor axis of approximately 1,500,000 km and a semiminor axis of approximately 374,000 km. When viewed in a coordinate system that rotates with a line containing Earth and the sun, the plane of the halo orbit is approximately perpendicular to this line, and 0.01 AU from Earth and 1.01 AU from the sun. The launch vehicle actually places the telescope and its servicing spacecraft into a nearly geostationary transfer orbit (GTO) with a C3 of -2.60 km^2/s^2. Afterward, the SIB main propulsion system is activated, which pushes the telescope on past the moon and eventually into the target halo orbit. The halo orbit is necessary to prevent the moon from crossing the line of sight between the telescope and Earth. Since the Sun-Earth L2 point is unstable[3] (meaning that a spacecraft placed there has a tendency to drift away from the L2 point), it is necessary for the telescope to incorporate a small propulsion system for station keeping. The station keeping budget, however, is very small. The estimated ΔV expenditure for five years is 20 m/s (Ref. 2). The station keeping is provided by the propulsion system on the SIB.

In order to fit within the length constraints of the Ares V shroud, the OTE must be shortened during launch, as shown in Fig. 5(a), which shows the telescope OTE in blue, the SIB in red, and the payload adapter structure which passes the launch loads to the launch vehicle. Once the telescope reaches the desired halo orbit, the OTE extends, as shown in Fig. 5(b) and the OTE doors open. This figure does not show the deployed solar arrays, which are also part



(a) (b)

Figure 5. The integrated telescope and SIB in (a) the launch configuration, showing the shortened optical tube enclosure in blue, and (b) the operational configuration, showing the optical tube enclosure extended and the doors opening. The spacecraft/instrument bus and payload adapter are shown in red.

of the SIB. Note that while the OTE changes length, the distance between the primary and secondary mirrors does not change.

V. Larger Monolithic Telescopes

Comparing the payload mass capability of the Ares V and the mass of the 6-meter telescope, one can see that the telescope is constrained in diameter, and not mass. With roughly 26 mT of available launch capability, the Ares V could put a much larger telescope at L2 provided the shroud diameter increased. If the Ares V were available with a larger diameter shroud, such as a 10- or 12-meter diameter shroud, the resulting payload dynamic envelope would be roughly 8.8- and 10.3 meters respectively. This could provide the necessary volume for a monolithic telescope with primary mirror diameter of 8 meters or more. Even allowing for the increased mass of the shroud and increased drag during ascent, it might be possible to place an 8-meter class monolithic space telescope into a halo orbit about the Sun-Earth L2 point.

VI. Conclusion

The primary benefits of the Ares V over currently available launch vehicles are payload mass and payload volume. These capabilities make possible the placement of a large monolithic telescope into a halo orbit about the Sun-Earth L2 point. The proposed 6-meter design, which compares with today's largest monolithic ground-based telescopes, would have a light gathering capacity six times that of the HST, yielding valuable data and more insight into the natural history and future of the universe. The monolithic primary mirror design eliminates the need for complex mechanisms to deploy and align the reflective surfaces of the telescope during deployment.

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