AN 8 METER MONOLITHIC UV/OPTICAL SPACE TELESCOPE

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ABSTRACT

The planned Ares V launch vehicle with its 10 meter fairing and at least 55,600 kg capacity to Earth Sun L2 enables entirely new classes of space telescopes. A consortium from NASA, Space Telescope Science Institute, and aerospace industry are studying an 8-meter monolithic primary mirror UV/optical/NIR space telescope to enable new astrophysical research that is not feasible with existing or near-term missions – either space or ground. This paper briefly reviews the science case for such a mission and presents the results of an on-going technical feasibility study, including: optical design; structural design/analysis including primary mirror support structure, sun shade and secondary mirror support structure; thermal analysis; launch vehicle performance and trajectory; spacecraft including structure, propulsion, GN&C, avionics, power systems and reaction wheels; operations & servicing; mass budget and cost.

1. INTRODUCTION

NASA's planned Ares V launch vehicle with its 10 meter fairing shroud and at least 55,600 kg capacity to the Sun Earth L2 point is a disruptive capability that enables an entirely new generation of 21st Century Space Observatories building on the Great Observatories legacy. These observatories can be 8-meter class monolithic mirror telescopes, 16-meter JWST class telescopes or even 25-meter class segmented telescopes. [1] An 8-meter class monolithic ultra-violet / optical / near-infrared space telescope offers the opportunity to answer some of the most compelling astrophysical questions. How does structure in the universe grow and evolve? How do galaxies assemble their dark matter and stellar components? How does the Solar System work? What are the conditions for planet formation and the emergence of life? And, maybe most importantly, are we alone? [2] When the scientific history of the 21st century is written, detection of life on other planets will certainly be one of its most significant pursuits.

Some of the fundamental astrophysical research that calls for the triple combination of high angular resolution, high photometric stability and high sensitivity provided by an 8-meter UVOIR space telescope are: 1) detecting habitability and bio-signatures on terrestrial mass exo-solar planets; 2) reconstructing the detailed history of the assembly of stellar mass; 3) determining the mass function and its evolution over time of super massive black holes; and 4) directly measuring the growth of structure in the universe by kinematic mapping galactic dark matter halos [2]. All of the above pursuits further require diffraction-limited performance at 400 to 500 nm and spectral coverage from 110 to 2500 nm. For example, only an 8-meter (or larger) filled-aperture telescope will be able to both observe the habitable zones in several hundered stars within 30 parsecs of Earth and be able to characterize any terrestrial-mass exoplanets. The spectral range of 300 to 1200 nm contains several key oxygen, water and vegetation bands that would be indicative of habitability and biological activity. An 8-meter class telescope will be able to obtain spatially resolved images and spectra of the disks of accreting gas around ~2000 super massive black holes, by imaging Lyman-alpha emission with redshifts at up to ~0.4 (corresponding to a look back in time of ~4Gyrs). Such measurements will provide unique insights into the fundamental relationship between galaxy and SMBH formation and evolution. The same telescope would provide a direct test of the gravitational instability paradigm as the driving physical process behind the formation of galaxies and large structures by enabling kinematic mass measurements of their dark matter halos as a function of time using absorption spectroscopy techniques.

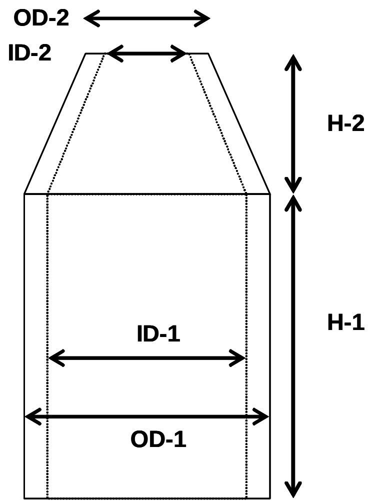
This paper reports on an on-going design study being conducted which shows that it is possible to package an 8 meter class monolithic observatory into a 10 meter Ares V fairing (Figure 1); have it survive launch; and place it in to a halo orbit about the Sun-Earth L2 point. Specific technical areas studied include optical design; structural design/analysis including primary mirror support structure, sun shade and secondary mirror support structure; thermal analysis; spacecraft including structure, propulsion, GN&C, avionics, power systems and reaction wheels; mass and power budgets; and system cost. Additionally, the study baseline architecture assumes servicing via autonomous rendezvous and docking to replace the spacecraft and science instruments as required - yielding an observatory operational lifetime of 20 to 30 years.

Figure 1 8-meter class monolithic mirror telescope launched in Ares V
(Image courtesy of Jack Frassanito & Associates and Harley Thronson)

2. ARES-V LAUNCH CAPABILITY ENABLES NEW DESIGN CONCEPTS

NASA's Ares V cargo launch vehicle, planed to enter service after 2018, will be a disrupting capability that promises to completely change the paradigm of future space science mission concepts. It has the potential to revolutionize space astronomy by being able to place into orbit far more volume and mass than any existing system. For this study, Launch Vehicle LV 51.00.39 is the baseline configuration with an ability to place 55,600 kg to the Sun Earth Second Lagrange Point (L2) and 140,000 to Low Earth Orbit (LEO). The current LV 51.00.48 configuration has more propulsion than LV 51.0039 and should be able to deliver significantly more mass to L2. Preliminary analysis indicates that it can deliver 180,000kg to LEO.

The current baseline Ares V shroud is a biconic fairing with a 10 meter outer diameter and 23 meter height. As summarized in Figure 2, this shroud has an 8.8 meter dynamic inner envelope diameter, a 17.2 meter envelope height and a payload volume of 860 cubic meters. This is nearly three times the 300 cubic meter volume of the Space Shuttle payload bay. A 'stretch' fairing is being considered that is 26 meter tall with 1410 cubic meters of volume. Additionally, a trade is underway to replace the biconic nose code with an ogive shape. The ogive configuration would have even more payload volume and useable internal vertical height. Finally, there is approximately 1.6 to 2.0 meters of reserved space below all of these shrouds for the payload to Ares V interface adapter. Depending upon payload design, some of this space may be available.



Shroud Outer Diameter	**10-m**	
Shroud Mass	7.8	**mT**
OD-1	10	**m**
ID-1	8.8	**m**
H-1	9.7	**m**
OD-2	5.6	**m**
ID-2	4.4	**m**
H-2	7.5	**m**
Total Height	17.2	**m**
Volume	860	**m3**
Payload to L2TO	55.8	**mT**

Figure 2 Ares V Baseline Shroud Dimensions and Payload Mass Capability.

3. OBSERVATORY DESIGN

3.1 Design Concept

Two specific unprecedented enabling capabilities of the Ares V form the basis for the MSFC design study – payload volume (fairing size) and mass. The Ares V baseline 10 meter fairing with its 8.8 meter internal dynamic envelope diameter can accommodate an 8-meter class monolithic circular primary mirror without the need for segmentation. A monolithic mirror provides superior science return because, as compared to a segmented mirror, it has a more uniform, symmetric and stable Point Spread Function. And, it avoids the risk of deployment and complex alignment and phasing control. The 10 meter shroud also allows an 8-meter monolithic mirror to be launched in a face up configuration which provides the most benign vibration and acoustic exposure.

Figure 3 shows the MSFC design concept for an 8-meter monolithic primary mirror ultraviolet/optical space observatory packaged inside the Ares V 10-m fairing's 8.8 meter diameter dynamic envelope. The concept has three main subsystems: telescope, support structure and spacecraft. The telescope consists of an 8-meter primary mirror, secondary mirror and forward structure/baffle tube. The spacecraft provides all normal spacecraft functions (such as propulsion; guidance, navigation and control; communication; etc.) and houses the science instruments. The support structure supports the primary mirror. And, it carries the observatory mass (of the primary mirror, telescope forward structure and spacecraft) providing the interface of this mass to the Ares V for launch.

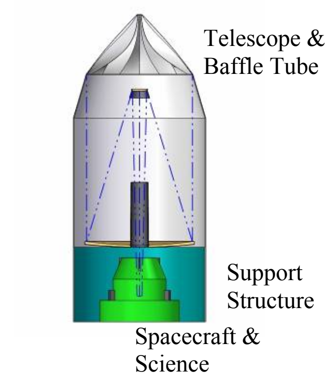


Figure 3 MSFC 8-meter observatory concept in Ares V dynamic envelope

The Ares V's ability to deliver 55,600 kg to an L2 Transfer Orbit is important to the MSFC concept because it enables an entirely new paradigm – design simplicity. Given the available mass, MSFC is proposing to use mature ground based primary mirror technology and higher structural design rule safety factors to eliminate complexity, to lower cost and to lower risk. By using higher design margins it is possible to minimize the marching army size which also reduces the management burden – every $100M in component cost savings reduces total program cost from $300M to $500M.

3.2 Optical Design

The feasibility study considered two telescope optical systems. An F/15 Ritchey-Chretién (RC) design was examined for its excellent on- and off-axis image quality, compact size, and ultra-violet throughput. Unfortunately, this optical design has only a relatively narrow 1-arc minute field of view (NFOV). The second design examined was a three mirror anastigmatic (TMA) telescope. TMA telescopes have the advantage of multi-spectral wide field performance with the disadvantage of lower ultra-violet throughput because of its two additional reflections.

The current study has base-lined a dual field design (Figure 4) with a 1 arc minute Cassegrain focus and a 16 x 10 arc minute off-axis wide field focus – UV and NFOV instruments operate at the Cassegrain focus and WFOV imaging cameras operate off-axis. The study assumes that the optical coatings will be the same aluminum with MgF overcoat used on Hubble to provide good spectral transmission from 120 nm to beyond 1 micrometers.

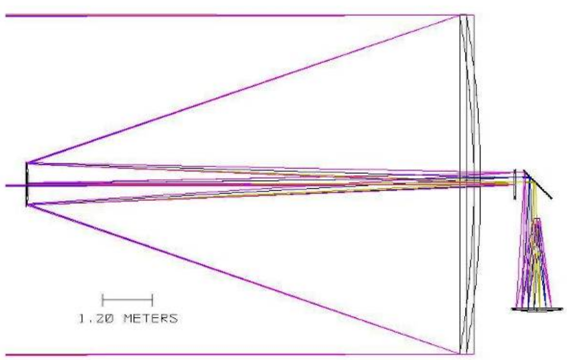


Figure 4. Dual Field TMA Design Concept

3.3 Primary Mirror

The monolithic primary mirror will be manufactured using existing ground based mirror technology. This approach has two specific advantages: technical maturity and cost risk. First, it has been demonstrated that one can actually polish an 8 meter class ground based telescope mirror to a surface figure of better than 8 nm rms [3] (which is close to the desired 5 nm rms surface figure for the 8 meter Terrestrial Planet Finder program). This is important because as shown in Table 1, while Hubble's 2.4 meter 180 kg/m2 mirror was polished to 6.4 nm rms, the AMSD program only achieved 20 nm rms on its 1.4 meter segment 18 kg/m2 mirror. The higher the mirror's areal density (or in actuality its specific stiffness), the easier it is to achieve a very good surface figure. Second, the cost for an 8 meter ground mirror is $20M to $40M or $0.4 to $0.8M/m2 while the cost of a 50 square meter space technology mirror will be $200 to $500M ($4M to $10M/m2). While this architectural choice adds approx 20,000 kg to the mass of the payload, the estimated $200M to $500M savings in mirror hardware costs translates into total program cost savings of from $700M to $2B (engineering design, system integration & test, management and fees/program reserves add to the total cost of any program by a factor of 2.5X to 3X of the hardware costs).

The reason for both advantages is that ground based mirrors are very massive and hence very stiff. Thus, they are much easier to fabricate than space mirrors. Historically, space mirrors are very low mass and thus not very stiff. They have large gravity sags and are difficult to handle, mount and fixture. All these factors make them difficult to fabricate to very high precision and thus very expensive.

Table 1. Comparison of Space and Ground Mirrors

Parameter	HST	Spitzer	AMSD	JWST	Ground	
Material	ULE	Beryllium	ULE & Be	Be	Various Glass	
Diameter	2.4	0.85	1.4	1.5 (6.5)	8.2	m
Area	4.5	0.5	~1	25	50	m2
Temperature	300	4	300/30	30	300	K
Surface Figure	6.4	75	20/77	25	7.5 to 15	nm rms
Areal Density	180	28	18	26	300 to 500	kg/m2
Areal Cost	10	10	4	6	0.5	$M/m2
Year	1984	1999	2005	2008	Various	

3.4 Structural Design

A fundamental question of the design study is whether an 8-meter class ground based telescope mirror can survive launch.

The Ares V launch environment has been analyzed by the NASA MSFC Advanced Concepts Office using POST3D (Program to Optimize Simulated Trajectories 3 Dimensional). The maximum launch loads for the Ares V (summarized in Table 2) are similar to those for existing launch vehicles. Please note that these loads are not concurrent and they are not the loads seen in the payload volume. They are the maximum loads experienced by the Ares V center of mass at some time during launch. Load factors are separated into a quasi-steady-state and oscillatory dynamic. Total load factors in a direction are obtained by adding the steady-state and dynamic terms. Lateral load factors are total and can be in any azimuth normal to the flight (longitudinal) axis. The dominant axial loads are experienced during flight and at main engine cut-off (MECO). The dominant lateral loads are from wind buffeting. At present acoustic vibration loads have not been analyzed.

Table 2 Maximum Ares V Launch Loads

Maximum Launch Load	Steady State [g]	Dynamic [g]
Axial	4	+/- 1
Lateral	1.5	+/- 0.5

A structural analysis determined that 66 axial support points keep the stress level on an 8.2 meter diameter 175 mm thick meniscus primary mirror below 1000 psi (Figure 5). Thus, the mirror can survive launch.

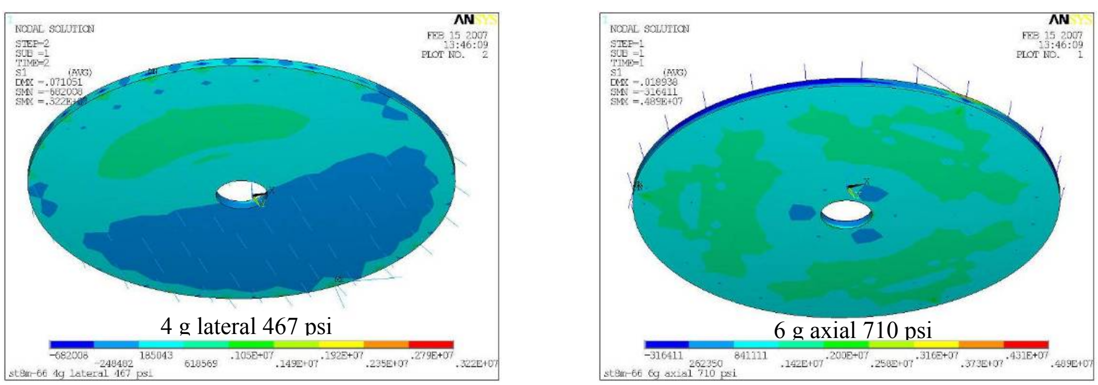


Figure 5 Launch Survival because 66 axial supports keep bulk mirror stress below 1000 psi

The observatory structure is divided between the forward and back structure. (Figure 6) The forward structure is similar to that of the Hubble Space Telescope. Because of fairing length limitations, the forward structure is split into an upper and lower part. The lower structure is load carrying. It provides the metering structure between the primary and secondary mirrors and holds the lower straylight baffle tube. It holds the secondary mirror assembly tripod structure and cover doors. The upper part slides forward on orbit to provide the upper straylight baffle. The cover doors open and close on-orbit as required. A secondary tripod structure extending from the primary mirror was considered but determined to be unable to achieve the desired system stiffness levels for an ultra stable telescope.

Figure 6 Observatory Support Structure packaged inside Ares V dynamic envelope

The back structure has multiple functions. It supports the primary mirror with 66 axial supports. And, the forward structure is attached to the back structure along with the spacecraft. A key design element of the MSFC concept is that all observatory mass is carried through the back support structure to an interface ring which attaches to the Ares V. This design concept allows the use of a completely conventional spacecraft, i.e. it does not need extra mass because it does not provide the interface between the observatory and the launch vehicle.

Structural design and analysis was performed using standard NASA guidelines. No technical problems were identified. The primary product of this effort was a mass budget for the spacecraft.

3.5 Thermal Design

Standard thermal design and analysis was performed for 4 different solar angles: 0, 45, 90 and 120 degrees where 0 degrees is the observatory back facing the sun and 90 degrees is the observatory broadside to the sun. It was modeled that the science instruments produce 750 W of heat and the avionic systems produce another 850 W of heat. The analysis assumed that the observatory is wrapped with five 10 layer MLI blankets and that the spacecraft has 16.0 m2 of thermal radiators. Thermal gradients were calculated for both the spacecraft and the 8 meter primary mirror. (Figure 7)

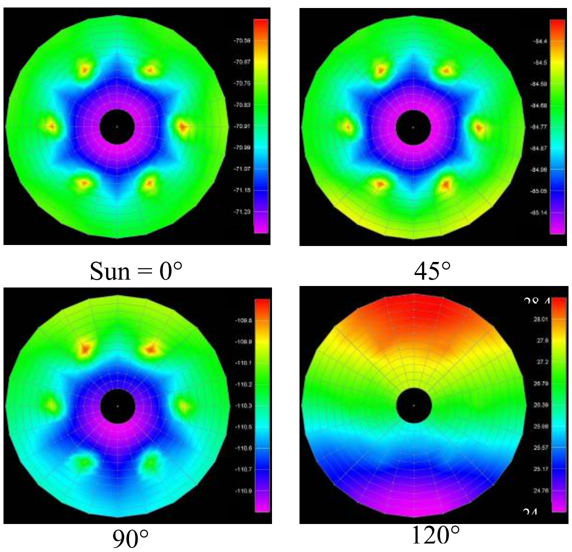


Figure 7 Mirror temperature (°C) vs sun angle

Without an active thermal management system, the primary mirror temperature varies as a function of sun angle from 160 K to 300K with approximately a 1K variation at each temperature.

Table 3 Primary Mirror Temperature	
Sun Angle	Temperature
0 deg	200K
45 deg	190K
90 deg	160K
120 deg	300K

Therefore, an active thermal management is required to hold the primary mirror temperature at a constant 300K for all sun angles with less than 1K of thermal gradient. On-going thermal analysis will determine exactly how small of a thermal gradient can be achieved. This is important because long exposure observations (such as extra-solar terrestrial planet finding and characterization) require a very stable observatory wavefront. And, the primary mirror surface figure varies as a function of temperature based on the substrate material coefficient of thermal expansion (CTE) value and uniformity.

3.6 Spacecraft

The observatory actually has two separate spacecraft: a telescope bus which is part of the optical telescope element (OTE), and a replaceable spacecraft/instrument bus (SIB) (Figure 8). The SIB houses science instruments and subsystems to communicate with and control the telescope. Each spacecraft produces its own power. The telescope has 18 m2 of body mounted solar arrays around the light tube. The SIB has 9 m2 of deployable solar array wings with pointing ability. The SIB power system includes 800W for primary mirror thermal control and 750W for science instruments. The OTE performs its own on-board health diagnostics and communication to the SIB. The SIB provides the primary communication down-link.

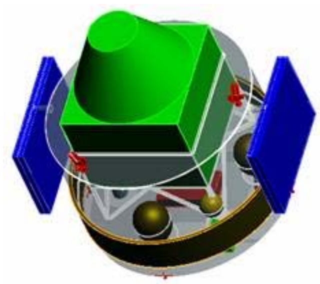


Figure 8 Spacecraft/Instrument Bus

The spacecraft has a dual mode hydrazine-NTP bi-prop/hydrazine mono-prop propulsion system with 5 yrs of propellant and redundant thrusters. The propulsion system is sized to get the observatory from a 185 x 300,000 km parking orbit (energy, or C3, of -2.60 km^2/s^2) into a halo orbit about L2 and perform all station keeping operations. The propellant load is based on an estimated station keeping ΔV expenditure of 20 m/s for 5 year, plus the ΔV to place the telescope onto the L2 transfer trajectory. Propulsion during the trip from the parking orbit to L2 is provided by hydrazine-BTP bi-prop 125 lbf thrusters (Northrop). Station keeping at L2 is provided by hydrazine mono-prop RCS 20/5 lbf thrusters (Aerojet). The telescope has an independent control system with mono-propellant hydrazine using 350/100 psi blowdown Aerojet thrusters. The telescope propulsion system has 30 kg of propellant for 30 year mission.

Guidance Navigation and Point Control is provided by the spacecraft reaction wheels. A trade study was performed to determine the optimum science performance as a function of wheel torque and momentum storage specifications. (Figure 9)

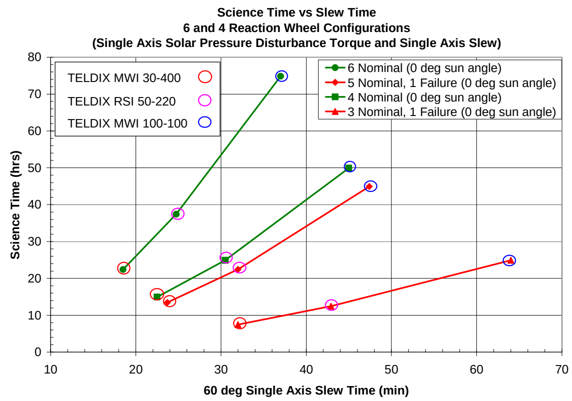


Figure 9 Science Time vs Slew Time Analysis

Two performance parameters were analyzed. The number of hours the telescope can stare at a fixed point in space (remain at an inertial hold) before needing to perform a momentum dump due to solar radiation pressure torque. And, how fast in minutes the telescope can perform a 60 degree slew. The analysis was done for a sun angle of 90 degrees, which is the worst condition for solar radiation pressure torque. At any other sun angle, the available science time increases. And it was assumed that momentum buildup occurs in only one axis (y-axis). Six wheel and four wheel configurations were analyzed along with the worst case single wheel failure for each configuration. Each configuration was analyzed for three different TELDIX reaction wheel versions (Torque-Momentum Storage).

3.7 Mass Budget

In the initial feasibility study, a mass budget was developed for a 6-meter observatory including primary mirror, structure, light baffle tube, instruments, space craft, avionics, etc. The total mass was less than 35,000 kg (Table 4) – a 38% mass margin on the Ares V's 55,600 kg Sun-Earth L2 launch capability. The mass budget for an 8 meter observatory is approximately 45,000 kg, with almost a 20% mass margin, of which the primary mirror is the largest contributor. These mass budgets clearly show that payload diameter/volume, and not the payload mass, is the limiting factor in the telescope size. Please note that several elements of this mass budget are allocations, including the science instrument package, launch adapter and docking stations. All mass elements will be subject to refinement as the design matures.

Table 4 Mass Budget for a 6 meter Telescope OTE and Spacecraft/Instrument Bus

	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

4. IN-SPACE SERVICING

To extend the mission life of the observatory, the science instruments and as many subsystem components as possible are designed to be replaced at periodic intervals. These are in the SIB (Figure 8) which can be replaced as a single unit using autonomous rendezvous and docking technology (as demonstrated on Orbital Express) [4]. Beyond the obvious technical advantages of upgrading detectors, electronics and computers periodically, it has been hypothesized that designing subsystems for 5 years of operation instead of 10 years will produce sufficient cost savings to fund the periodic servicing missions. The SIB diameter is set at 4.5 meters such that these servicing missions can be launched via a conventional EELV. Eventually, it might be possible to have two SIBs on station with the ability to switch between suites of science instruments. When the SIB is undocked from the observatory, the telescope spacecraft provides basic guidance and navigation for station keeping. The telescope has 18 m2 of body mounted solar array around light tube, used for station keeping, and batteries for up to 0.5 hour of attitude control contingency. Its avionics systems are 3-fault tolerant for a 30 year life. The telescope has a mono-propellant blow-down thrust system. It also has a low gain antenna for communicating with the servicing spacecraft. All health and status data is sent directly to the spacecraft avionics system. 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. The SIB avionics and power systems are 1-fault tolerant for 5 year life. Power is generated from two 9 m2 deployable solar array wings with pointing ability. Batteries are sized for 2 hours of power during midcourse and rendezvous operations (when the power arrays are retracted). The SIB power system includes 800W for mirror thermal control and 750W for the telescope instrument package. The guidance and navigation system includes star trackers, sun sensors and inertial measurement units. AR&D will be facilitated with a LIDAR long range system and an optical short range system. The communication systems consist of Ka-band HGA for ground, and s-band for local communication and backup capability

5. COST REDUCTION

The proposed 8 meter telescope concept seeks to disprove the old adage that the primary predictor of mission cost is mass. The Ares V mass capacity is a disruptive capability that creates a new paradigm - by trading mass for simplicity it is possible to build lower-cost lower-risk missions. By eliminating complexity, it should be possible to design and build an 8-meter monolithic telescope with 2X the collecting area of the 6.5 meter JWST for less cost. Consider for example the complexity difference between packaging a 6.5 meter segmented primary mirror into a 4.5 meter dynamic launch envelope versus the simplicity of packaging an 8 meter monolithic mirror into an 8.8 meter dynamic launch envelope. The current cost for the JWST telescope and spacecraft (excluding science instruments and operation) is approximately $3B ($4B with instruments). By comparison, the MSFC Advanced Concept Office estimates that the cost for a 6-meter monolithic mirror ambient temperature observatory (excluding science instruments and operations) might be approximately $1.2B ($2B with instruments). Furthermore, the NASA Advanced Missions Cost Model [5] indicates that a low to very low difficulty mission with mass of 40,000 to 50,000 kg might cost in the $2B to $4B range. (Figure 10)

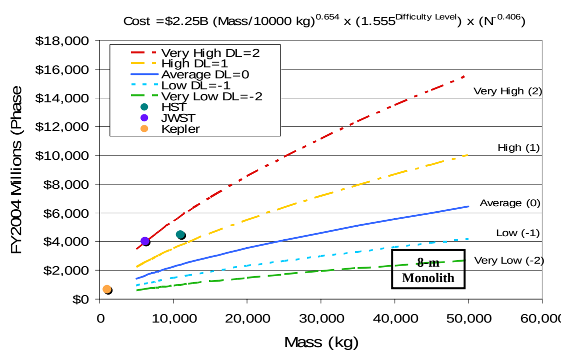


Figure 10. NASA Advanced Mission Cost Model

6. CONCLUSION

NASA Marshall Space Flight Center and the Space Telescope Science Institute are conducting a preliminary design study which indicates that it is feasible to launch an 8 meter class monolithic primary mirror ultraviolet/visible observatory. An 8-meter class UV/optical space observatory with its very high angular resolution, very high sensitivity, broad spectral coverage, and high performance stability offers the opportunity to answer some of the most compelling science questions. How did the present Universe come into existence and of what is it made? What are the fundamental components that govern the formation of today's galaxies? How does the Solar System work? What are the conditions for planet formation and the emergence of life? And maybe most importantly, are we alone?

The unprecedented mass and volume capabilities of NASA's planned Ares V cargo launch vehicle enable entire new mission concepts and completely change the paradigm for future space telescopes – simplicity. The Ares V capacities allow one to use mass to buy down performance, cost and schedule risk by using proven technology (such as ground based mirrors) and higher structural design margins.

Finally, there is no inherent reason that an 8-meter space telescope using robust design concepts should have only a 5 to 10 year mission life. A 20 to 30 years extended mission life can be obtained via periodic robotic servicing of the spacecraft and science instruments using autonomous rendezvous and docking technology.

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