A Cost-effective and Serviceable ATLAST 9.2m Telescope Architecture

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ABSTRACT

The ATLAST 9.2m architecture has evolved to be more cost effective while also meeting a more thorough understanding of the driving science requirements. The new approach can fit in an existing Delta IV Heavy rocket and makes extensive use of heritage and selective use of technology in order to minimize development time and cost. We have performed a more thorough look at how to meet the stability requirements for both thermal and dynamics and have an approach consistent with an initial error budget. In addition, we have developed concepts to support robotic or human servicing in a cost effective manner through a modular approach that relies on simple, external access and metrology. These refinements to the architecture enable a cost-effective, long-lifecycle, and relatively low risk approach to development.

Keywords: Space Telescope, JWST, OTE, James Webb Space Telescope, Pathfinder

1. INTRODUCTION

Several mission concepts for the Advanced Telescope Large Aperture Space Telescope (ATLAST)[i] were proposed in 2009 as potential follow-on missions to the James Webb Space Telescope. All of these architectures assumed a minimum of an 8-m aperture and their architectures were largely driven by the ability to perform high contrast coronagraphy. At the time, all of the approaches proposed assumed a rocket with a larger fairing and mass would be developed and would be available in time for a new start soon after the 2020 decadal. Since those proposals, the Ares V was cancelled and while larger rockets have been proposed, no new large rocket with a large fairing will have been built by the end of the decade. With this in mind, our team has set out to continue to refine the ATLAST architecture while also developing it to fit in an existing fairing. This architecture is really a reference design that can be scaled up to take advantage of larger rockets in the future. Larger rockets provide opportunities for even larger apertures and more mass margin. We have focused on making the architecture as cost-effective as possible and making it serviceable which provides program flexibility, reduces risk of failure and extends the life of the mission.

With this goal in mine, our team has focused on assessing whether the ATLAST 9.2m architecture can fit in a Delta IV Heavy which as seen in Figure 1 is the most capable existing rocket from a mass perspective. This 10-meter class telescope uses a light-weighted segmented mirror geometry that takes advantages of economies of scale in its manufacturing and heavily leverages integration and testing methods from JWST. For simplicity in this reference design, we use the exact segment size used on JWST but with an extra ring of mirrors and thus 36 segments, exactly double the number on JWST. The Delta IV Heavy is capable of launching 9800Kg to L2 so that sets the mass of the total observatory including margins. The Delta IV Heavy defines the key characteristics of mass and fairing volume for the design. However, the key performance driver that needs to be considered is stability in order to achieve 10^{10} system contrast. For stability, this can be achieved either using an internal coronagraph or an external coronagraph. In the case of the external coronagraph, or starshade, the stability requirements on the telescope are greatly relaxed such that the stability needed for a general class Ultra-Violet Optical Infrared (UVOIR) telescope will suffice. However, a starshade for a 10-m class telescope is both a technological challenge due to size and has the issue of retargeting time which can be on order several weeks – not fast enough to survey a large number of potential earth-like planets in a 5-10 year mission life. To be conservative, our team has assessed the telescope assuming an internal coronagraph which does not suffer from the retargeting limitation but places much tighter requirements on the stability of the telescope. We have also assumed the tightest possible requirements on the telescope, but upcoming developments in coronagraph design may result in the relaxation of certain telescope requirements.

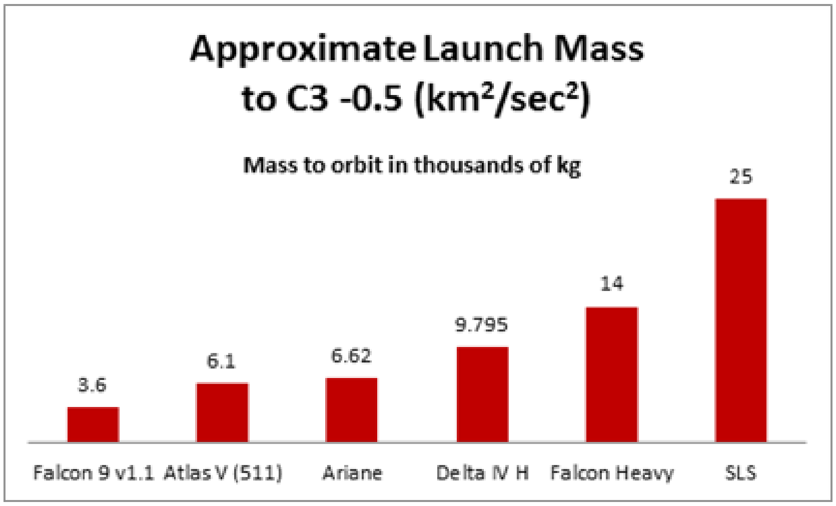

Figure 1: Mass to L2 of Various Rockets

Another key consideration beyond mass, volume and stability is serviceability. Assuring serviceability allows extending and expanding the science capabilities along with providing the potential for significant risk mitigation. With these considerations, our team has developed a 10-m class segmented telescope architecture which can feasibly achieve these objectives in a Delta IV Heavy. To do this, we have performed some simple scaling calculations, mass budgets, and initial layouts which will require further detailed study. We have also developed a new packaging approach which retains heritage from JWST to reduce risk and cost. In the end, we don't see any showstoppers to being able to achieve a 10-m class telescope in a Delta IV Heavy and are sufficiently optimistic to already be working on more detailed assessments.

2. REQUIREMENTS

The set of science requirements for the ATLAST telescope has been studied by Postman[ii] and the key requirements have been laid out. The telescope is both a general class Ultra-Violet Optical Infrared (UVOIR) observatory capable of powerful science that includes high throughput far-ultraviolet science and wide field visible imaging with the potential for multi-object spectroscopy. These general class capabilities can be thought of as extending the Hubble and JWST great observatory general class capabilities and will serve a large user community. In addition to these capabilities, there is one additional science area which is the study of exoplanets including detecting a large number of earth-like planets and obtaining their bio-signatures. While the requirements for detecting earth-like planets are challenging, the discovery potential includes finding bio-signatures around earthlike habitable planets and is perhaps the most significant objective of the mission. The combined set of requirements for the observatory are shown in Figure 2 and are appropriate for accomplishing all of these goals in a single observatory. As Stark[iii] has shown, many hundreds of target stars will need to be surveyed just to find 10's of exoearths. In addition, targets will likely need to be viewed more than once to separate out the background galaxies or to do orbit determination. This means the observatory will have to efficiently survey many stars with short settling times. The need for short settling times is a key guiding principle in the stability architecture.

Telescope Parameter	Consensus Requirement
Primary Mirror Aperture	≥ 8 meters
Primary Mirror Temperature	~20 C, pending detailed thermal design
UV Coverage	100 nm (90 nm goal) – 300 nm
Vis/NIR Coverage	300 nm – 2500 nm
Mid-IR Coverage	Under evaluation to ~ 8000 nm
Vis/NIR Image Quality	Diffraction-limited performance at 500 nm
Stray Light	Zodi-limited in 400 nm – 2000 nm wavelengths
Wavefront Error Stability for Exoplanet Imaging Using an Internal Coronagraph	1 x 10^{-10} system contrast < 10 pm rms residual system WFE for < 10 min bandpass between λ/D – 10λ/D

Figure 2: Top Level Requirements Summary

In addition to understanding the science driven observatory requirements, there are some derived requirements like lifetime, field of regard, and percentage of time spent on Exoplanet science. Without specifying these requirements, we do know that our goal is the maximum field of regard (minimum for Exoplanet work is +/-45 degrees of pitch), the longest possible life (perhaps 10 years or more) and the maximum feasible time spent doing Exoplanet science instead of waiting for settling or slewing.

3. OPTICAL ARCHITECTURE

The basic optical architecture for the ATLAST observatory remains a Three Mirror Anastigmat (TMA) design shown in Figure 3. However, as seen in Figure 3, the coronagraph and UV instruments will only use the first two mirror Cassegrain (coated with a UV quality coating like AlMgF) and the follow-on reflections for the TMA and fine steering mirror will inject light into the wide field TMA instruments. The Tertiary and follow-on TMA optics can be coated with Silver which is high throughput in the visible. The coronagraph includes a back end spectrometer and the guiders in these configurations are internally redundant. The dual guider allows for roll control. In addition, the star trackers will be mounted to the telescope structure to minimize drift between them and the telescope.

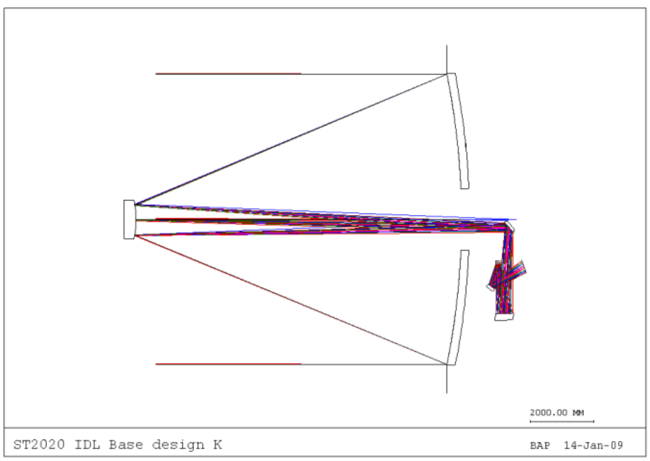

Figure 3: Three Mirror Anastigmat Design

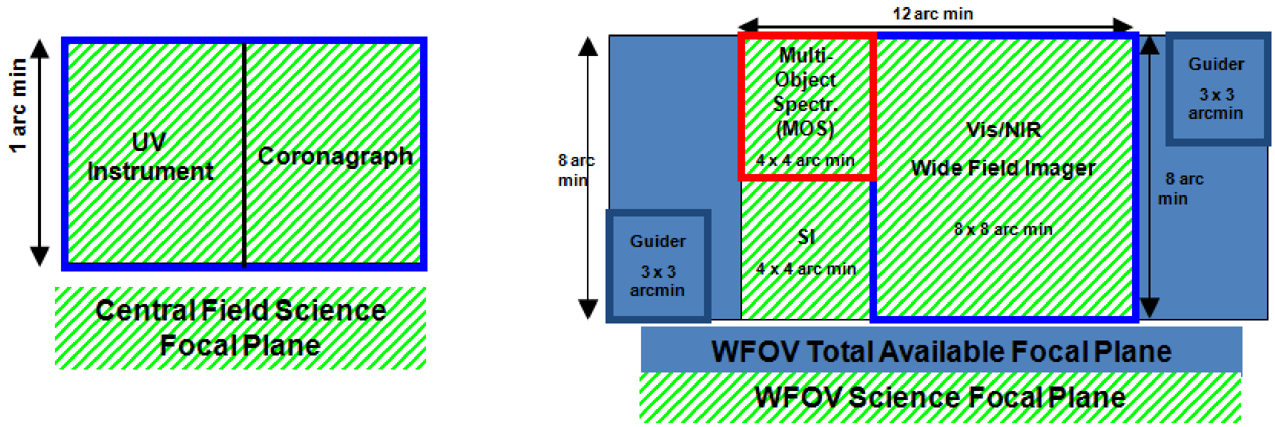

Figure 4: Science Instrument Optical Layout

The performance of the TMA is sufficient to provide low enough wavefront error to be diffraction limited in the visible and was documented in 2009 ATLAST studies. Also studied in 2009 was the straylight architecture. What is shown in a central deployed baffle that was not part of JWST but which will provide protection against "Rogue Path" light that can come around the secondary mirror. In addition, the planar sunshield has been shown to provide sufficient straylight suppression such that the limiting source of straylight in visible wavelengths is the in-field Zodiacal and starlight which a circular baffle would not block. Like JWST, the assumption is that micrometeoroids are small and of relatively low rate such that they represent low risk to system performance.

4. LAUNCH CONFIGURATION

Perhaps the most significant change since the 2009 studies is a new way to configure the telescope for launch which allows the telescope to fit in an existing shroud (earlier studies assumed larger fairings). The key to this new architecture is that it continues to make use of the JWST wing deployment method which utilizes latches and hinges for the JWST wings. In this new architecture, the two wing approach has been replaced with a mutli-wing design which configures the telescope in a circular fashion which best optimizes the circular launch vehicle but continues to use the JWST deployment methods. In this new architecture, wings are attached to wings using the same basic latch and hinge approach and the wings themselves can be snubbed against a central core backplane which has a modified geometry to accommodate this while still allowing the instruments to be serviceable externally. This architecture is shown in Figure 5 and the left side and center of the figure denotes the 9.2 meter reference design architecture which uses a secondary mirror deployment similar to that used on JWST. The right side of the figure shows a conceptual 11.2m architecture which uses a different secondary mirror deployment method but demonstrates that some additional scaling may be possible with this basic approach. In these architectures, the sunshield is stowed below the telescope and is based on a 4 boom approach in a volume efficient manner.

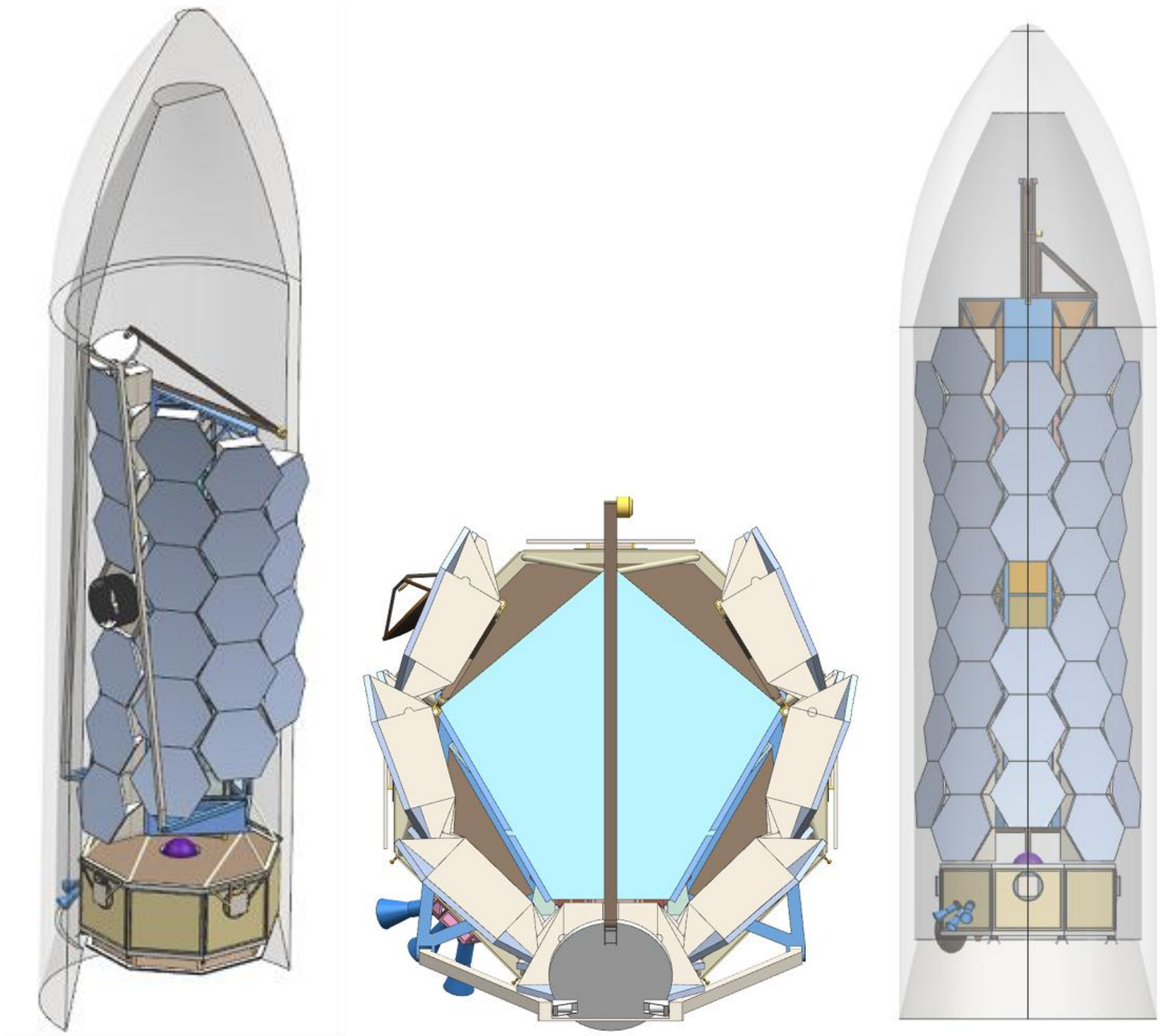

Figure 5: Launch Configuration: 9.2m Side, 9.2m Top, 11.2m Side

The other critical question for fitting in the fairing is the mass of the observatory. Since the Delta IV Heavy can launch 9800 Kgs to L2, this gives 3200Kg's more mass than the JWST mass of 6600Kg's. Based on an initial assessment, a 9.2 meter telescope presents feasible mass compatibility with the Delta IV Heavy launch vehicle. Compared to the segmented mirror system already validated on JWST, a more efficient architecture enabled by the fact that the mirrors are room temperature should allow a significant reduction in mirror areal density. Additional study is planned with sufficient detail to assess whether larger apertures are possible. A related and important mass trade is segment size. Smaller segments help both thermal and dynamic stability and are lower areal density. Given that the system is room temperature, once the mirrors are small enough (perhaps 1-meter scale), then only 3 actuators per mirror may be needed. The biggest drawback of this type of architecture is the increase in the number of mirror edges but this is a parameter that can be improved with polishing techniques. For now, we use JWST segment sizes which are easy to study based on JWST analogs.

5. DEPLOYED CONFIGURATION

The deployed configuration of the ATLAST 9.2 meter reference design is shown below in Figure 6. The architecture is optimized for both mass and for stability. A key part of the architecture is the primary mirror where there are several mirror technologies under study including Silicon Carbide, ULE and Zerodur. For the case shown, we stick with the JWST 6-degree of freedom mount design and higher authority is really a trade depending on the mirror material and how one wants to handle gravity distortion (via polishing or on-orbit control). The mirror assemblies are heated from the back radiatively to very tight control. The secondary mirror is also on a 6-dof mount but has high speed tip/tilt/piston controllability if needed combined with a laser truss. The sunshield is only a 3-layer sunshield (the number of layers chosen to protect it from micrometeoroids). The backplane is inside a heated cavity which maintains the backplane in a very stable warm cocoon. Between the telescope and the spacecraft is a gimbal that allows pointing the telescope over a large field of regard while keeping a constant center of gravity so that the frequency of momentum offloading is minimized. This approach keeps the sunshield normal to the sun at all times to provide a very stable interface. In addition, the primary mirror is only allowed to face deep space which minimizes the delta Q that strikes the front surface of the primary mirror allowing for a very stable thermal design. The secondary mirror deployment system is very similar to JWST. Between the gimbal and the telescope is a non-contact isolation system that allows the telescope to essentially float with sensing and control between the spacecraft and the telescope. The main sources of disturbance are the reaction wheels so these will be sufficiently isolated. The last aspect of the architecture is that it will be serviceable which includes externally accessed instruments and spacecraft elements and will include docking features.

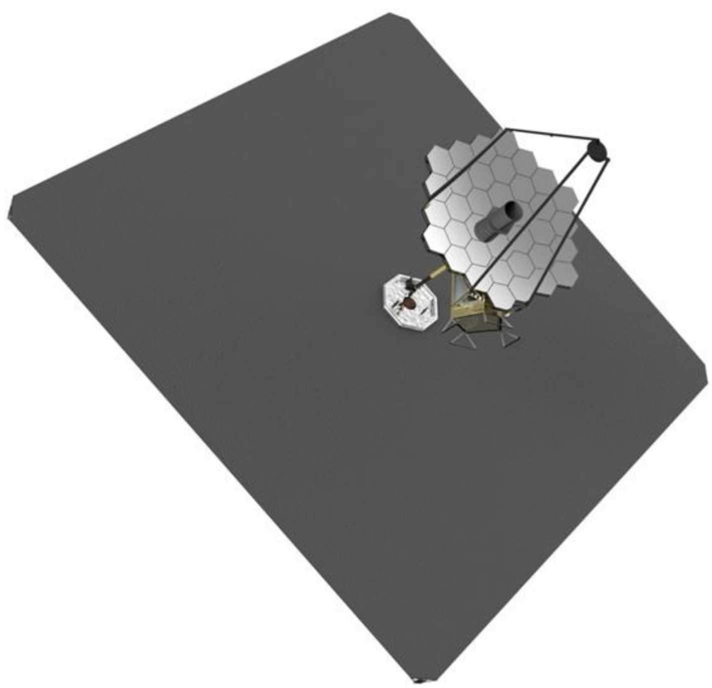

Figure 6: ATLAST 9.2m Reference Design Deployed Configuration

6. STABILITY ARCHTITECTURE

One of the key challenges for the ATLAST architecture is stability. To first order, the requirements for ATLAST can be compared to the original Terrestrial Planet Finder dynamics requirements[iv] with the big distinction being that newer sensing and control algorithms have reduced the amount of time needed for stability to approximately 10 minutes. The simple conservative requirement on wavefront stability of the 10 minutes is 10 picometers of residual wavefront error after any sensing and control has been performed. The 10 picometers comes from comparing the speckles produced by the instability to the exoplanet itself. The 10 picometers would break down to smaller (approximate 5 picometer contributions). TPF budgeted these contributors in terms of contrast and showed thermal and dynamic stability of the primary and secondary mirror are the dominant terms. Since the ATLAST concepts are segmented, we have changed the stability landscape slightly in that we can separate segment level stability from primary mirror system stability. We have adopted the assumption that the primary mirror is the primary stability challenge both because of the picometer level requirements unique to it and the fact that TPF had addressed secondary mirror beamwalk requirements using a non-contact isolation system as being done here. Thus, we have focused primarily on the question of segment level stability both dynamically and thermally to demonstrate feasibility. To do this, we provide scaling of the JWST segmented system dynamics. JWST has very detailed and mature models so scaling off of JWST provides the best opportunity to check the feasibility of the dynamics solution.

Since ATLAST will not require a cryocooler, the key relevant JWST estimate is for reaction wheel-induced jitter. The current (April 2014) estimated Wavefront Error (WFE) jitter performance for JWST is given in Figure 7 below.

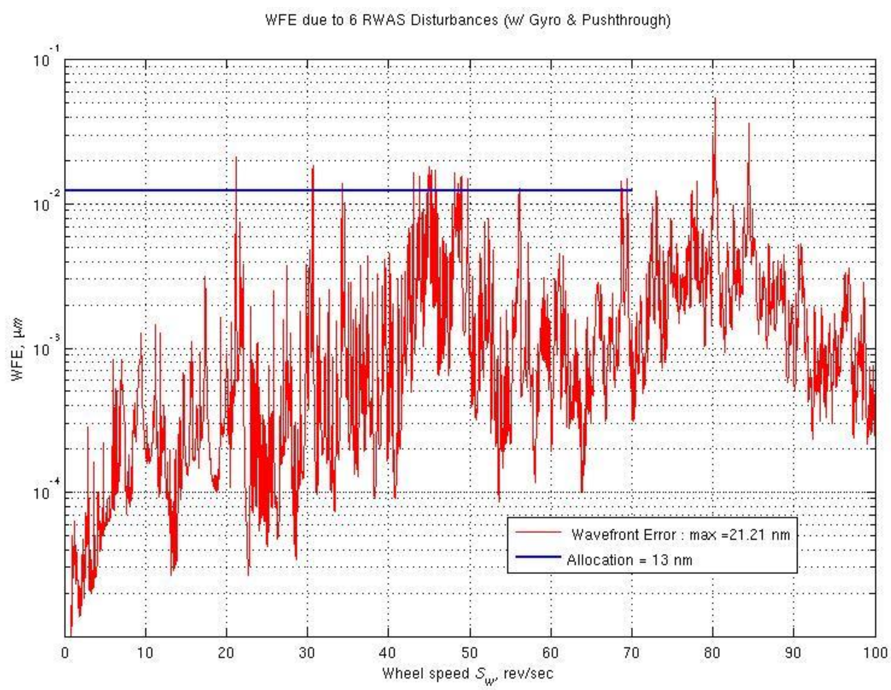

Figure 7 – JWST Reaction Wheel-induced Wavefront Error Estimated Performance

Jitter response is evaluated for each of the six reaction wheels as a function of wheel speed. The curve shown above is the maximum (envelope) of the six responses at any given speed. The responses include a model uncertainty factor (MUF) of 1.9 below 20 Hz and 3.7 above 40 Hz, with a linear ramp from 20-40 Hz. The horizontal line from 0-70 rev/sec is the 13 nm allocation plotted over the operational wheel speed range, extended by 10% to allow for frequency uncertainty in the structural model. Note that for JWST the 13 nm is not a hard requirement, but rather a goal, as jitter is just one error term among many that affect JWST's Strehl and Encircled Energy Stability requirements. As these requirements are met with margin the exceedances shown above are not a concern.

For purposes of deriving the ATLAST isolation system requirement, the sharp peaks at 21 Hz, 30.5 Hz and 34 Hz are ignored. These are driven by discrete structural modes that do not involve tip/tilt of the primary mirror (PM) segments. For ATLAST it is assumed that any similar modes will be handled through use of tuned mass dampers, reaction wheel speed-control algorithms, or other means. The cluster of peaks between 40-50 Hz corresponds to a band of modes associated with PM tip/tilt. These modes are less amenable to attenuation than the discrete modes below 40 Hz and hence an improvement in JWST's broadband isolation system would be required to achieve ATLAST performance levels.

So per Figure 1 the starting point for the calculations to derive ATLAST isolation requirements is ~20 nm RMS for frequencies > 40 Hz. The first step is to make an adjustment for structural damping. JWST uses 0.02% of critical damping for the cold (~40K) telescope. Conservatively, a minimum of 0.2% damping could be assumed for a room-temperature (RT) structure. Hence, we could assume that jitter for a warm JWST-like structure would be ~2 nm RMS.

The next step is to estimate the attenuation provided by JWST's vibration isolation system. JWST uses a two-stage isolation system, with stage 1 being the 1-Hz Isolator Assembly at the spacecraft-payload interface and stage 2 being the 8-Hz Reaction Wheel Isolator Assemblies (one hexapod per wheel) at the wheel-spacecraft interfaces.

Figure 2 shows the theoretical performance of the JWST two-stage passive isolation system, from reaction wheels to optics. The frequency response plotted above was developed by modeling each stage as single-degree-of-freedom spring-mass-damper systems and then concatenating the two models in series. At 40 Hz the attenuation is -92 dB as shown by the figure inset. As an aside, single-stage transmissibility tests on JWST engineering hardware models match the single-DOF analytical models quite well. A transmissibility test for the two-stage design is a future activity.

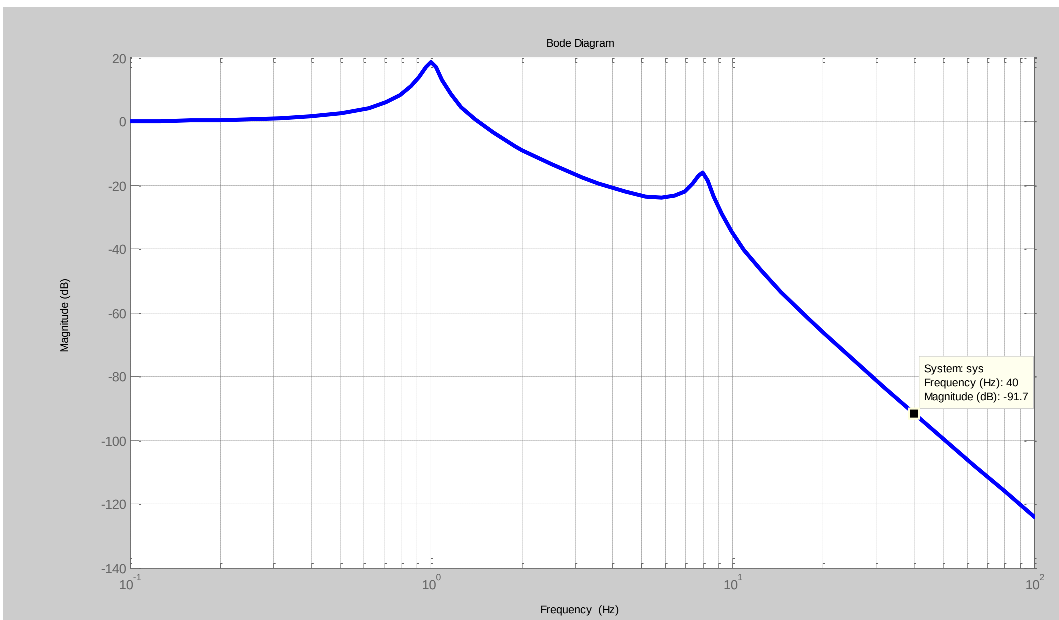

Figure 8 – Theoretical Performance of the JWST two-stage Vibration Isolation System

The final steps are to calculate the additional attenuation required to reduce room temperature JWST-like performance from ~2nm to the ATLAST performance requirements (see reference below), and from that derive the ATLAST isolation requirements. The results of these calculations are summarized below in Table 1.

ATLAST PM Jitter Requirement	Additional attenuation required starting from 2 nm PM Jitter, -92 dB	ATLAST Isolation System Requirement (> 40HZ)
100 picometers (minimum)	-26 dB (0.005)	-118 dB
10 picometers (goal)	-46 dB (0.0005)	-138 dB

Table 1 – ATLAST Vibration Isolation System Requirements

These additional attenuation levels were compared against the Disturbance Free Payload (DFP) non-contact isolation systems proposed originally to JWST and proposed for TPF. A simple scaling of the peak reduction at the 40-50hz range where the main primary mirror segment contributors are found gives approximately a 40dB (100x) reduction which is very close to the minimum specified. This is further substantiated by a plot given on the Lockheed website for the DFP technology[v] which cites a 100x LOS improvement over a conventional passive system. This of course is based on continuous reaction wheel disturbance and does not factor in other factors like slewing but is believed to be the hardest challenge. It does however include the JWST model uncertainty factors which perhaps could be reduced through a test validation program. It is also based on a JWST design that was optimized for mass and where significant dynamic improvement is known to be possible through simple design improvements of the backplane and structure. With that said, this is obviously a very simple and first order analysis and more detailed modeling and architecture studies are needed.

In addition to dynamic stability, we have also begun to study primary mirror segment thermal stability. Segment alone stability is the biggest concern because it cannot be easily corrected and shows up in mid to high spatial frequencies which contribute in the spatial frequencies of interest. Based on experience, our assessment is that front to back gradient changes will be the dominant segment level thermal stability contributor to wavefront stability. Front to back gradients cause segment power changes. A simple calculation for an ATLAST size ULE segment static front to back gradient yields a wavefront of 46 picometers for a 1mK front to back gradient so we will need to limit the change for this case to 10% of the gradient. Since the primary mirror will always face deep space, we expect the changes to the front surface of the coated optic to greatly limit the delta Q and thus the gradient change induced from the front. However, we will also need to control the mirror from the back and this is limited to our controllability based on sensor resolution. The .1 mK is pushing the state of the art on commercial thermal sensor resolution. We can reduce this effect by either reducing the CTE, thickness or diameter of the segments. Note the front to back gradient wavefront change goes with the square of the diameter so smaller segments will greatly help this. Other mirror materials like Silicon Carbide will also have their own parameters and requirements[vi]. We believe these simple calculations suggest that this requirement is within reach and this is certainly a key area of more thorough analysis. One possible outcome of this will be the need to improve temperature sensor resolution and mirror thermal control.

A related topic is the stability of the full primary mirror (all 36 segments) which is dictated by the backplane. The strategy for this is to build heater plates around the backplane to control the boundary conditions to milli-Kelvin levels. If the boundary conditions are kept stable, the backplane will not deform. The backplane has higher thermal mass which will also limit these effects and it is likely local effects at mount interfaces will prove to be the challenge. Early TPF budgeting showed lower order aberrations are not as critical and we believe that mid and higher spatial frequency changes can be managed through edge metrology if required. For example, 1 picometer level laser metrology has been demonstrated to work in seconds and there are many methods for doing this. Another option here is to use the out of band wavefront sensing of the science target. It may also be possible to reduce the 10 minute bandpass of the overall control system which would relax the requirements. In the end, a solution that relies only on thermal control methods is the goal to minimize mass and cost but metrology methods can be employed if needed.

7. COST CONSIDERATIONS

An important consideration for the design is to be cost effective. Based on our experience from JWST, the main driver in the cost of a large observatory is the size and the duration of the marching army. One clear time driver on JWST was the cryogenic requirement. For JWST, this required significantly more time in both the design and in the integration and testing phase. A particularly time consuming aspect of JWST was the combination of being lightweight and cryogenic because it meant every bond type and flexure required detailed cryogenic structural analysis that was very time consuming and required associated material and coupon and element testing, none of which would be required for ATLAST. In addition, the long duration cooldown and warm-ups of mirror, telescope and instrument tests would also be avoided with a room temperature telescope. While high performance (lower diffraction limit) systems requires some additional time for final polishing, our assessment is that most of the effort is in getting the metrology right during the technology phase and this is not a significant increase to the production phase. In addition, the isolation system needed for ATLAST could be built in parallel so dynamics in general are not a critical path impact.

Other methods to decrease the critical path exist. It is well known that one can decrease the critical path by early investments in technology to reduce the risk. One can also facilitize the mirror fabrication with more parallel lines than done for JWST so that mirrors can be made in less time. For JWST, segments were Beryllium which had superior cryogenic properties but were known to take a long time to grind and polish. The ATLAST mirror options include much faster grinding and polishing times and more improvements in these areas are possible. With early investment in technology and engineering design units, mirrors with sufficient facilitization could be made in nearly half the amount of time (5 years for 36 segments vs. 10 years for 18 segments on JWST) which would have a significant effect on the total duration and thus cost of the mission.

8. SERVICEABILIY ARCHITECTURE

As space observatories become larger and more complex, the need for Program flexibility, cost-control options, and extended mission operations become increasingly important. Spacecraft modularity and on-orbit servicing technologies and capabilities – which are defined and examined in more depth below – can help program managers overcome these challenges throughout both the prelaunch and on-orbit phases of the program. Historical missions such as Solar Max, the Hubble Space Telescope (HST), and the ongoing maintenance of the International Space Station have demonstrated the value of modularity and servicing. Observatory programs today are also adding servicing to their core requirements, which will continue this advancement. The ATLAST observatory will be in a position to significantly benefit from these technologies as it enters its design phase.

Servicing capabilities deliver the ability to autonomously rendezvous and dock with a spacecraft to either repair, or extend its life through component replacement, supporting system upgrades and refueling. The technologies that support satellite servicing – dexterous robotics, high-speed computing, and advanced tools – unlock a suite of extended options for mission operators. Closely related to servicing capabilities are built-in spacecraft modularity and cooperative servicing interfaces. When these elements and objectives are combined, servicing allows for more than just extended mission operations.

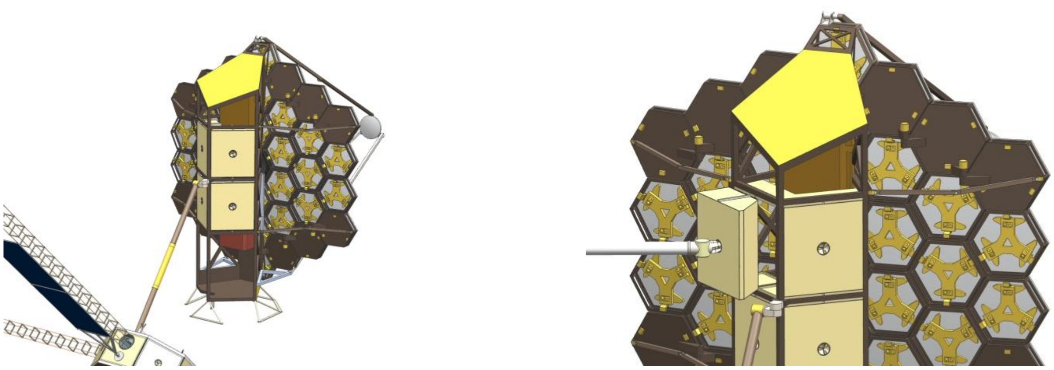

Figure 9: Instrument Serviceability from Externally Accessible Robot Arm

Mission designers gain new programmatic flexibility during ground processing when a spacecraft is designed for quick and easy instrument replacement on orbit. Modularity allows mission developers to smoothly remove an instrument on the ground during or even after observatory level environmental testing to install new components. As robots become autonomous and are integrated with 3D spatial information, the potential for autonomous servicing increases. ATLAST has been designed in an externally accessible modular way such that autonomous instrument change-out may prove feasible. An example of this interface for science instrument change-out can be seen in Figure 9. The instrument change-out which was performed by astronauts on HST could be performed with a semi-autonomous robot.

The servicing technologies applicable to ATLAST are continuing to be advanced through ground test and flight programs. Demonstrations on the International Space Station such as the Robotic Refueling Mission are demonstrating robotic manipulation of non-cooperative electrical connectors and hazardous refueling capabilities. Planned future demonstrations will test advanced rendezvous and proximity operations systems, cryogen and Xenon transfer, and other missions such as Raven will test integrated multisensory autonomous rendezvous and docking systems and advanced computing. Concept missions such as Restore and the Asteroid Redirect Mission (which leverages investment in satellite-servicing technology) have engineering-level test programs that are planning to start this year.

Assuming these technology advancements continue, ATLAST will have access to a mature and flight-proven suite of servicing technologies that will provide the Program with flexibility to help manage their development and position the observatory for a long and productive science campaign.

10. SUMMARY

Significant progress has been made on demonstrating that a 9.2m ATLAST can be launched in an existing rocket and with sufficient stability. More development work is needed to further validate the requirements and design. Technology development is needed particularly in the area of starlight suppression, mirrors, and mechanical isolation. Modeling is underway to probe dynamic and thermal stability analytically so that the architecture can be refined and the volume and mass better quantified. No showstoppers have been found and there is hope that a slightly larger aperture (eg, 11.2m) may fit. The architecture as presented is scalable up to larger sizes and the critical enabling technologies continue to progress to make this a feasible approach.

9. ACKNOWLEDGEMENT

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