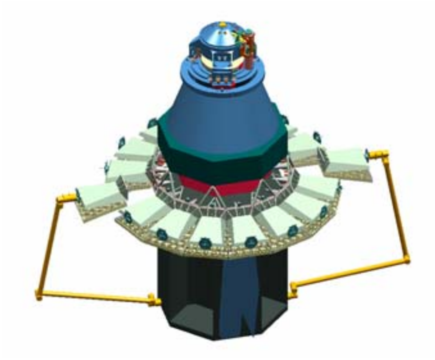
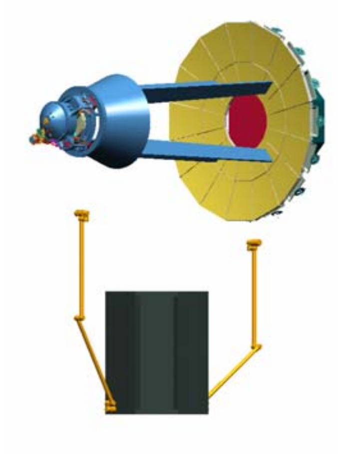
# *The Modern Universe Space Telescope*

## A Vision Mission Concept Study for
## A Large UV-Optical Space Telescope





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# The Modern Universe Space Telescope

## *A Large UV-Optical Space Telescope*

# *Executive Summary*

The **M**odern **U**niverse **S**pace **T**elescope (MUST) is a 10 meter, diffraction limited optical-ultraviolet telescope that crosses a new threshold in terms of sensitivity, imaging resolution and scientific return. The optical/UV is, and will remain, the most powerful bandpass for studying physical processes in the modern (local and low redshift) universe. Stars emit most of their light in this wavelength regime, and the diffraction limit in the optical/UV is 5 – 10 times better than in the infrared for the same telescope aperture. The power of high resolution imaging, coupled with high performance spectroscopy, is unmatched for enabling a broad spectrum of scientific inquiry and public engagement. Even the next generation of extremely large ground-based telescopes currently under study cannot match the performance of a space telescope. Exquisite imaging over wide fields, and access to the ultraviolet are ruled out by the atmosphere. One need only look at the science continuing to be achieved by the 2.4 meter HST today, even with competing ten meter telescopes on the ground, to recognize that both ground and space-based capabilities are needed to address the fundamental science issues. MUST is not merely a continuation of HST – it is intended as the logical and worthy successor to the HST – arguably the most successful scientific mission in the history of NASA. We present here an observatory that will be worthy of assuming that title.

The MUST observatory will be robotically assembled at sun-earth L2, paving the way for a mission architecture that will be scalable to even larger mirror concepts in the future. MUST will have high resolution imaging capability of 0.01″ over a 300″ x 300″ field of view. This unprecedented level of resolution in the optical and ultraviolet will isolate individual stars in other galaxies and extend the evaluative techniques familiar with objects in our own galaxy to distant ones. For the first time, we will be able to understand the nature of other galaxies to a level approaching our understanding of the Milky Way. The spectroscopic capabilities of MUST will encompass both high resolution and high sensitivity in a variety of modes that extend down to the far ultraviolet (1150 Å). MUST will include coronagraphic capabilities, but not at the exquisite levels needed for terrestrial planet finding. Instead, we have set a goal of $10^{-6}$ contrast capability, for studying of AGN host galaxies and to probe into young stellar systems and their forming planets. The power of greater collecting area, finer angular resolution, and larger format detectors means that each MUST high resolution and wide field images will have more than 1000 times the information density[1] of an HST-ACS image.

Great Observatories have now flown in the optical/UV, γ-ray, x-ray and infrared. This combination of capabilities has synergistically created a revolution in astronomy with their unprecedented performance. The next revolution will be to extend to new thresholds of performance in both sensitivity and resolution. Just as HST has led the first revolution, in both scientific advancements and public support, the unique diagnostic capabilities of a large UV-optical space telescope will remain the keystone of the next generation of astronomical inquiry.

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[1] Information density = effective area * number of simultaneously illuminated independent resolution elements = effective area * field of view / resolution$^2$. When applied to a new camera on an existing telescope, information density is equivalent to the familiar “discovery factor” of QE* field of view

## *Relation to NASA and the Science Mission Directorate Strategic Plans*

The most recent measure of NASA's long-range strategic planning for astrophysical missions comes from the NASA Roadmap Committee reports, submitted May 20, 2005. These committees considered missions currently in the NASA plan (e.g., JWST, SIM, Con-X, LISA, TPF) as well as a number of "Vision Missions". The Large UV-Optical Observatory (LUVO), of which MUST is an example, appeared in the reports of both the Science Roadmap #4 (Search for Extrasolar Planets) and #8 (Universe Exploration). The latter report, "Universe Exploration: From the Big Bang to Life", included a 10-meter LUVO mission under the category of "Pathways to Life Observatories". These missions will explore the history of star formation, chart the assembly of galaxies and large black holes, and gauge the impact these objects have on their host galaxies and surrounding gas. These Pathways missions will thus allow astronomers to connect the observations of the early universe and first objects down to the present, a Roadmap that leads from the Big Bang to the "Emergence of the Modern Universe".

The primary goal of the Pathways program is to explore the structure and evolution of the universe and to "determine how the infant universe grew into the galaxies, stars, and planets, setting the stage for life". This top objective had three key components:

- *Map directly the structure and evolution of the Cosmic Web.*
- *Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars and planets.*
- *Trace the evolution of nuclei, atoms, and molecules that became life.*

The Pathways to Life Program builds on the historic legacy of the Hubble Space Telescope. As noted by the Roadmap (SR#8) report, LUVO/MUST will explore the interconnected evolution of galaxies, gas, stars, and planets from the pre-galactic era to the present. The first stages of structure formation in the cosmos involved the gravitational pull of invisible cold dark matter (CDM) that collected matter and atoms together, reversing the expansion in places and creating a cosmic web of clustered matter, distributed in knots connected by filamentary gas clouds. Gas falling into this web produced the first stars and galaxies, and the accompanying formation of stars and black holes transformed matter and released energy in many forms. The result was a complex system of stars, dark matter, and heavy elements necessary for the formation of planets and life. These processes have taken billions of years; to understand them requires observing the universe over billions of years of its history. The primary physical diagnostics during the critical epoch in the history of the modern universe is observable only through optical and ultraviolet telescopes such as LUVO. (A lookback time of 10 billion years corresponds to a redshift of $z \approx 2$.) Only with the light-gathering power of a 10-meter telescope in space, coupled with exquisite imagers and spectrographs, will we be able to study in detail the components of the cosmic web and investigate the transformative processes that produced the modern universe.

## *Key Scientific Objectives*

Predicting the compelling science questions that will be most relevant 15 - 20 years in the future is difficult. However, there are thresholds in observational capability that open large areas of discovery space and enable many future scientific investigations which are currently impossible. For example, we recognize that an order of magnitude increase in imaging resolution will cross a threshold in astronomical inquiry, permitting detailed study of the stellar populations of other galaxies. Extending the sensitivity of spectroscopy to V=21 for distant quasars will allow a thorough dissection of the structure of the local universe through absorption spectroscopy. We emphasize that this is not an incremental gain in power, yielding an incremental increase in knowledge. By enabling the study of individual stars in other galaxies, the detailed analysis of extragalactic outflows, and dissecting the structure of matter, we bring the tools of quantitative analysis to questions that have not previously been accessible.

We have identified four fundamental questions that are essential to any future large UV/optical telescope, and require that the observatory be capable of addressing these issues. These are analogous to the key science programs identified during the development phase of the Hubble Space Telescope. However, we acknowledge that the most compelling issues of the 2020's may be currently unknown, and that the greatest discoveries of MUST may involve science that is currently unanticipated. For example, the majority of Hubble's greatest accomplishments were not predicted during its design. Who in 1985 could have predicted that determining the nature of dark energy would be a compelling scientific issues 20 years later? Therefore, these science questions should be viewed as guideposts, driving our performance in imaging and spectroscopy to ensure that compelling science will be done – but not defining, or in any sense, limiting, the enormous potential of a 10 meter telescope.

### *How are metals (elements beyond helium) created and distributed through the modern universe?*

This program is intended to understand the basic "feedback processes" of stars and galaxies: stellar winds, supernovae and superbubbles, galactic outflows, and outflows from active galactic nuclei. Galaxies and QSOs are widely believed to expel their interstellar gas into the intergalactic medium (IGM), chemically enriching intergalactic space with the heavy elements - the same elements that in galaxies seed successive generations of star formation and even life. However, we currently do not know how uniformly the metals are distributed.

To attack this fundamental question, we need to perform three basic types of observations. First, we must observe the production sites of the heavy elements – hot young stars, supernovae, and their surrounding emission nebulae. Second, we need to observe and understand the processes by which these chemical elements are transported into the interstellar medium (ISM), and more generally throughout the Galaxy and halo. Third, on the grandest stage of all, we wish to study the flows of metals from various types of galaxies out into the IGM, and back into galaxies.

To conduct a systematic study of chemical evolution and transport will require a wide range of instruments, from filter-imaging over wide fields to emission-line and absorption-line spectroscopy. A critical factor in chemical studies will be to find background targets (at V = 19-21) suitably located behind galaxies and throughout the halos of the Milky Way and external galaxies, to follow the extent of metal transport. The desired studies will range from high-resolution spectroscopy of interstellar and nebular gas to low-resolution studies of external galaxies of all masses, shapes, and types. Spectroscopic studies of the diffuse IGM and collapsed structures (Lyman-Limit systems, Damped Lyα systems) will probe the cycles of feedback and heavy-element reincorporation into galaxies through outflows, followed by fallback in galactic fountains. These processes must be studied outside the Milky Way, to test their dependence on star formation efficiency and galactic morphology. They also must capture a broad set of elements and ionization stages to provide nucleosynthetic signatures of the stellar production sources (alpha-process, Fe group, R and S process elements, etc.).

**Figure 1: A section of the Cas A SNR as seen by Hubble in emission lines of oxygen and sulfur. The SN debris in this spectacular example of feedback enrich the ISM with elements necessary for life. MUST will study this process in detail in the Milky Way and other galaxies**

The desired experiments will search for metallicity gradients with galactocentric radius, up into galactic halos, and out into the IGM. Metallicity studies of matter in the IGM and the damped Lyα absorbers, from redshifts z = 0 to 1.5, will cover the major epoch of galaxy assembly and metal production. Ideally, these chemical studies will be combined with the images of galaxy assembly and with spectroscopic studies of D/H evolution and astration (the monotonic destruction of D in material processed through stars). Performing these surveys throughout the Milky Way, as well as for M31, M33, and other nearby galaxies, will provide valuable information, currently unavailable from our limited vantage point.

The ability to dissect the galactic halo and potential outflows from a target galaxy is a strong function of redshift. At large distances, the halo and immediate region of the target galaxy subtend a significantly smaller solid angle than for nearby galaxies. Therefore, at low redshift, the number of potential background sources for dissecting galactic structure and interactions with the local IGM is significantly greater. The potential for finding many nearby target galaxies with a large number of acceptable background sources is therefore greatly enhanced by working in the UV-optical. Observing these lines at large redshifts (in the IR) makes it significantly more difficult to accomplish these science goals.

### *How are galaxies assembled, and how do they evolve?*

Studies of galaxies within the Local Group and to distances of about 10 Mpc have begun to reveal a startling complexity and variety in star formation and chemical enrichment histories - implying that the evolutionary paths of "normal" galaxies are widely divergent. The driving mechanisms are a mixture of continuous and discrete, disruptive processes. As yet, we have no firm theoretical foundation for understanding these processes, which therefore can only be addressed empirically by high precision observations of a large sample of galaxies in the full range of evolutionary states.

Most of the activity that shaped the present-day galaxy population occurred at redshifts below $0 < z < 2$ (Van Dokkum & Ellis, 2002, Madau et al, 1988). Even giant elliptical galaxies, with the oldest and most quiescent populations, have been found to undergo major transformations in this range. To reconstruct the evolution of star formation, chemical abundances, morphologies, dynamics, and interstellar media for galaxies over the past 8 billion years requires a potent optical-UV telescope. It must be large because galaxies and their stellar populations are faint. High spatial resolution of 0.01" is essential, first to resolve individual stars in nearby galaxies, and second to resolve important structural features (e.g. star clusters, H II regions, spiral arms, bulges) in more distant ones. Simultaneously, one requires a wide field of view in order to cover the large surface area of nearby galaxies and to isolate and sample significant numbers of distant galaxies, e.g. in large clusters. Furthermore, the restframe optical-UV spectral region, particularly below 4000 Å, is by far the most sensitive to stellar age and abundance, and permits dissection of stellar populations in ways that are impossible at restframe infrared wavelengths.

**HST z ~ 0, today** **MUST z = 1.5, ~ 9Byr ago** **JWST z = 4, ~11Byr ago**

**Figure 2: Three images of the same galaxy, under varying assumptions. The MUST image assumes a galaxy diameter of 1" at 0.01" resolution; the JWST image assumes a galaxy diameter of 0.6" at 0.068" resolution (0.068" = λ/D for 2µm/6m). (Galaxy diameters from Ferguson et al, 2004.)**

The requirements of a wide field of view and high spatial resolution with a stable and uniform point spread function (PSF) at optical-UV wavelengths will not be met by any planned space or ground-based telescope. JWST is unlikely to offer diffraction-limited performance at wavelengths below 2µm. Ground-based telescopes equipped with adaptive optics (AO) systems promise high-quality imaging at infrared wavelengths, but not at optical wavelengths and only over small fields of view. Neither JWST nor ground-based telescopes can take advantage of the GALEX survey, the first deep survey of the vacuum-UV sky, which represents a factor of over one million increase in the volume explored for UV sources.

Super star clusters (SSCs) are another important avenue for MUST. One of HST's major accomplishments has been to show that formation of these massive, globular star clusters with $M > 10^5 M_\odot$ continues to the present day in some environments. SSCs are found preferentially in the aftermath of strong tidal interactions or mergers. Some galaxies contain hundreds of SSCs, and they are common in starbursts. Because they are luminous and nearly coeval systems, they are invaluable tracers of the history of star formation and chemical enrichment in galaxies, particularly in disturbed environments. Since some SSCs are as luminous as $M_V \sim -12$ to -15, their integrated properties could be determined at large distances with MUST. With its high resolution and sensitivity, MUST will produce color-magnitude diagrams of the outer parts of many young SSCs that otherwise could only be studied in integrated light. Studies of SSC systems can answer important open astrophysical questions: for instance, the dynamical evolution of cluster mass functions, the conditions that favor the formation of massive clusters, the fraction of total star formation that occurs in clusters, and the "feedback" effect of young clusters on their environments in the form of ionization and winds, which is one of the major uncertainties in building realistic galaxy formation models.

The star formation history of elliptical galaxies remains a fundamental, unsolved problem. The most direct information about a stellar population comes from applying stellar evolution theory to color--magnitude diagrams (CMD). However, there are no elliptical galaxies close enough to make the critical observation of the main sequence turnoff. MUST will have sufficient resolution and sensitivity to measure the old main-sequence population in M32 and Centaurus, as well as below the horizontal branch in elliptical galaxies in Leo (e.g. NGC 3379). The issue is one of crowding -- resolving the individual main-sequence stars in these galaxies. JWST lacks both the blue sensitivity and angular resolution required to make headway on this problem. Optical (blue and visual) observations are needed to settle unambiguously the question of whether elliptical galaxies have blue horizontal branch stars (which could mimic a young blue population).

### *How do stars and planetary systems form, and how does this impact their likelihood of supporting life?*

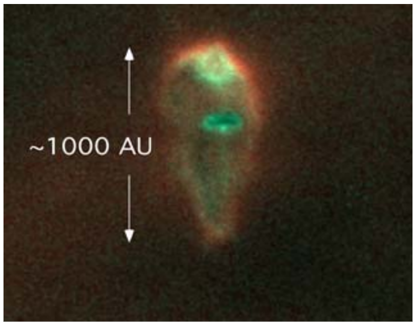


**Figure 3: A potential proto-solar system in the Orion nebula as seen with HST. At 0.01" resolution, MUST will resolve structures to 4.5 AU at Orion, and 1 AU at Taurus.**

Star formation is the fundamental process that determines the fate of baryonic matter in the cosmos. Stars render galaxies visible, forge the chemical elements, and generate the kinetic energy and radiation that regulate the phases of the interstellar medium. They may also govern the production of galactic outflows that drive metals into the IGM.

Planets are the home to any potential life that we might recognize. However, one can imagine innumerable combinations of stellar type and planetary system, and the cradle of life might exist in many disguises. The possibility of detecting life requires an understanding of planetary formation in combination with star formation.

Near-UV and optical wavelength observations with MUST will provide 0.01" resolution over wide fields-of-view with high contrast not achievable at any other wave-band (in the IR, the diffraction limit restricts performance, while in the x-ray, optical performance is limiting). Even with technology such as adaptive optics, these levels of performance cannot be achieved over wide fields. Imaging at 0.01" and proper motion studies to 10's of km/s will enable scientific investigations of star/planet forming regions that would otherwise be impossible.

Many stars are born in OB associations near massive stars, which rapidly erode the dusty molecular clouds shrouding the earliest phases of star birth. The majority of young stars and their proto-planetary disks become accessible to high resolution studies at UV-optical wavelengths less than a million years after birth, thereby rendering the early phases of planet formation, cluster evolution, and stellar youth open to investigation. While longer wavelength studies can probe the earliest, dusty phases, they cannot provide the high spatial resolution necessary for deconstructing the physical mechanisms. For example, at the distance of Orion (450 pc) the resolution of MUST provides information on the physical scales of 4.5 AU. JWST, with its performance of 0.068", will provide information on a 30 AU scale. Thus, only an integrated stellar/disk image/spectrum will be possible. It is in the ultraviolet where the accretion products can be directly observed and quantitatively evaluated through absorption spectroscopy against the star. Together, the high spatial resolution, wide fields, and UV spectroscopy are needed for a complete picture of solar system formation.

In addition, the exquisite point PSF of MUST and its long lifetime (assumed to be ≥ 5 years) will provide unprecedented proper motion studies of star clusters. The nature of these clusters (bound or unbound) can be directly determined by combining radial and transverse velocity measurements.

Conventional imaging systems, even with the diffraction-limited space telescopes, cannot penetrate the halo of light around stars or AGN to the deepest levels where many features of interest lie. The task requires a highly corrected telescopic wavefront and instrument based on an aggressive Fourier-optical technique, particularly coronagraphy, to suppress the halo. NASA and the community have made major advances in recent years, studying “optimized coronagraphs” with deformable mirrors to correct wavefront errors for Hubble, Discovery missions, and the Terrestrial Planet Finder (TPF). However, current concepts for TPF-C indicate that the requirements needed to support planet finding contrast ratios are extremely stringent, and probably not scientifically and technically compatible with the broad science program of a facility telescope in the Hubble style. The coronagraph on MUST will be optimized differently than a coronagraphic/optical TPF, so as to enable different science. The contrast required for planet detection is not the same as that required for AGN/star formation/black hole science. In fact, we have set a goal of contrast of $10^{-6}$ in the MUST coronagraph, sufficient for planet forming regions and AGN host galaxies, but not terrestrial planet finding. We believe that this level of performance, while still challenging, will not impact the broader science objectives of the observatory.

### *Where are the baryons in the modern universe, and how are they distributed?*

One of the fundamental mysteries of the modern universe is the location of the "missing baryons". Both big-bang nucleosynthesis and cosmological background models indicate that $\Omega_b$ is approximately 0.046 (for $H_0$ = 70 km/s/Mpc). However, a census of galaxies, groups, and clusters at low redshifts can account for less than

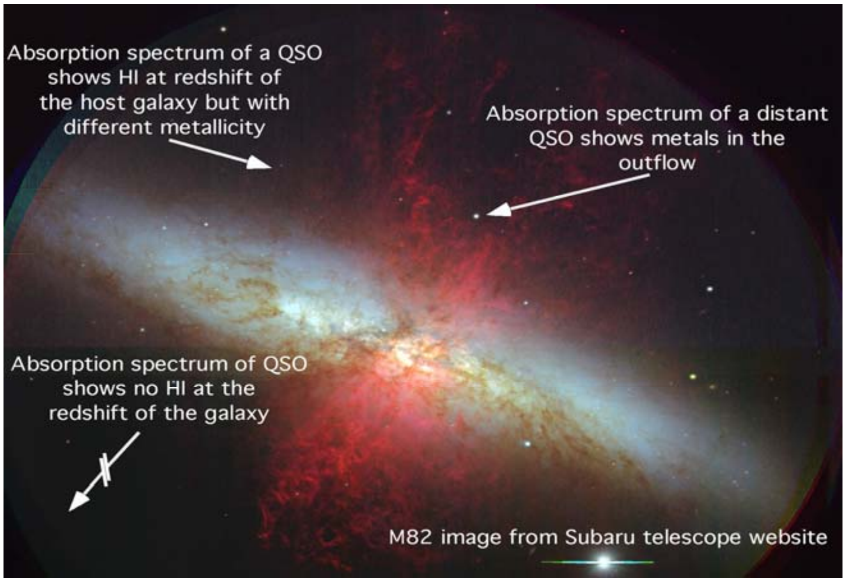


**Figure 4: The galaxy M82. showing its outflow, showing example lines of sight that would dissect its interaction with the IGM.**

10% of this matter. Presumably, the rest of the baryons reside in intergalactic structures, with densities too low to support star formation.

Numerical simulations of the low-z IGM (Cen & Ostriker 1999; Dave et al. 2001) predict that the IGM gas is distributed nearly equally (30-40% each) in three phases: warm photoionized gas ($10^4$ K); (2) warm/hot shocked gas ($10^{5-7}$ K); and (3) collapsed halos, galaxies, and clusters with much hotter gas ($T > 10^7$ K). The warm phase is observable through UV absorption lines such as the H I Lyman lines, C III, C IV, Si III, and Si IV, while the warm/hot phase is detectable in O VI and Ne VIII (UV lines) and in X-ray lines such as O VII, O VIII, and Ne IX. One of the major advantages of the UV lines is their strong absorption oscillator strengths and the much better spectral resolution than is available in the infrared or x-ray. As a result, the UV lines are 500-1000 times more sensitive than their x-ray counterparts.

The warm-hot intergalactic medium (WHIM) is thought to be produced by shock-heating during gravitational infall into dark matter filaments that co-evolve with the rise in cosmic metallicity. These heavy elements are probably expelled from galaxies by a combination of supernova activity, tidal stripping, and starburst winds.

Unfortunately, the number of IGM samples toward background AGN is currently insufficient to understand the exact nature of these absorbers and their contribution to the baryon reservoir. Correcting from H I or O VI to total hydrogen requires understanding the physical conditions (radiation field, gas density and temperature, metallicity) in the IGM. HST-COS will begin to attack this problem, but its sensitivity limit ($V = 17.5$ for a typical exposure on background QSO's) provides an insufficient sky density of targets to characterize the "cosmic web" of intergalactic matter except in a statistical manner. Only at $V = 21$ do QSO populations have sufficient spatial density (one QSO every 5 arcmin, on average) to sample the IGM absorbers, measure their redshift evolution, and map the warm/hot IGM along with galaxies. We need MUST to determine the physical conditions and redshift evolution of the absorbers, rather than just their H I column and redshift. This information is best deduced from trace ionized metals and from the velocity profiles of weak and intrinsically narrow absorption lines. In order to make progress in this field, one needs to observe background targets at $V = 21$, obtain high-S/N ultraviolet spectra, and dissect the IGM filaments and halos. This science will require spectroscopic sensitivity an order of magnitude beyond COS, and an observing efficiency (through multi-object spectroscopy) of 1000 times COS.

### *Beyond the Roadmap*

We have also identified some capabilities that have not been specifically called out in the roadmap, but nevertheless, hold great interest to the astronomical community. For example, with the exquisite angular resolution of MUST, we can possibly track the proper motions of stars in other galaxies, and perform detailed dynamical analysis of their mass distributions to better understand galactic black holes and dark matter halos. We may be able to obtain absorption spectroscopy of atmospheres of terrestrial planets that eclipse nearby stars – after their discovery with TPF. We should be able to extend the direct measurement of Cepheids beyond the Coma cluster. The list of compelling scientific investigations will only increase with further and broader consideration of the capabilities of MUST, just as it has with HST.

## *Science Requirements Flow Down*

| Science Goals | Measurement Capabilities | Engineering Implications | Key Technologies |
|---|---|---|---|
| **How are modern galaxies assembled and how do they evolve?**<br>**How metals are created and distributed through the modern universe?**<br>**How do stars and planetary systems form and how does this impact their likelihood of supporting life?**<br>**Where are the baryons in the modern universe and how are they distributed?** | **UV/Optical imaging**<br>• Sensitivity to $V = 29$ stars in hour-long exposures<br>• 100 independent resolution elements across a one arcsecond galaxy at $z \sim 2$<br>• Large field for efficient sky coverage<br>• Narrow filters suitable for studying gas processes in both local and extragalactic environments<br>• Separate stars in super star clusters at modest redshift ($< 0.2$) (0.01 arcseconds)<br>• Measure proper motion of 10 $\text{kms}^{-1}$ out to 8 kpc<br>• Resolve scales of 4.5 AU at Orion (0.01 arcseconds)<br>• High contrast imaging<br>• UV/Optical spectroscopy of $m_v = 21$ objects at $\lambda/\Delta\lambda > 20,000$<br>• Multi-object spectroscopy<br>• Integral Field Spectroscopy | **Detectors**<br>• Large format, high QE arrays for NUV-Visible<br>• High QE large format UV photon counting detectors<br>• Radiation tolerant detectors<br>**Optics**<br>• 10 meter primary, segmented primary<br>• Diffraction limited at 500nm<br>• Low UV scatter optics<br>• High throughput UV/Optical spectrograph<br>• Tunable filters for arbitrary bandpass selection.<br>**Miscellaneous**<br>• Fine pointing/ correction (< 1 mas)<br>• Extremely large data volume drives telemetry systems<br>• Efficient maneuvering of large, massive observatory | **Detectors**<br>• 4 edge buttable NUV/Visible solid state devices<br>• High resolution, large format anodes for microchannel plate detectors<br>• Improved microchannel plates for lower gain/higher count rate applications<br>• Improved photocathodes for microchannel plate based detector systems<br>• Higher efficiency for solid state detectors<br>**Optics**<br>• On orbit assembly and verification process for large optics<br>• Coronagraphy with segmented primary optic<br>• Coating techniques for large optics<br>• Tunable filter technology applied to large sizes for space based systems<br>**Miscellaneous**<br>• Stable attitude control<br>• High bandwidth, continuous telemetry (laser, ka band, etc)<br>• Optical coating for 100 nm performance without sacrificing hardiness/throughput (stretch goal) |

### Uniqueness or Scientific Advantages of the Proposed Approach Compared to Alternatives

Two potential alternatives might be considered to a large optical-UV telescope. However, neither can match the scientific return of a 10m optical-UV system.

*Large Infrared Telescope*: Operating in the infrared, the diffraction limit of even a 10m IR telescope will be approximately a factor of four worse than an optical telescope ($\lambda/D$ at 0.5 μm compared to $\lambda/D$ at 2.0 μm). A 10 meter diameter IR telescope operating at 2μm has the same diffraction limit as a 2.5 meter telescope in the visible – e.g. the current HST. This level of spatial resolution will not allow the extragalactic stellar science that a 10m optical telescope enables. The primary diagnostic lines exist in the UV and optical – while these will appear in the IR in distant, redshifted systems, this restricts an IR telescope to performing the stellar and galactic science described herein in the early universe. The UV diagnostics would have to be redshifted by $z \approx 4$ or more to be available in the infrared, confining their access to the first 2-3 billion years of the universe. The universe has substantially evolved since $z \approx 4$, so that infrared observations do not address the science issues outlined here.

*Ground Based Telescopes*: The atmosphere will prevent high quality imaging over wide fields, even with ideal adaptive optics systems, because of the variations in the atmospheric column above any ground-based telescope. The vacuum ultraviolet cannot be accessed from the ground under any circumstance. Atmospheric background will always be greater than the darkness of the sky experienced at L2, so that the faint limit of space telescopes will always be superior to ground based systems of similar aperture. Ground based telescopes are capable of great observing power and are an essential element in the overall astronomical toolkit – but they can never replace the advantages of a space telescope.

## *Architecture and Implementation Approach*

### Space Systems Architecture

*Overview*

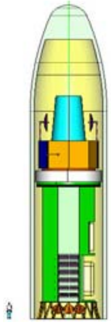
Our baseline concept for the MUST mission consists of one observatory in a Lissajous orbit near the sun-earth L2 point. For the discussion in this report the observatory consists of four elements:

- a large telescope
- four or more science instruments
- a spacecraft bus that provides standard services
- a sunshield/baffle

The telescope has an aperture diameter of 10m to provide the required angular resolution, and a collecting area of greater than $50m^2$ to achieve the needed sensitivity. The primary mirror is segmented and includes capabilities for active alignment and phasing during flight. The science instruments provide wide field and high resolution imaging, spectroscopy and moderate contrast coronagraphy. The science payload provides wavelength coverage from 1150Å in the ultraviolet to approximately 2.5μm in the near-infrared, limited by the reflective coating at the short end and background emission from the warm telescope at the long wavelength end. The telescope and instruments operate near room temperature, not at cryogenic temperatures. The spacecraft carries a propulsion system for periodic orbit maintenance and momentum unloading. Communications use X-band for normal command uplink and engineering data downlink, Ka-band for high volume science data downlink, and an S-band omni for emergencies. High efficiency solar arrays and batteries provide electrical power. The attitude control system provides a three-axis stabilized platform using a combination of sun-sensors, star trackers, gyroscopes and reaction wheels. A large sunshield/baffle allows the boresight to point (at a minimum) anywhere greater than approximately 85° from the sun, giving access to over 50% of the sky at any time, and 100% over the course of a year. The LOS jitter is controlled to milli-arc second precision to preserve diffraction-limited image quality at optical wavelengths.

At launch the payload is partially disassembled, with components such as the primary mirror segments stowed safely in a module referred to as the Dispenser, or the Robotic Service Module. We offer a concept whereby robotic capabilities investigated for the Hubble Space Telescope service mission, and developed for the International Space Station and the Exploration Initiative will be used to assemble the observatory in space. Our assembly concept is discussed in detail in Section 4. The observatory will have all of the capabilities needed to complete a nominal five-year core science mission. It will be designed with modularity and standard interfaces intended to facilitate robotic servicing for an extended mission – with a goal of a 10+ year lifetime, as achieved with HST.

Observatory and dispenser in launch configuration



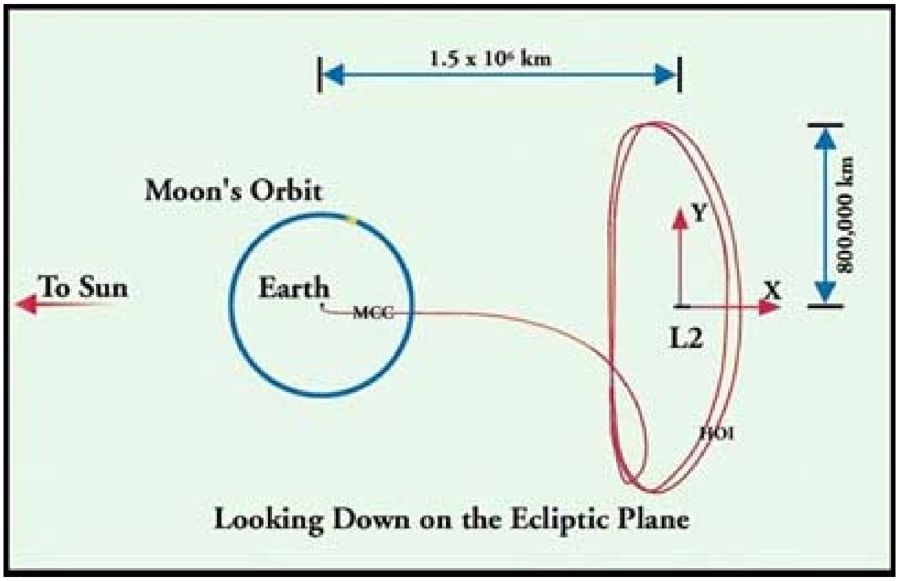
*Orbit*

We performed a trade study of many possible orbits for the MUST mission, and concluded that the earth-sun L2 point is the best choice. During our IMDC run at GSFC the flight dynamics team did a detailed analysis of the implications for launch mass, propulsion, communications, thermal and power requirements for low earth and geosynchronous orbits, lunar surface and lunar orbit, Earth-Moon L4, Earth-trailing drift-away, and L2 halo orbits. Members of our team also considered the possible scientific costs and benefits of low earth polar obits, Molniya and GPS-like orbits, Chandra-like elliptical, and heliocentric orbits that do not remain near the earth. Although a UV-optical telescope does not require the thermal environment that a heliocentric orbit offers to infrared missions such as Spitzer and James Webb, there are other advantages that compel us to recommend L2:

- Access to large fraction of celestial sphere without frequent occultations
- Stable thermal environment without frequent day-night transitions
- Low disturbance torques other than solar radiation pressure
- Near constant solar illumination simplifies power system design
- Near constant range simplifies communications system design
- Extensive operations experience from previous missions
- Efficient science operations, especially for programs with long exposure times
- Flight dynamics allows direct transfer from launch to insertion
- Infrequent station-keeping maneuvers required with minimal propellant
- Safe disposal into earth-trailing drift-away at end of mission
- Ability to reach L2 for either manned or robotic servicing may be developed as part of Exploration initiative

*The Spacecraft Bus*

Our study of the requirements on the spacecraft bus was done in collaboration with the engineers at the IMDC, and the mission systems engineering group at Ball Aerospace & Technologies Corp. The bus provides the standard services of navigation, propulsion, attitude control, data management, communications and electrical power distribution. Although MUST is larger than usual, the types of services needed are not qualitatively different from other astronomical observatories operating at L2. In most cases the engineers were able to identify components or subsystems from existing inventory, or at least identify the requirements on larger capacity components.



L2 orbit

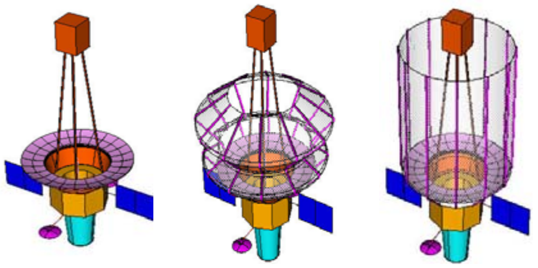
## Spacecraft Bus Properties

| Property | Value |
|---|---|
| | |
| Mechanical properties | Hexagonal aluminum structure |
| | 3500 kg total wet mass (with margin) |
| | ~5m diameter, ~3m height |
| | Deployable solar arrays & HGA |
| | |
| Attitude control system | 3 axis stabilized, zero momentum |
| | Coarse sun sensor |
| | Redundant, high performance Startrackers |
| | Four reaction wheels with isolators |
| | Thrusters for momentum unloading |
| | Inertial Reference Units (Gyros) |
| | High precision Fine Guidance Sensor |
| | Fine Steering Mirror in optical system |
| | Boresight accuracy after slew ~1 arc sec |
| | RMS LOS jitter during exposure ~1 mas |
| | |
| Propulsion | 12 one pound thrusters on bus |
| | Monopropellant hydrazine |
| | Fuel for 10 years of station-keeping |
| | |
| Electrical power subsystem | 18 $m^2$ triple junction GaAs solar arrays |
| | Deployed, dual wing, single-axis steerable |
| | 80 amp-hour Li-ion batteries |
| | |
| Command & Data Handling | Redundant spacecraft computer |
| | Solid state bulk memory 200 GBytes/day |
| | Data network > 100 Mbps |
| | Spacecraft flight software |
| | |
| Communications | Two 2m deployed, steerable HGA |
| | 0.3° beamwidth |
| | 34m DSN or equivalent ground station |
| | 50 W Ka band data downlink @ 500Mbps |
| | X-band telemetry downlink @ 10 kbps |
| | X-band command uplink @ 2 kbps |
| | S-band omni emergency uplink @ 2 kbps |
| | S-band omni telemetry downlink @ 6 kbps |
| | S-band transponder for ranging |
| | |
| Thermal | Body-mounted radiator |
| | Thermal control coatings and blankets |
| | Heat pipes and straps as needed |
| | |
| Reliability approach | Fully redundant, designed for 5 yrs |
| | |

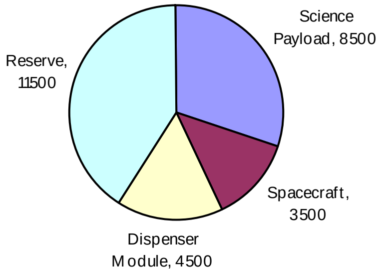
*The Sunshield/Baffle*

The MUST observatory will have a sunshield to minimize stray light and to assist in maintaining a stable thermal environment for the optical system. The large size of the system leads to consideration of a design that can be stowed for launch then deployed, assembled or inflated in space. Since MUST does not need to cool passively to low temperatures, an open, single-sided configuration like JWST is not required. A cylindrical concept that surrounds the primary mirror, and extends from the primary to secondary, as is being developed for TPF-C, appears appropriate. The requirements for temperature stability for MUST will be less demanding than those for TPF-C, so a design with fewer layers will be acceptable.

Sunshield deployment



As part of the IMDC study we derived mass estimates for all of the components of the observatory. In most cases, such as spacecraft subsystems, robotics and propellant, the components were sufficiently well defined to permit a “bottoms up” estimate based on databases of known values. A 30% margin was applied to all values. In other cases the concept was less well defined and we resorted to what we consider to be a reasonable allocation. For example, the designs of the instruments were immature at the time of our IMDC session. We allocated 1000kg to each of four instrument module, approximately twice the mass of HST instruments. We summed all of the components into three categories, the Dispenser Module, the Spacecraft and the Science Payload. For the purposes of this report we rounded these sums to the next higher 500 kg. The result suggests a launch mass of 16500 kg, well within the advertised capacity of 28000 kg for the launch vehicle. Given the existence of such a launch vehicle it appears that a concept such as MUST will not be severely mass constrained. The preliminary mass budget derived in this manner is shown in the following table and chart.



Mass budget summary

| | kg |
|---|---|
| Science Payload | 8500 |
| Spacecraft | 3500 |
| Dispenser Module | 4500 |
| Budgeted total | 16500 |
| LV capacity to L2 | 28000 |
| reserve | 11500 |
| % of capacity | 41% |

## Science Instrumentation

### *The Telescope*

The optical form used in our study is a Ritchey-Chretien similar to the Hubble Space Telescope, but scaled up to the dimensions required to provide the MUST angular resolution and sensitivity, and "compressed" to allow a more compact observatory. The goal of our study was to identify a plausible path to achieving a large UV optical space telescope with a reasonable development schedule and cost, and a technical approach that is consistent with NASA's future initiatives. A significant advantage of the RC telescope is that the on-axis symmetry allows all of the segments to be identical. This is a simplification for manufacturing and testing, and allows an obvious spares policy. We also considered the three mirror anastigmatic design, which provides high quality imaging over large fields of view. Regardless of the final design, additional optics beyond the primary and secondary will presumably be required for wavefront correction and aberration control.

The driving requirements for $D = 10\text{m}$ and $A > 50\text{m}^2$ allow the annular shape with $e = 0.6$ shown in several figures in this report. Although this form easily meets the specifications for angular resolution, the distribution of light in the rings is different from the Airy pattern of an unobscured circular aperture. Future refinements to the design will investigate how the instruments may be optimized for this point-spread function, or whether a central mirror segment should be added to produce a more conventional aspect ratio. Several figures show the primary mirror including a more filled aperture. In any case – the ability to extract high reliability spatial knowledge to the advertised performance: 0.01″ at 5000 Å, even at low signal to noise, is the essential science driver for MUST, and any necessary changes to the optical design baseline will be incorporated to ensure that the promised performance is delivered. An error budget accounting for design, manufacturing, assembly, alignment and stability factors will need to be developed. We also recognize that future studies may consider other telescope designs intended to provide a larger field of view, a different assembly approach, or to allow addition of segments for future growth. While we believe that a robotically assembled telescope is the best implementation given our understanding of present and future capabilities, the exact nature of the telescope optical design will require a much more detailed study as the mission becomes more developed.

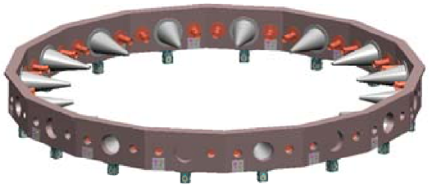
The properties of our baseline telescope are summarized below.

## Telescope Properties

| Property | Value |
|---|---|
| | |
| Diameter of Primary Mirror | 10m |
| Available collecting area | $> 50m^2$ |
| Annular central linear diameter | < 60% of outer diameter |
| System focal ratio | f/11 |
| Effective system focal length | 110m |
| Field of View | 7.2 arc min diameter |
| Image surface | 234mm diameter, curved with R=1.8m |
| Back focal distance | 3m |
| Plate scale at RC focal surface | 1.86 arc sec/mm |
| | |
| Wavelength for diffraction-limited imaging | 5000Å |
| Wave front error | $\lambda/14 = 36nm$ |
| Angular resolution | $\lambda/D = 10.3mas$ |
| RMS jitter allowed | $1/10\ \lambda/D = 1mas$ |
| Reflective coating | $Al + MgF_2$ |
| Wavelength range | $1150Å < \lambda < 2.5\mu m$ |
| | |
| Primary mirror segments | 16 with same prescription |
| Primary mirror focal ratio | f/1.2 |
| Segment size | Each edge ~2m, area = $3.2m^2$ |
| Segment active control | Rigid body + low order figure |
| Gaps between segments | Few mm |
| Secondary mirror diameter | 1.4m |
| Primary to secondary distance | 11.7m |
| Mirror material | Open to study, ULE, Zerodur would do |
| Operational temperature | Ambient or slightly cooler, not cryo |
| | |

### *The Metering Ring*

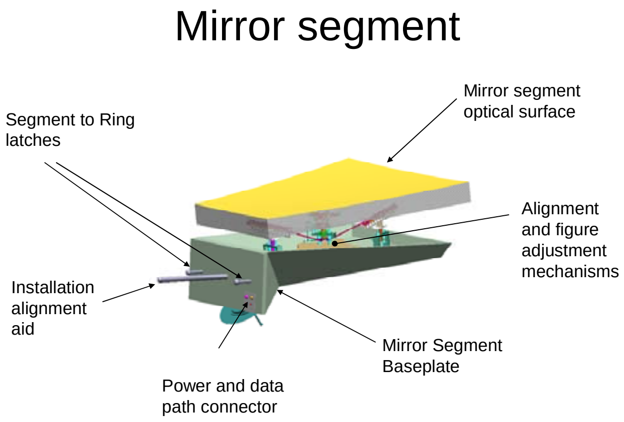
Metering ring



An important element in our concept for on-orbit assembly is the metering ring, or hub, to which other components are attached. This structure has the following characteristics:

- Single structural element, assembled, aligned and tested before launch
- Does not require deployment or assembly itself
- Contains docking stations for 16 primary

mirror segments
  - Recognition, installation and alignment aids
  - Attachment fittings and locking mechanisms
  - Reversible, may be disengaged if necessary
  - Provisions for metrology of segments to guide initial alignment
- Thermal conductivity and control provides uniform temperature
- Attachment fittings for other observatory components
  - Secondary mirror support structure
  - Spacecraft bus
  - Instrument module
  - Outer sunshield/baffle
- Connectors for power and data paths
  - Primary mirror segments
  - Secondary mirror
  - Spacecraft bus



*Primary Mirror Segments*

Any architecture for a 10m space telescope will require segmentation of the primary mirror. In our approach the segments have the following characteristics:

- Stow in the dispenser module for launch and cruise
- Grapple fixture enables manipulation by robot
- Identification aid to associate segment with place on hub
- Installation and alignment aids, sensors
- Segment side of attachment fittings and locking mechanisms
- Mirror petal support system
  - Supporting structure
  - Rigid body position adjustment actuators
  - Figure adjustment actuator(s)
  - Mirror petals
  - Removable protective cover
- Electrical components
  - Segment side of connector interface
  - Power distribution from hub
  - Command and data paths
  - Control of segment actuators & sensors
  - Thermal control sensors and heaters

## Science Instrumentation

We have identified a minimum suite of instruments necessary to achieve the fundamental science requirements.

*High Resolution Camera*: This is the primary camera for the system – achieving 0.01″ resolution at 5000 Å. The detector array will be 100K X 100K (10 gigapixels) with each pixel subtending 0.0033 arcseconds (3 pixels/resolution element). This provides a field of view of 333″ x 333″. The size of the array is approximately 800 mm (~32 inches) on a side, assuming 8μm pixels. The diffraction limit at shorter wavelengths are even better than 0.01″ and it is hoped that the figure quality and control will be sufficient to take advantage of this – 0.006″ resolution at 3000 Å for example. The instrument should cover a minimum bandpass of 0.2 μm to 1 μm. Multiple mirror anastigmatic designs can provide the aberration control over these fields; the primary technological challenge will be the detectors – providing large mosaic arrays with high QE over large bandpasses. They will also require low readout noise and dark currents, as well as high radiation tolerance so that the large effective areas can be fully utilized and the system remains signal limited on the faintest sources.

A resolution of 0.01″ represents the following physical scales:

- Cosmology/galaxy assembly: ~80 pc at $z = 1$
- Virgo (D = 18 Mpc): 0.9 pc = $2.7\times10^{18}$ cm
- M31/M32 (D = 0.7 Mpc): 0.034 pc = $1\times10^{17}$ cm
- Globular Cluster (D = 8 kpc): $1.2\times10^{15}$ cm
- Orion Nebula (D = 460 pc): $6.8\times10^{13}$ cm = 4.6 AU
- Taurus Cloud (D = 140 pc): $2.1\times10^{13}$ cm = 1.4 AU
- Jupiter (D = 4 AU at opposition): $3.0\times10^{6}$ cm = 30 km

We estimate, for example, that MUST/HRI can reach 1 magnitude below the main sequence in M32 (5σ at V~29, ~4 nJy) in just a few hours per bandpass (taking into account the high background of the crowded field), over an order of magnitude faster than could be accomplished with HST/ACS-HRC and with 10 times higher spatial resolution.

*Wide Field Camera*: The wide field camera will utilize a similar (or possibly, the same) 10 gigapixel array at a plate scale of 0.015 arcseconds/pixel (0.03 arcsecond resolution) – yielding a field of view of 1500 x 1500 arcseconds (625 square arc minutes). Each wide field image will contain over 10,000 times the information of a HST image. The ability to survey faint galaxies, and discover low surface brightness objects will be enhanced by a similar factor. Discovering and monitoring transient events such as distant supernova will be made vastly more efficient and accurate.

*FUV Imager:* The beautiful UV images being obtained by GALEX (with ~5" angular resolution) demonstrates how massive stars in the nearby universe can be studied with virtually no background contamination from A-type or later-type stars at far-UV wavelengths (~1500 Å). An imager that probes the 1150-2000 Å spectral region may need to rely on different detector technologies. However, detectors in this wavelength regime will be needed to support the UV spectroscopic capabilities. A far-UV imager would provide access to the continuum of hot stars and emission lines such as Lyα, C IV λλ1550, and O VI λλ1032 (possibly only at modest redshift) for characterizing local star forming counterparts to high-redshift galaxies at exquisite spatial resolution. This UV imager would provide an outstanding tool for studying the ISM in the Milky Way and Local Group galaxies. If acceptable mirror coatings could be found that would extend the UV performance down to 1000 Å (making OVI accessible even at zero redshift) the power of the instrument would be even greater, and this is a technological advance that merits investment.

*Multi-object and Imaging Spectrograph:* We have identified two fundamental requirements for the spectrograph. First, the instrument shall be at least 25 times more sensitive than HST/COS. This will enable the observation of V = 21 QSO's, and provide the needed sky density of background targets for a detailed deconstruction of the cosmic web and its interface with galaxies. Second, the instrument shall have a multi-object and long slit spectroscopic capability over a reasonable field of view, to maximize observing efficiency. Without this capability, the total observing time necessary to observe the many QSO's now available would prohibit the successful completion of the science program. With a 40-object capability, for example, *MUST can collect spectroscopic information at 1000 times the rate of HST.* In addition, any future optical-UV mission should broadly cover the optical-UV at low and moderate resolution (R = 30,000 and below) while providing high resolution (R = 100,000 +) over a selectable, limited bandpass. Such capabilities are necessary to push the frontier of ISM science, probe planet forming debris disks, and search for black holes spectroscopically.

We feel that the most promising applications in the optical are a lenslet fed optical bundle array creating a true integral field spectrograph that provides full-field imaging spectroscopy on both diffuse sources and fields of point sources. Using lenslet arrays at differing sample scales (for example, over wider fields of view) provides efficient multi-object spectroscopy over the fields appropriate for QSO absorption line studies. In the ultraviolet, future micro-mirror arrays can be used in the same away, and this is an identified technological capability worthy of investment.

*Coronagraph:* We have chosen to assume that planet finding will either have already occurred or is undergoing parallel development, given its prominence in the strategic plan. However, moderate level coronagraphy, at a level of $10^{-6}$ contrast, still has significant applications, including the study of AGN host galaxies and the study of star and planet forming regions. Utilizing TPF-C and JWST techniques as a baseline, we have identified scattered light control with a segmented mirror as the primary technological challenge.

## Instrumental Technological Areas for Future Study

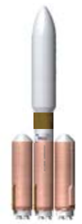
Large format (gigapixel) solid state arrays
High QE detectors over the full bandpass
Low noise, radiation tolerant systems
Large Format MCP detectors for the FUV Imaging Camera
Micro-mirror arrays for all-reflective integral field spectroscopy
Coronagraphic techniques with segmented telescopes

## Infrastructure and Constraints

Before launch the telescope will be assembled and tested. A robotics testbed in which the assembly techniques and sequence are developed would be highly desirable.

A cleanroom and thermal-vacuum facility large enough to accommodate the telescope, at least the primary and secondary mirrors plus a flight or surrogate science instrument, will be needed. To minimize distortions due to gravity the telescope should be oriented vertically in both facilities. Our preliminary design suggests a height of at least 15m.

Atlas V Phase 2 with 7m fairing



The 10m version of a large UV-optical telescope will require a large launch vehicle with a 7m payload fairing if it is to be accommodated by a single launch. Our IMDC study identified an Atlas V Phase 2 with a 7.2m fairing as having the needed capabilities. Preliminary information about this vehicle indicates that it can use launch pad infrastructure being developed for the current generation of Atlas V Heavy. We believe that this single launch approach is the simplest and probably the lowest cost option. In the absence of a suitable vehicle the observatory could either be partitioned for multiple launches or scaled down to fit an available EELV Heavy and its largest fairing.

The core of our concept is robotic assembly in space. Ideally the capability to perform the required tasks will be developed as part of the infrastructure for Exploration. Should that not come to fruition, they could be developed specifically for the MUST mission.

MUST will produce a large volume of data with its large focal plane arrays and frequent readouts. We estimate that approximately 200GB/day will need to be downlinked. The telecommunications analysis during our IMDC study concluded that a Ka band link to a 34m dish at a DSN or other facility will be needed.

## Role of humans

Our concept for robotic assembly of the observatory will require human supervision. As robotic technology for Exploration advances many functions will become routine and highly autonomous. Critical sequences such as the assembly of the primary mirror segments will consist of a series of tasks that can be performed automatically, with hold points for evaluation of progress. It will be humans who perform this evaluation and either give approval to proceed or take corrective action. In our baseline concept the assembly takes place near the operational L2 orbit. We would not expect the humans to be present at the worksite, but would be monitoring the process from closer to earth. There is discussion of development of a facility for construction activities, perhaps at an earth-moon libration point, that would include a crew of astronauts. If such a facility were to be available in the MUST timeframe the mission design could certainly be crafted to take advantage of it. The assembly could be monitored, or even performed at such a depot. If the earth-moon transfer station becomes likely, we recommend that MUST, and other large telescopes, utilize this station for assembly and test prior to transfer to their operational orbit, and that this be developed as the standard model for future large science missions. MUST will be an unmanned observatory, operated by onboard computers, programmed by controllers on ground.

## ***Technology***

This section describes our recommendations for development of technologies needed to implement a large optical telescope such as MUST. We identify both those that are unique to our concept, such as mirror segments, and those which are generic capabilities that NASA will need for the Exploration initiative, such as large launch vehicles and robotic techniques. The items are listed here more or less in order of priority.

### Mirror segments

#### *Unique requirements, their priority, and sensitivity of design to each*

The highest priority enabling technology for a telescope like MUST is mirror segments that are compatible with the assembly requirements and that provide the needed optical performance. Without suitable mirror segments and a means to combine them into one optical surface there is no telescope. Any architecture for a 10m diameter or larger primary mirror will require segments, whether the telescope is assembled by robots or astronauts, or deployed like JWST. The UV and optical wavelength range of MUST imposes tighter requirements on surface figure and alignment than do the infrared wavelengths of JWST or SAFIR. On the other hand, MUST will not require cryogenic temperatures. Specific requirements on the segments include:

- Mechanical interface to metering ring
- Electrical interface to metering ring
- Aids for robotic or human handling
- Ability to withstand launch loads
- Mass-efficient design
- Installation accuracy within capture range of alignment mechanisms
- Stability of alignment during operations

#### *Key technology risks and uncertainties*

An uncertainty at this point in the development is which mode of assembly or deployment will ultimately be chosen; robotic, astronaut, deployment. Each will have different requirements for the interfaces to the supporting structure and the mechanical or human system.

An attractive benefit of our concept is the mass efficiency to be realized by separating the functionality of absorbing launch loads and providing precise optical positioning in orbit. However, this is an assumption that we used as a starting point, not a proven fact derived from detailed design. As with all UV optical systems, contamination of the reflecting surfaces is a technical risk.

Our baseline concept requires mirror segments that are close to 2m on a side. A more detailed design must be sure that such a size will be within the comfort range for manufacture and test.

### *Development roadmap, with alternative approaches*

A helpful early step in the development of a Large UV Optical telescope will be an architecture evaluation that makes decisions regarding aperture diameter and area, assembly or deployment approach, fixed size vs. later additions, and relationship to the infrastructure of Exploration, especially robotic capabilities. Several concepts for large telescopes have been introduced by scientists and by engineers. Progress towards developing the technology depends on selection of an architectural approach.

Following that, the second step would produce a preliminary system design with budgets such as mass, and can offer allocations for the segments and the hub. A hardware development effort much like the JWST AMSD program would then explore several approaches, with a progressive down-select to two or three viable candidates. The segment designs will need to address all of the technical concerns identified above, in addition to incorporating actual mirror surfaces. Efficient replication of identical segments will also be a consideration.

### *Validation and/or demonstration approach*

The first approach to validation should be detailed computer modeling, including the metering ring, the segments and the robotic system. Initial models can be primarily mechanical, with later incorporation of thermal and optical performance. A laboratory test-bed should be developed and used to validate the computer models and develop confidence in the approach using actual hardware. Such facilities could be developed at NASA centers, aerospace or optical manufacturing industry, or at an academic institution.

We foresee little justification for space-based experiments unless they were incorporated into a demonstration of Exploration related capabilities. As the NEXUS experience for NGST showed, flight projects are expensive and time-consuming, even if they have no scientific mission.

## Optical performance

*Unique requirements, their priority, and sensitivity of design to each*

After assembly or deployment, the individual segments must be co-aligned and with the rest of the optical system to achieve the required image quality. The driving scientific requirement in the MUST concept is to provide 10 milli-arc seconds angular resolution in visible light, with a goal of fully diffraction limited imaging performance for $D = 10m$ and $\lambda = 0.5\mu m$. As a first approximation the optical requirements are four times tighter than for JWST.

*Key technology risks and uncertainties*

The system must be capable of installing the segments, erecting the secondary mirror, and aligning them to provide proper images to the science instruments. The systems engineering process will include the tolerances of robotic assembly, large-scale adjustment of the segment locations, fine alignment of the mirror positions (primary and secondary mirrors), and active adjustment to compensate for at least low-order figure errors such as radius of curvature. Each stage must bring the mirrors to within the capture and control range of the next phase. The segments in our design are slightly asymmetrical. Adjusting any component of figure must be done without introducing other distortions or aberrations. A key component of the process is defining the hardware and software procedures used to obtain and interpret information about the wave-front errors. These will include hardware sensors such as actuator positions and edge-sensors, on-board optical metrology and certainly ground-based analysis of stellar images. The algorithms must converge to a unique solution that guides the adjustments of the mirror surfaces. The entire system must be both mass and time efficient. The telescope must provide a combination of passive stability and active control that maintains the required imaging performance for scientifically useful periods of time – hours at least.

*Development roadmap, with alternative approaches*

The development process should start with a clear statement of optical performance requirements directly traceable to scientific requirements. These should be expressed as metrics such as Strehl ratio, encircled energy, FWHM, etc., that can be analyzed and measured. Optical designs will be created that achieve these requirements with sufficient margin. An error budget process will then allocate deficiencies to the design, manufacture, assembly, alignment, and stability of the system.

Trade studies during this period will consider alternative approaches for the mirror segment rigidity (semi-rigid vs. highly flexible), number of actuators needed, range and precision of actuators, flight metrology sensors, mathematical algorithms and other factors. This process builds directly on the experience being gained with JWST and TPF-C.

*Validation and/or demonstration approach*

Integrated system modeling that includes high resolution representation of wavefront errors will be a powerful tool for developing the approach and conducting trade studies. Laboratory demonstrations of key concepts should be carried out at one or more of the wave-front test-beds. Collaboration with JWST and TPF-C on hardware and algorithm development, or at least building on the results of their efforts, would be valuable.

## Robotic assembly techniques

*Unique requirements, their priority, and sensitivity of design to each*

We have described a concept for building a large astronomical telescope that is derived from the capabilities investigated for Hubble, and is supportive of and consistent with NASA's Exploration initiative. Our approach uses robotic assembly techniques, rather than mechanical deployment, to arrange mirror segments in their required final location. We expect that none of the techniques or hardware items will be truly unique to MUST, but are representative of the larger suite of capabilities that will be developed for Exploration. We wish to leverage advances made by other NASA programs to enable a powerful scientific tool, and to provide some motivation and encouragement for their development. The MUST mission as envisioned here requires:

- Efficient and safe stowage of components for launch in the RSM
- Assembly in space
- Recognition, alignment aids, sensors
- Latches, connectors, metrology

*Key technology risks and uncertainties*

The main uncertainty is what the schedule for development of Exploration capabilities will be, and what technical capabilities can be assumed to exist at each time.

*Development roadmap, with alternative approaches*

The most important task may be careful coordination between Exploration and the Science Mission Directorate to communicate each other's plans and needs. If the scientists and engineers developing future SMD missions have an understanding of EI capabilities, that knowledge can flow into architecture & design studies of MUST to take advantage of synergies.

There is a general acknowledgement that small telescopes, $D < 4$m, should be built and launched as monoliths. Intermediate size systems, say $4\text{m} < D < 10\text{m}$, are best achieved as deployable systems. Significantly larger systems will require assembly in space, either by humans or by robots. There is an intuitive belief that the "breakpoint" between deployment and assembly is near D = 10m. The development roadmap for the MUST observatory should therefore contain an early trade study to investigate the advantages and drawbacks of each approach and attempt to determine which is right path for D = 10m. This study should consider current and projected capabilities for materials, structures, active controls, launch vehicles, fairings and other items. The IMDC at GSFC would be an ideal venue for such a study.

Common interests of MUST and other space astronomy missions should be understood and exploited. The HST development work on robotics should be carefully documented and evaluated. Capabilities developed for ISS should be incorporated into future studies. SMD should identify common requirements between MUST and other initiatives, such at TPF, SAFIR, LifeFinder, and Planet Imager.

The roadmap should seek to develop hardware components that have interfaces, assembly techniques, sensors, controls, etc., that are standardized and whose use would be low risk. This includes hardware on the observatory side, and on the robotic systems side.

NASA should seek cooperative development programs with other agencies whose customers have needs for large optical telescopes. The meteorological community is interested in large telescopes at geosynchronous orbits to provide improved spatial resolution. The intelligence agencies are always interested in better angular resolution. Laser-com communications with missions to the outer planets may need systems with apertures large enough to consider assembly in space. Missions such as Orbital Express are developing techniques for robotic servicing of space-based assets.

Should the robotic assembly approach be considered unattractive for any reason, two obvious alternatives are deployment and astronaut assembly.

*Validation and/or demonstration approach*

- Integrated modeling and simulation
- Laboratory testbed experiments with individual components and techniques
- ISS demonstrations of system concepts
- Other Exploration missions & demonstrators

## Robotic Infrastructure

*Unique requirements, their priority, and sensitivity of design to each*

As with the specific robotic capabilities, we assume (hope) that the basic infrastructure needed to perform such missions will be developed under the auspices of the Exploration program. While the needs of the exploration program will presumably define the requirements for the infrastructure, it is hoped that science missions such as MUST will be considered during the design, and be able to leverage the capabilities of whatever infrastructure actually becomes reality. MUST requires:

- Assembly at either a space depot or at earth-sun L2

- A Robotic Service Module with robust capabilities
- A possible capability/facility for future servicing

*Key technology risks and uncertainties*

The nature of the capabilities and the schedule for development of the Exploration infrastructure are currently unknown.

*Development roadmap, with alternative approaches*

The Science Mission Directorate should collaborate with Exploration to coordinate mission architecture with the planned infrastructure to enable future ambitious science missions, with MUST being one example. An alternative to waiting for Exploration to provide the infrastructure would be to develop the robotic capabilities uniquely for MUST or other science missions.

*Validation and/or demonstration approach*

MUST should position itself as an early customer of the Exploration infrastructure, and should participate in demonstrations of capabilities that support both.

- Stowage and launch of mirror segments (or other delicate components) in a dispenser module
- Removal of segments and attachment to prototype metering ring
- Alignment of mirror surfaces after installation
- Safe operation of robotic services near contamination sensitive optics

### Sunshield

*Unique requirements, their priority, and sensitivity of design to each*

As an optical telescope MUST needs an external baffle/sunshield. The requirements on its performance are not unique to MUST, but include the following:

- Encircle the primary mirror and extend past the secondary mirror
- Stow in a compact configuration for launch
- Inflate, deploy or assemble in space
- Present no contamination risk to UV optics during its activation
- Suppress sunlight and other external stray light sources
- Allow any orientation of the telescope within the field of regard
- Maintain thermal stability of telescope
- Allow a minimum 5 year lifetime

*Key technology risks and uncertainties*

- Dependable deployment/assembly scheme

- Structural rigidity after deployment
- Stability during maneuvers, settling afterwards
- Vulnerability to degradation in the space environment

*Development roadmap, with alternative approaches*

The sunshield for MUST will be similar to that envisioned for TPF-C. MUST may be slightly larger, but will not be required to provide the exquisite thermal stability of TPF-C. We recommend that the two projects collaborate on development of the underlying technologies.
Alternative approaches to the structural framework include

- Deployment of a stowed system such as JWST
- Assembly by the robotic system used for the telescope
- Inflation of tubes
- Use of shape-memory polymer based materials

*Validation and/or demonstration approach*

- Engineering design studies
- Structural model of activation approaches
- Subscale laboratory demonstrations
- Full-scale prototypes of critical components or processes
- Large-scale demonstrations in cooperation with other missions

## Instrument technologies

The imaging capabilities of MUST depend upon high quality images (primarily a telescope issue) coupled with large format detectors. It is possible that deformable mirrors may be necessary within each instrument for further image quality control. For spectroscopy, techniques in the visible are reasonably well developed, but all-reflective systems need further technological demonstration. Coronagraphic techniques should leverage developments in the TPF-C program.

*Unique requirements, their priority, and sensitivity of design to each*

- Optical detectors (critical)
- UV detectors (critical)
- Deformable mirrors (important)
- Large filters & other components (important)
- Micro-mirror arrays (important)
- Coronagraphy with segmented mirrors (important)

*Key technology risks and uncertainties*

Experience on previous programs has shown that deferring development of detectors, in format and noise properties, has resulted in the detectors frequently becoming the critical path item in mission development. Detector development work must be initiated at serious levels, and advanced to TRL 6 or higher before phase C/D.

*Development roadmap, with alternative approaches*

Mechanisms for development already exist within the ROSES program. Funding for these issues should be provided, and technological development should include suborbital payloads

*Validation and/or demonstration approach*

Laboratory demonstrations followed by space demonstrations on suborbital platforms represents a demonstrated path to flight qualification

## Spacecraft technologies

*Unique requirements, their priority, and sensitivity of design to each*

The MUST observatory is larger than previous facilities. It will require a spacecraft bus whose capabilities are quantitatively greater, but not conceptually different than other space astronomy missions located at L2. The engineers at the IMDC and Ball Aerospace identified a number of subsystems whose required capacity exceeds the current state of the art. These will need development to enable the MUST mission.

- Attitude control system with high capacity, high performance reaction wheels to enable slews
- Hardware and techniques for momentum management that accommodate the large surface area exposed to solar radiation pressure and possible CP-CG offsets, and that make small and infrequent disturbances to the flight dynamics
- Techniques for navigation and orbit determination that provide information to ground controllers to plan station-keeping maneuvers
- High efficiency solar cells that allow reduced array size, simplified design & reduced disturbances
- High capacity solid state memory to accommodate several days of data volume
- LOS jitter control to milli-arc second levels required for image quality, including disturbance control, fine guidance sensor, and fine steering mirror

*Key technology risks and uncertainties*

Deficiencies in the performance of any subsystem may limit capabilities of the MUST observatory. Uncertainty about time of availability makes it difficult to define a credible schedule for the overall development of the MUST flight system.

*Development roadmap, with alternative approaches*

Many of the Vision Mission concepts will have similar needs regarding spacecraft components. Other elements of NASA's Vision for Space Exploration will also require capabilities that exceed the current state-of-the-art. The needs that we have identified should be incorporated into the larger development roadmap. Alternatively, if the needs of space astronomy missions such as MUST are not being adequately addressed, the SMD will need to fund development of components that will enable its future missions directly.

*Validation and/or demonstration approach*

Laboratory demonstrations by the vendors developing the technologies will be the primary method of validation. Incorporation into testbeds at NASA facilities will ensure performance when integrated into systems.

## Launch vehicle

*Unique requirements, their priority, and sensitivity of design to each*

During our IMDC session we conducted a trade study of launch options, and concluded that a single launch in one vehicle is the preferred approach. The size of the MUST observatory requires a mass to L2 that exceeds the capability of currently available EELV-H. Our concept of a 6m diameter, monolithic metering ring requires a fairing diameter at least that wide. Therefore, the baseline MUST mission concept requires a next-generation heavy-lift launch vehicle with a 7m diameter fairing.

*Key technology risks and uncertainties*

- A vehicle with this launch capacity or fairing size might not be developed.
- Such a vehicle might not be affordable for a cost-capped science mission.
- The launch loads need definition in order to define requirements on the dispenser module and mirror segments.

*Development roadmap, with alternative approaches*

The SMD should examine the launch capacity requirements for MUST and other future large observatories within its jurisdiction. SMD should ensure that the requirements for its programs are recognized when the capabilities of future large launch vehicles are defined. SMD should coordinate with Exploration's development of boosters for lunar and Mars missions, and seek cooperation with other agencies with large space assets.

The development of mission architectures for a MUST mission should include the recognition that a launch vehicle with the required capabilities might not be available. The implications of multiple launches with smaller vehicles and fairings should be analyzed. In particular the requirements for rendezvous at L2 should be considered.

A third alternative is to develop a design for a slightly smaller observatory that would be compatible with an existing launcher, such as an Atlas V or Delta IV Heavy with the tallest 5m fairing. We believe that an 8m telescope of the same general architecture as MUST could be launched this way.

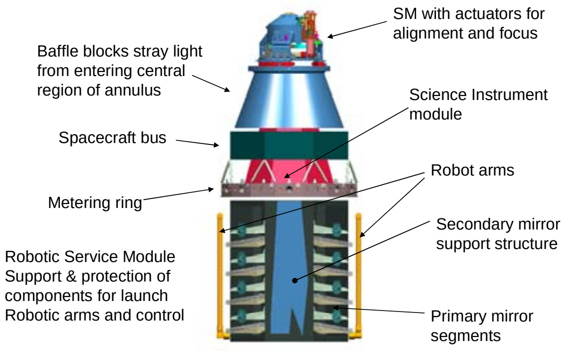
## *Deployment*

### Transportation to operational location

As discussed in section 2, the preferred operational location for MUST will be near the sun-earth L2 point. Two options for reaching this orbit are direct transfer from earth followed by assembly at L2, or delivery to an intermediate staging area for assembly, with later transfer to L2. We adopted the first option as our baseline, since the capability for direct launch to L2 exists. Should the concept of a depot in space be developed, such as at an earth-moon Lagrange point, assembly and activation of MUST at that facility, and use of a space tug for final delivery to L2 would be an attractive option.

Early in the study we considered the trade of one vs. multiple launches. With the help of GSFC IMDC we concluded that large launch vehicles projected to be available in the future will have the capacity to deliver a MUST-size payload to L2. The launch vehicle considered is a large next-generation EELV with a 7m diameter fairing, such as an Atlas 7.2. It is expected to be able to send 28000 kg to L2. The launch vehicle provides all of the propulsion needed for the departure from earth and approach to L2. A single launch avoids the complication of rendezvous at L2 that would be required by multiple launches. We have therefore developed a concept that uses one launch of a self-contained payload to establish a powerful facility that can address the core scientific mission.

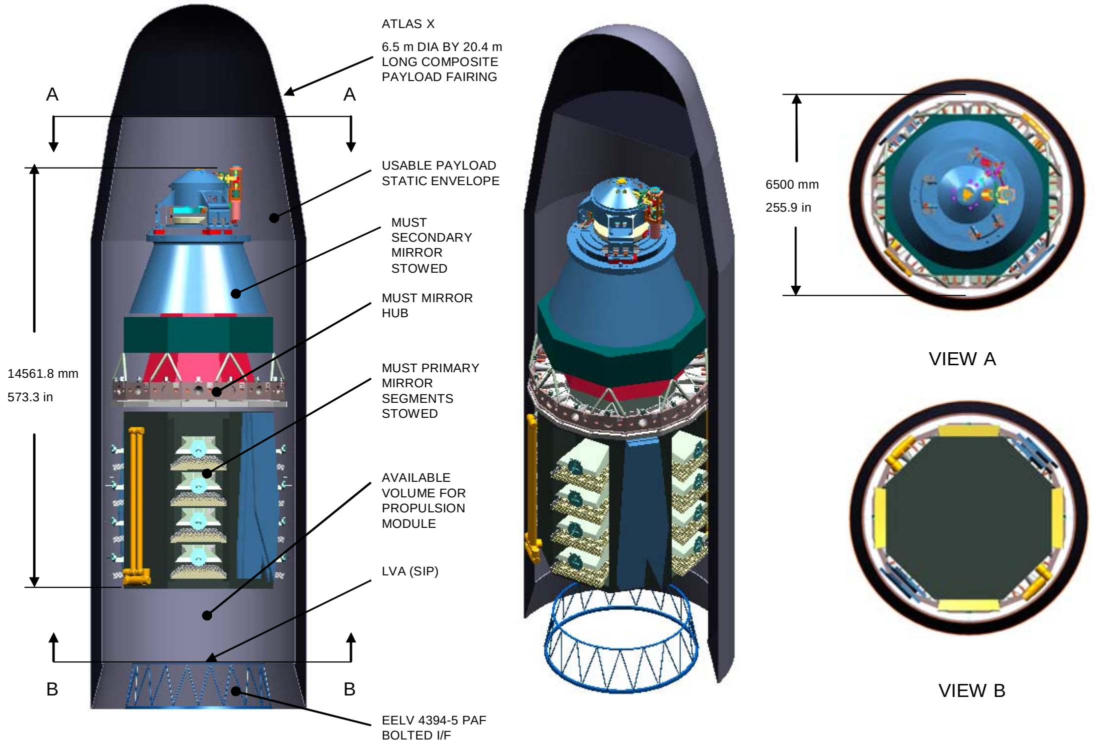
MUST launch configuration



The payload associated with the MUST mission consists of the observatory itself and a Robotic Service Module. For launch the observatory is in a state of disassembly that allows optimum packaging in the fairing and a logical assembly sequence in space. The segments that will comprise the large primary mirror are stowed for launch in the Service Module (also called the storage canister or the dispenser). This module provides the structure that absorbs launch loads, maintains a safe thermal environment and protects against contamination. Its requirements are based on storage and protection. There are no requirements for optical-level precision of its structures or mechanisms.

The Service Module needs to be a capable spacecraft in its own right, with communications, attitude control and propulsion for mid-course corrections and L2 insertion. It will also be required to operate with some degree of autonomy after completing the MUST assembly tasks. Although its exact status will be considered in future studies, at the least it will need to maneuver to a safe separation from the observatory. The Service Module may be considered a high-value resource whose return and recovery would be desired.

ATLAS 7.2 m LAUNCH VEHICLE INSTALLATION

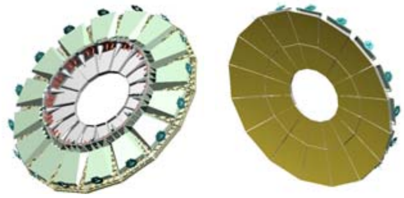


## Assembly or deployment

As described in Section 2, the observatory has four elements; telescope, science instrument module, spacecraft bus, sunshield/baffle. The telescope and the sunshield will be assembled in space. The observatory will be assembled around a metering ring, or "hub", that provides a primary structure and alignment references. In our baseline concept the spacecraft and instrument module have been assembled and attached to hub before launch. In addition to the obvious simplification of having fewer in-space assembly requirements there are two strong benefits of this approach. The metering ring will have power and signal interfaces to the spacecraft, which it will in turn provide to the primary and secondary mirrors. Establishing and verifying these interfaces before launch is a significant risk-reduction. In the case of the instruments this approach is intended to allow alignment of the instruments to the metering ring during pre-launch processing. This reduces one source of uncertainty and risk in the performance of the telescope/science instruments system. Future studies may reexamine these conclusions, particularly regarding the possibility that the science instruments should be stowed in the Service Module for launch, and installed into the Instrument Module as part of the observatory assembly.

Realizing a telescope that is significantly larger than the dimensions of the fairing means that it must be launched in a stowed configuration and either deployed or assembled in space. Deployments are routine for solar arrays, antennas and other appendages, and there is considerable heritage with hinges, actuators, controls, latches

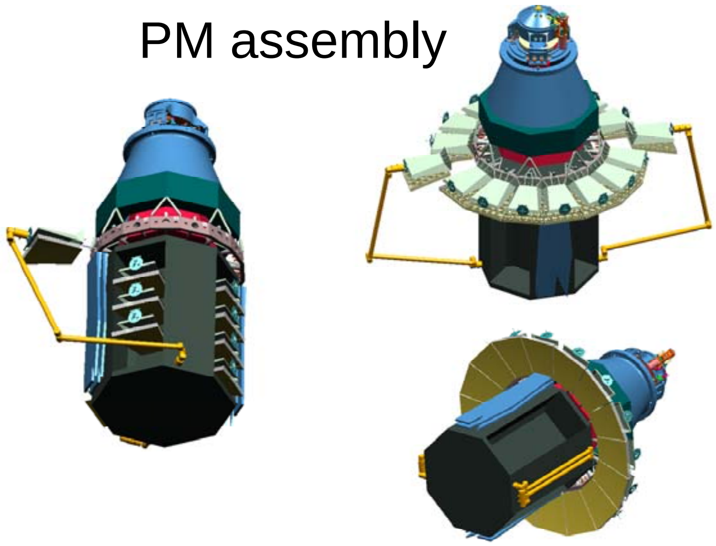
MUST PRIMARY MIRROR
(Assembled)



and associated hardware. Clever geometries have been developed for stowing and unfurling large systems. Deployable structures for optical systems usually must be sufficiently robust to absorb launch loads on the components they support, then perform as precision optical benches that can establish and maintain alignments to nanometer scales. While deployment is certainly feasible, we chose to develop an architecture based on assembly. Our approach seeks to separate functions and simplify requirements and implementation. Critical components, such as the primary mirror segments, are stowed in the Service Module for launch. The SM can be designed as a mass-efficient protective "storage rack" with no requirements for precision movement or stability. The mechanisms that provide fine adjustments of the optical surfaces do not need to be significant structural members during launch. The location of the components in the rack can be optimized for packaging efficiency, and has no relationship to their geometrical arrangements in the finished observatory. We should be able to meet LV requirements on CG in both axial and lateral dimensions more easily. Assembly in space is a pathway to achieving a very large telescope and efficient use of the mass and volume capacity of the launch vehicle.

Robotic assembly is a routine process in modern manufacturing industries. NASA has developed human-robotic technologies for use on the Space Shuttle and the International Space Station. Serious consideration has been given to robotic servicing of the Hubble Space Telescope. Many aspects of future Exploration initiatives envision robotic participation, either autonomous or human mediated. Our concept for MUST is heavily invested in these initiatives. Whether the robotic activities are completely autonomous, or tele-robotic procedures supervised and controlled by remotely located human operators is a detail to be studied in later phases.

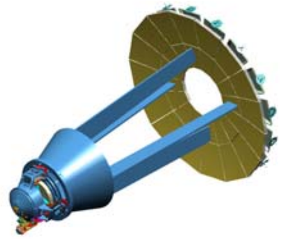
Robotic construction of the telescope involves three main tasks: assembling the primary mirror, erecting the secondary mirror support structure, and attaching the secondary mirror assembly. A central monolith could be included in the primary mirror if the PSF of the annulus is found to be undesirable.

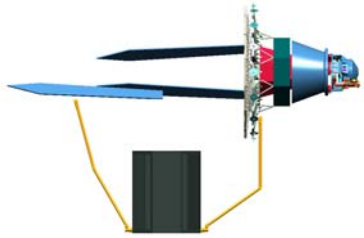


Assembly sequence.

- Remove PM segments from Service Module
- Attach segments to hub
- Detach assembled Primary Mirror from Service Module
- Remove Secondary Mirror support

structure legs from service module
- Install SM support structure legs to hub
- Remove Secondary Mirror assembly from telescope stack
- Attach Secondary Mirror assembly to support structure
- Install the sunshield/baffle system

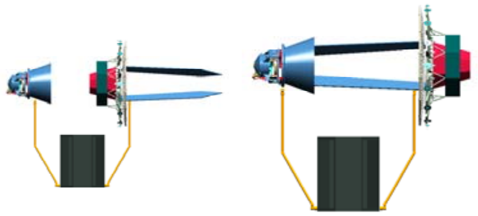

MUST TELESCOPE

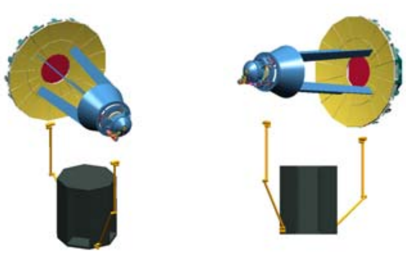

SECONDARY BEAM SUPPORT INSTALLATION

The mirror segments are removed from the dispenser one at a time by the robot arm. Each is installed at its predetermined location on the hub. Identification markings allow unambiguous association. Alignment aids facilitate installation and reduce the precision with which the robot must place the segment. Latches are captured and locked by active receptacles on the hub side of the interface. These attachment devices are part of the structural frame of each segment, but are not attached directly to the mirrors. The combination of the contact surfaces on the segments and on the hub, and the latch mechanisms allow each segment to be aligned with respect to the hub with sufficient precision that small actuators can later bring the mirror surfaces into precise optical alignment. This is the role of the hub as the “metering ring” for the optical system. Good thermal contact between the segments and the hub, and good conductivity will minimize temperature gradients that could lead to distortions or misalignments. Blind mate connectors provide power, commands, telemetry between the segments and the ring.

The Secondary Mirror Support Structure consists of legs attached to anchor points on the metering ring. Either hinged or telescoping designs would allow compact stowage of the legs in the Service Module. Tower-based support structures, such as those used by Spitzer and planned for TPF-C are also possible, although they do not lend themselves to a very compact arrangement for launch.

SM assembly




OBSERVATORY UNLATCHED FROM DISPENSER

The Secondary Mirror assembly consists of the mirror itself, its structural framework, attachment mechanisms for the support structure, actuators for rigid-body motion alignment, heaters, telemetry and a baffle. This module is fully assembled before launch. The robotic arm removes it from its launch accommodation and positions it on the support structure, where latch mechanisms engage. Requirements for positioning accuracy are divided between the support structure, the SM assembly latches and the mirror adjustment actuators to ensure that the primary and secondary can be brought into the required alignment. The sunshield/baffle was identified and described in Sections 2 and 3.

## Alignment and phasing

The most important characteristic of MUST is the angular resolution possible with a 10m aperture that is diffraction-limited in visible light. In order to achieve this performance all of the optical surfaces must be aligned to a fraction of a wavelength. We cannot demand that the robot install components to this level of precision. Rather, the system-level performance with respect to wave-front errors will be a balance between design residuals, manufacturing tolerances, assembly accuracy, structural and thermal stability, rigid-body alignments and surface figure authority. At a very high level the steps needed to adjust the telescope in orbit include the following:

- Initial alignment provided by installation & attachment
- Release mirrors from launch configuration & move to starting points
- First light
- Adjust SM
- Adjust ROC of PM segments
- Adjust solid body alignments of PM segments

### Benefits of this approach

- Robotic assembly departs from the paradigm of telescope size being constrained by the dimensions of the fairing. This departure was pioneered by JWST. Deployments still constrain the geometry and impose difficult and conflicting requirements on structures and actuators.
- Assembly, rather than deployment, allows the components of the observatory to be packaged efficiently for launch. This approach allows the operational geometry and the launch geometry to be separated.
- Structures that accommodate launch loads do not need to be precision optical benches.
- Precision optical actuators do not need to bear launch loads.
- The total system may be more mass-efficient.
- Precision mechanisms are concentrated in two robotic arms, not distributed to multiple subsystems with hinges, actuators, sensors, latches etc.
- Repeated use of identical components simplifies design, manufacturing and testing.
- Each segment is a reasonable size. Two meter optics can be manufactured and tested.
- The shape of each segment allows ROC control with minimum number of actuators or complexity of algorithms.
- The total number of segments is reasonable.
- MUST takes advantage of robotic capabilities being developed for ISS & Exploration.
- Starting with the intention of performing robotic operations allows us to design it to be easily done. We will know what the robotic capabilities are and design the system to take advantage of them.
- The concept is scalable to larger or smaller systems.

## *System Resilience*

### Maintenance or Servicing

Our study gave careful consideration to the benefits and costs of in-orbit maintenance and servicing. Our conclusions regarding the best approach are the following:

- Design the observatory to ensure a minimum five year science mission following the completion of all assembly and commissioning activities. All consumables, reliability projections and limited lifetime items should be mindful of this requirement. No servicing of maintenance should be required or planned to accomplish the core science mission.
- The design that enables robotic assembly will be inherently modular, with simple physical interfaces and good accessibility. This design philosophy should be extended to items that may not be included in the initial assembly process, but which could be candidates for replacement at a later time. The observatory should be designed to be a cooperative target for robotic servicing, with navigation aids, markings for identification and metrology, hold points, interfaces and other considerations.
- Limited-life resources such as solar arrays, batteries, gyros, reaction wheels and thermal insulation should be designed with the expectation that they will be replaced robotically. In some cases it may be preferable to leave the old unit in place but install a new unit in an easily accessed spare compartment. Deactivation of the old unit and bringing the replacement online might me accomplished with software commands.
- Consumables such as station-keeping fuel and cryogenics should be accommodated in a manner that allows either replenishment from a robotic service vehicle or replacement by installation of fresh tanks.
- Subsystems vulnerable to technological obsolescence, such as science instruments, computers and data management systems should be designed with the expectation of robotic removal and replacement.
- The Mission Operations Center that manages the initial launch support, assembly and commissioning should expect to perform an analogous role during one or more robotic service missions.
- The role of humans during servicing should be similar to the assembly phase.

### Safety

We have identified no unique safety issues for this mission. There is no manned component, no planetary protection issues, or end-of-mission disposal issues. The safety of the launch vehicle is assumed to have been established, and we have identified no unique aspects of MUST that would require additional launch safety precautions.

## Conclusions

Astronomy is an observationally driven field. New observing capability leads to unexplained, and unanticipated results, which drives theory and in turn, the need for greater observing capability. While telescopes have been developed to address specific questions, many of the most famous discoveries in astronomy have been serendipitous, including the cosmic microwave background and pulsars. We don't know everything that is out there, and discovery is one the most exciting aspects of astronomy.

A large UV-Optical telescope will provide enormous scientific return: directly addressing key scientific issues identified in the strategic plan but also enabling a multitude of currently unanticipated new scientific results. The technology to move beyond HST is in development now – and the time to begin planning the next great optical space observatory is now. Under the 2005 roadmap, the launch of an observatory like MUST is no earlier than 2025 – 35 years after the HST launch. Scientific priorities, instrument and telescope technologies, and space infrastructure capabilities will certainly have changed significantly between now and then – but the need for ever greater observing capability will not. Grand planning requires grand vision – tempered by technological and programmatic realities. The next generation large UV-optical space telescope will produce a revolution in astronomy even greater than that of HST. None of the technologies are beyond our grasp, and this is the first step towards the more difficult observatories of the future – expanding into the more technologically challenging wavelengths, with effective apertures of tens or even thousands of meters.

The Modern Universe Space Telescope is a concept for an observatory that is ambitious but realistic, with the scientific potential to engage the world and address the multitude of questions that we appreciate today, but also those unpredictable questions of the future. We hope that the current generation of astronomers will be able to use it to explore the universe.

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