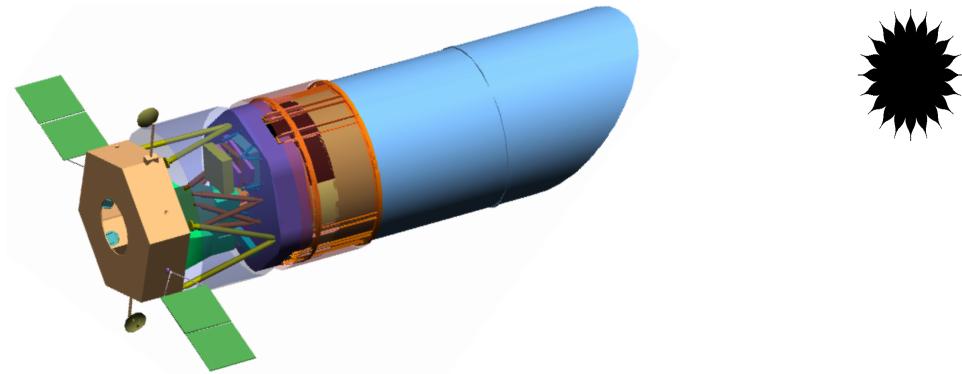


THEIA

Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy

White Paper Submitted to NRC ASTRO-2010 Survey

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I. THEIA Overview

Over the past 25 years, the Hubble Space Telescope has revolutionized our view of the universe, excited and engaged the general public with its compelling images, and has been a workhorse for astrophysics. We propose that NASA build THEIA, Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy, a flagship 4-meter on-axis optical/UV telescope as a worthy successor to HST and companion to the James Webb Space Telescope (JWST). With a wide field imager, an ultraviolet spectrograph, a planet imager/spectrograph and a companion occulter, THEIA is capable of addressing many of the most important questions in astronomy: Are we alone? Are there other habitable planets? How frequently do solar systems form and survive? How do stars and galaxies form and evolve? How is dark matter distributed in galaxies and in the filaments? Where are most of the atoms in the universe? How were the heavy elements necessary for life created and distributed through cosmic time?

In this white paper we describe the THEIA Observatory¹, an on-axis three-mirror anastigmat telescope with a 4-meter Al/MgF₂-coated primary, an Al/LiF-coated secondary and three main instruments: Star Formation Camera (SFC), a dual-channel wide field UV/optical imager covering 19' x 15' on the sky with 18 mas pixels; UltraViolet Spectrograph (UVS) , a multi-purpose spectrometer optimized for high sensitivity observations of faint astronomical sources at spectral resolutions, $\lambda/\Delta\lambda$, of 30,000 to 100,000 in the 100-300 nm wavelength range; and eXtrasolar Planet Characterizer (XPC), which consists of three narrow-field cameras (250-400 nm; 400-700 nm; 700-1000 nm) and two R/70 integral field spectrographs (IFS).

There are many approaches to creating the needed contrast for exoplanet exploration, most of which use either an internal coronagraph or an external occulter. Both have the potential to yield similar exoplanet science (measured in number of planets discovered and characterized) with a 4 meter telescope, yet each has different technical challenges. For this study we focused on an external occulter as a demonstration that a suitable mission architecture exists that can be built in the next decade. This choice allows an on-axis telescope without wavefront control, relaxes stability requirements, and simplifies the optical design and packaging for all of the instruments. Nevertheless, we welcome a robust technology development program for both categories of starlight suppression.

THEIA's companion occulter is 40 meters in diameter and stationkeeps at 55,000 km from the telescope for imaging from 400-700 nm and at 35,000 km to characterize from 700-1000 nm. While the occulter is on target (25% of mission time), XPC detects and characterizes extrasolar planets and SFC does deep field science. While the occulter moves, THEIA conducts a rich program of general astrophysics.

For the occulter/telescope system we anticipate three main tall poles: (1) building and deploying the occulter to demanding tolerances; (2) building a 4-meter telescope diffraction-limited at 300 nm; and (3) building large focal plane arrays. We summarize plans, including cost and schedule, to advance technology readiness levels for each on a path toward flight system development. THEIA is a flagship class mission with an estimated life-cycle cost of \$5 billion (including \$0.9B reserve). The biggest development cost items are the telescope (\$1.2B) and the instruments (\$0.8B).

¹In Greek mythology, Theia is the Titan goddess of sight (thea), is also called the “far-seeing one”. She is the mother of the Sun, the Moon and Dawn.

2. THEIA Science

THEIA is a multi-purpose space observatory operating in the optical/UV band. A successor to the Hubble Space Telescope, it will perform a broad range of science including exoplanet imaging and characterization, star and galaxy formation, and studies of the intergalactic medium (IGM) and the interstellar medium (ISM). Its three instruments enable an efficient and powerful science program. While the occulter is on target, XPC detects and characterizes planets and SFC deeply images adjacent fields. While the occulter is moving, SFC and UVS carry out a rich program of general astrophysics. In our baseline design reference mission (DRM), we allocate 25% of the prime mission observing time to each primary investigation, with the remaining 25% allocated to a guest observer program.

Are we alone?

A primary goal of THEIA is to find and characterize true Earth analogs: an Earth-size planet in an Earth-like orbit about a Sun-like star. Direct imaging is the only way to characterize a reasonable number of Earth analogs around nearby stars.[1] The occulter can suppress the light of the much brighter star by more than 25 magnitudes when the projected separation of the planet exceeds the Inner Working Angle (IWA) of the system. Our observatory and mission are optimized so that even if only 10% of all stars have terrestrial planets, THEIA should still detect and characterize at least 5 of these planets among its 130 target stars. Our design reference mission (DRM) studies also found that a precursor astrometric mission did not significantly enhance the number of detected planets.[2]

During its search for other Earths, THEIA will also automatically find planets that are easier to detect than Earth analogs. These planets include those larger and brighter than Earth (including super Earths and Jupiter-sized planets). By systematically studying the nearby stars, THEIA will determine the frequency and properties of extrasolar systems.

Searching for Biosignatures[3]

XPC's extensive wavelength range from 250 to 1000 nm will enable detection and identification of both expected and unanticipated spectral features. Oxygen (O_2) and ozone (O_3) are the most important biosignatures for Earth-like planets; on Earth, O_2 is produced in large quantities only by life. O_3 is a photolytic byproduct of O_2 and is a very important nonlinear indicator of O_2 because only small, undetectable amounts of O_2 ($\sim 1\%$ of the atmosphere by volume) are needed to generate a strong O_3 signature.

All life on Earth requires liquid water, and water vapor absorption is suggestive of liquid water oceans. Three absorption bands of H_2O fall into the XPC spectral range. Other gas

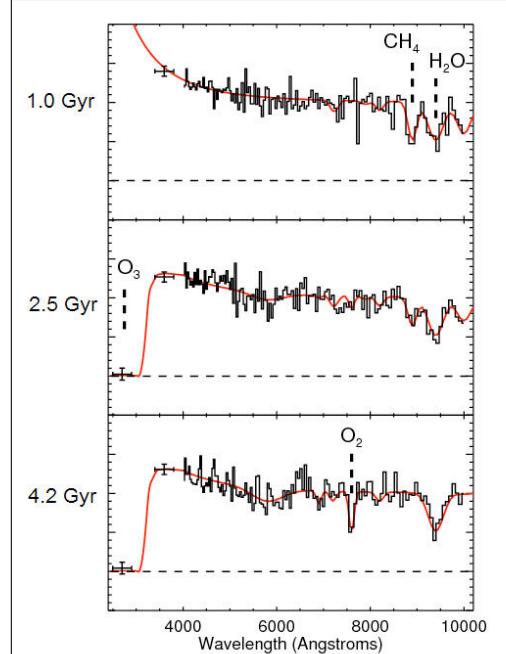


Figure 1: Earth's normalized reflectance spectrum at different times. The smooth curve is the low-resolution input spectrum. The histograms shows simulated 5 day THEIA observation of an Earth-like planet at 10 pc. THEIA's broad wavelength coverage enables detection of O_2 , O_3 , H_2O as well as the “red edge” and the Rayleigh scattering induced “blue sky”.

absorption features, including the potential biosignature methane, are present in the XPC wavelength range. Methane would be detectable if present in much larger quantities than on Earth, potentially in the atmospheres of super Earths and mini-Neptunes.

With multiple visits and extended integrations for characterization, XPC should detect photometric variability. These observations could lead to a measurement of the planet's rotation rate, detection of weather, and even the inference of continents.

Design Reference Mission and Science Optimization

In our study, we used a Monte-Carlo based Design Reference Mission (DRM) generator[2] to compare the scientific effectiveness of three different terrestrial planet finding approaches using a 4m telescope: (1) a coronagraph with the optimistic assumption of a $2 \lambda/D$ inner working angle; (2) a 52 m diameter occulter with 19 m petals flown 70,400 km from the telescope (occultor edge IWA of 75 mas and a 50% throughput angle of 60 mas) and (3) our baseline design of a 40 m diameter occulter with 10 m petals that has the same IWAs for 250-700 nm when flown 55,000 km from the telescope, but does longer wavelength characterization (700-1000 nm) by moving closer to the telescope (edge IWA of 118 mas). Since the planet spends a significant fraction of its orbits at smaller separations, minimizing the IWA enables more planet detections and characterizations. We also strove for the smallest occulter possible; a smaller occulter brings many benefits, including lower mass (allowing more fuel), easier deployment, better packaging in the launch vehicle, lower fuel use, more rapid retargeting maneuvers, and easier testing.

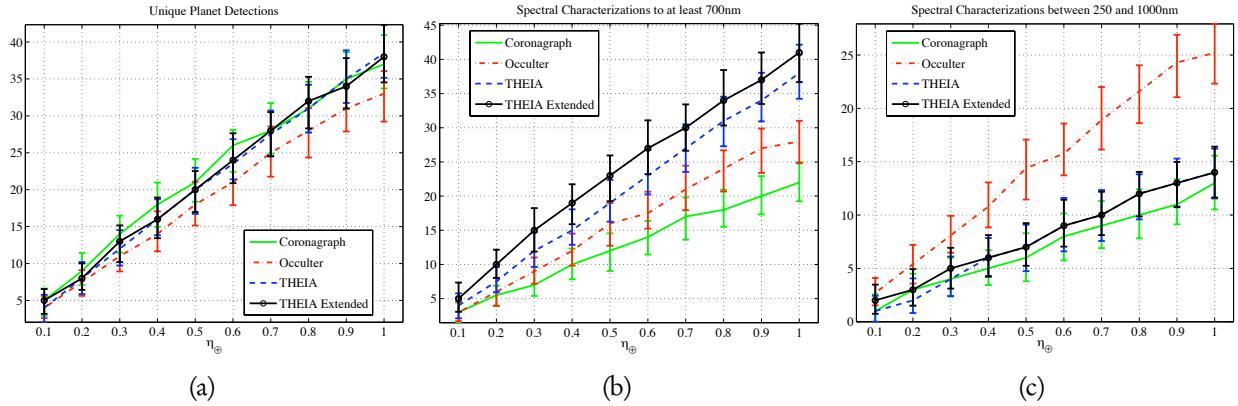


Figure 2: The performance for four DRMs: (1) $2 \lambda/D$ coronagraph; (2) a single distance 52 m occulter; (3) baseline THEIA design and (4) an extended mission. The left figure (a) shows the number of unique planet detections. The center figure (b) shows the total number of planets characterized at $\lambda < 700$ nm; the right figure (c) shows the total number of planet characterized over the full wavelength range for the different DRMs.

Figure 2 shows that the different approaches yield a comparable number of unique planet detections. Because of its inner working angle advantage at $700 < \lambda < 1000$ nm, the single distance occulter obtains more full spectral characterizations (thus finding oxygen and water on more planets). However, the larger occulter has several disadvantages as well: the additional mass limits the mission to at most 5 years (assuming an Atlas V launch vehicle), at which point it runs out of fuel. The petals are significantly longer, greatly complicating packaging (no design currently exists that fits in the available 5m fairings). Manufacturing tolerances on the larger occulter are more challenging. The limited fuel also severely curtails its ability to revisit discovered planets and determine orbits. For our extended mission DRM, we chose to prioritize orbit

characterization and found that the smaller occulter provides good orbital fits in 5 systems by revisiting each system at least 4 times and achieving 10% period determination.

The choice between the occulter and coronagraph comes down to technical readiness, risk, and cost. An occulter introduces formidable manufacturing, deployment and test challenges, as well as the dynamics and control problems associated with positioning and slewing the occulter. The coronagraph presents its own challenges associated with a large, off-axis, UV-diffraction-limited telescope with exquisite stability requirements, a small IWA coronagraph, and a wave-front control system. We also explored hybrid approaches that might share the burden of starlight suppression between the two systems, but concluded that the alignment requirements on the occulter in the hybrid system were too severe. While both coronagraphs and occulters warrant careful study, for our point design we chose the occulter system because of its simpler telescope, unlimited outer working angle, and the fewer challenges associated with packaging the multiple instruments.

Transiting Planets

One of HST's important (and unanticipated) uses has been the characterization of the atmospheres of two of the fifty-eight known transiting planets.[4] THEIA tremendously expands this capability; the UVS instrument will perform FUV transit spectroscopy on a much larger set of targets and enable the detection of strong transitions of abundant atomic and molecular species, including H, C, N, O and H₂. With future surveys likely to find even more targets including possible super-Earths, THEIA's FUV capabilities will be an important complement to our direct imaging program.

How do planets form? [5]

With its starlight suppression system, THEIA will make the most sensitive inventory and detailed images of protoplanetary and debris disks possible with any planned or existing telescope. THEIA will trace the formation and rearrangement of small body belts, sense otherwise undetectable planets via disk patterns and probe structure and composition throughout, revealing the environments where terrestrial planets form, migrate, and receive their important final dose of volatiles.

How do stars form in galaxies across time and environments?

Understanding the physics of star formation is another major theme for the THEIA mission. We designed a four-tiered program of observing star formation on different scales that utilizes the SFC and UVS instruments. Within our own Galaxy (Tier 1), SFC will image all high-mass star formation sites within 2.5 kpc of the Sun ($\sim 41 \text{ deg}^2$) covering the full range of apparent star formation (SF) modes and environments.[15] The observations will be complemented by UVS spectral observations of specific star formation regions.[6] Our SFC dataset will resolve billions of individual stars and detect circumstellar material and associated jets and shocks around many stars.

On the local group scale (Tier 2), we plan a complete SFC imaging survey of the Magellanic Clouds and star-forming galaxies in 8 broadband and 4 narrow-band emission line filters.[7] The goals are to take a complete a census of the richly varied stellar populations, to investigate feedback from massive stars in both HII regions and in the diffuse warm ISM, and to quantitatively parameterize stellar clustering and star formation propagation. We will determine how giant

star-bursting HII regions differ from smaller HII regions within the Milky Way, and determine the impact of metallicity on star formation by comparing a set of 21 similar HII regions of $0.1 Z_{\odot}$ in the Magellanic Clouds with counterparts in the Milky Way using additional filters to provide nebular diagnostics.

Moving outward, we plan a deep survey of 100 galaxies and a medium-deep survey of 500 local galaxies in narrow and broadband filters that span the 190-1075 nm wavelength range (Tier 3).[9] We aim to understand these galaxies as a whole through their resolved and unresolved stars, ISM, and immediate environments (“near field cosmology”). Stellar populations will be analyzed using color-magnitude and color-color fitting and population synthesis modeling to provide spatially resolved star formation histories; the ISM will be studied to understand the energetic sources and effects of metallicity and galactic environment. The combination of medium and deep surveys will provide statistics over the full parameter space of physical conditions and environments.

Lastly, in SFC’s Tier 4 survey, [10] we will conduct a panchromatic imaging survey of cosmological targets across wide fields covering $\sim 10 \text{ deg}^2$ in two epochs to $AB < 28 \text{ mag}$ and $\sim 1 \text{ deg}^2$ in 20 epochs to $AB < 30 \text{ mag}$. The survey will provide spectrophotometric redshifts accurate to within 2% and will measure faint source variability for 5 million galaxies.

Deep parallel imaging taken during the long (up to 50 day) integrations on planetary targets will complement the wide field survey. For a four filter imaging survey covering 550-1100 nm, SFC will integrate to a depth of $> 2.0 \text{ mag}$ greater than the Hubble Ultra Deep Field with over 25 times the area in each parallel mode integration.

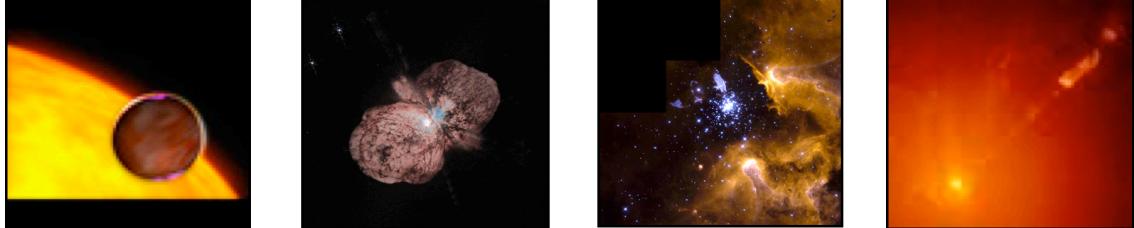


Figure 3: UVS’ slit capability allows spatially resolved spectroscopy of transiting planetary atmospheres, circumstellar disks, starburst galaxy outflows, and active galactic nuclei. Because its wavelength coverage extends down to 1000 Å, UVS can measure key diagnostics of coronal gas (O VI), massive star winds (O VI, P V, S IV), molecular gas (H_2), planetary atmosphere markers (O I, C II), and neutral hydrogen (Ly- β). Extensive wavelength grasp in single exposures increases the number of diagnostics available for studies requiring information at multiple redshifts, such as the IGM, or needing broad spectral coverage, such as stellar atmospheres and AGN.[11]

Tracing the evolution of the IGM[11]

At the core of the UVS science program is a comprehensive investigation of the cosmic web, the repository for most of the baryons in the universe and the raw material for galaxy formation. A primary challenge in the next decade is to advance beyond simple detections of the cosmic web gas to determine how the cosmic web is organized, how it has changed with time, and how it has been assembled into galaxies. The UVS cosmic web survey will do exactly this, by observing the intergalactic absorption toward 250-500 QSOs at redshifts of 0.2-1.0. The survey will result in the detection of thousands of O VI absorption systems, and tens of thousands of Ly- α absorption systems, along with accompanying metal lines providing information about the

ionization, composition, and metallicity of the gas. The total redshift path probed along these sight lines will exceed that observed by HST/COS by at least a factor of 10. Combining these data with galaxy redshifts and UVS observations of the gas in the immediate environments of galaxies will provide a deeper understanding of how galaxies and the universe evolve.

UVS will observe the He II Gunn-Peterson absorption and its transition to the He II Lyman- α forest in multiple directions to gain a detailed picture of the complete reionization of the universe and the structure growth at $z \sim 3$. SFC's Tier 4 survey will yield escape fractions of UV photons from high redshift objects and the contribution of dwarf galaxies and Ly- α emitters to the UV flux.

Dark matter and dark energy

SFC's spatial resolution and positional accuracy will revolutionize strong lensing studies in galaxies and clusters by improving dark matter substructure mass limits by two to three orders of magnitude. This will constrain warm dark matter models. SFC will also enable a tripling of the number of detected lensed sources in a typical field cluster. High-precision measurements of the positions of multiple images deriving from the lensing of sources at different redshifts by a single cluster lens will provide important independent means of measuring the geometry of the universe and the dark energy properties. UVS measurements of the cosmic web complement these observations by measuring the matter power spectrum at small scales.

Unanticipated discoveries

This section has outlined a number of the possible astrophysical applications of THEIA observations identified in this study. Nevertheless, the track record of HST suggests that many of THEIA's most important discoveries will be unanticipated. With its suite of powerful instruments and a spatial resolution more than double that of HST and JWST, THEIA will be a powerful tool for quick follow up of targets discovered by LSST, Pan-STARRS, LIGO, and other upcoming large-surveys. Just as HST's imaging and UV capabilities have complemented Keck spectroscopy, THEIA will complement JWST, ALMA and the next generation of ground-based telescopes.

Science Requirement	Performance Requirement	Design
Detect Earth twin at 10 parsec	Detect Earth twin at 10 parsec	40m occulter for starlight suppression over 0.4-1um band.
Detect ≥ 1 HZ planet with 95% confidence, if 30% of target stars have planets	Contrast ≥ 26 mags IWA ≤ 75 mas	
Detect Jupiter twin at 10 pc	OWA ≥ 500 mas	No restriction, not a design driver
Measure planet brightness within 10%	Contrast stability ≥ 28 mags	Main driver to occulter stability 1 mm stability at tip, 100 um petal deformation 100 mK PM stability
Detect atmospheric O ₂ , H ₂ O, O ₃	Bandpass = 0.5 to 1.0 μ m Spectral resolution ≥ 70	2 broadband science channels feed 2 IFUs UV Ozone Camera - 4m aperture for throughput.
Survey formation & evolution of stars & galaxies with red-shifts up to 9	FOV = 15' x 19' Pixel FOV = 18 mas Diffraction limited to 10' off-axis	Star Formation Camera with 2 channels High efficiency detectors & large focal planes 6 Tbytes/day after x2 loss-less compression
Survey intergalactic web & investigate galactic interactions & effect on evolution	Bandpass = 100 to 300 nm Spectral resolution $\geq 30,000$	UV Spectrograph with 2 channels on-axis entrance at Cassegrain-like focus LiF coated secondary mirror No extra reflections - UVS extends into bus

Table 1: Theia Science Requirements

3. THEIA Technical Overview

The THEIA system design is an answer to the scientific challenges posed above, combining exoplanet discovery and characterization with general astrophysics into a single mission architecture. The mission consists of two spacecraft, a 4-m primary telescope at the Sun-Earth L₂ point with a suite of three primary instruments, the eXoPlanet Characterizer (XPC), the Star Formation Camera (SFC), and the Ultraviolet Spectrograph (UVS), and an occulter spacecraft flying in formation to maintain sufficient starlight suppression for the required exoplanet science. Our design for THEIA satisfies all of our science requirements with large technical margins, fits on two Atlas-V launch vehicles, and has a cost and schedule profile consistent with a launch late in the next decade. The prime mission duration is 5 years with a 10-year life goal. Earth communication and navigation tracking is via S-Band and Near-Earth Ka-Band channels of the 34 m DSN.

The THEIA observatory is a natural evolution from HST and JWST. The 4-m, on-axis telescope, and attached instruments, is mated with a conventional spacecraft system. The observatory is 3-axis pointed within 3 arcsec using reaction wheels with hydrazine thrusters for momentum desaturation and stationkeeping. The telescope bore-sight is pointed to within 30 milliarcsec using active struts and the final beam is pointed to within 4 mas using fine steering mirrors (FSMs). Sensing is accomplished through a combination of rate gyros, fine guidance sensors, and star trackers. The observatory communicates with the occulter spacecraft and Earth using separate S-band links. The observatory can downlink up to 6 TBytes of data per day with a 1 Gbps downlink rate and 12 TBytes of storage. The observatory has a maximum expected mass of 5,700 kg as compared to a launch mass capacity of 6,300 kg. Observatory solar arrays are conservatively sized for 5kW of power at end of life, providing large margins.

The occulter system, with starshade shown later in Figure 9 and attached spacecraft shown in Figure 4, consists of a 40-meter starshade attached to a spacecraft bus equipped for repositioning, stationkeeping, and pointing. The solar array is sized for 15 kW of end of life power to accommodate 2 NEXT-Ion thrusters firing simultaneously at maximum power (which can be adjusted in flight) plus 1 kW for other bus equipment. This thruster subsystem consists of 6 total thrusters with 3-for-2 redundancy on each side of the starshade. During exoplanet observations, the occulter system is held on targets constrained to lie between 45 and 85 degrees from the sun line to avoid stellar leak into the telescope or reflections off the starshade. Stationkeeping does not employ electric thrusters because they produce a bright plume potentially contaminating the observations. The spacecraft is thus also equipped with a set of on/off hydrazine thrusters that control position to within ± 75 cm. A shutter is employed during the short, infrequent hydrazine pulses to avoid light contamination from the plume. After a retargeting slew, the observatory/occulter formation is acquired in 4 overlapping stages of position sensing: 1) Conventional RF Ground tracking (± 100 km), 2) Observatory angle sensing of a Ka-Band beacon from the occulter spacecraft (± 16 km), 3) XPC IR imaging of a laser beacon (± 70 m) and 4) XPC IR imaging of light leaking around the

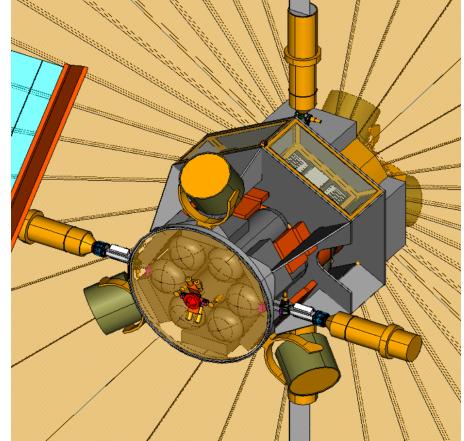


Figure 4: The occulter spacecraft system.

occultor (± 35 cm). The Observatory measures occultor range via the S-Band link. The occultor system has a maximum expected mass of 5,700 kg as compared to a launch mass capacity of 6,300 kg. The remaining mass margin will be used for additional fuel for extended operations.

Telescope and Instrument Accommodations

THEIA's telescope is an on-axis three mirror anastigmat (TMA) optical design with a 4 m aperture and diffraction limited performance to 300 nm. The design highly leverages a 2m class OTA dynamic testbed design that is traceable to space hardware developed at ITT Space Systems Division, LLC. Overall, the design corresponds to a Korsch system with a primary/secondary combination similar to a Cassegrain telescope. There is a different set of tertiary optics for each instrument. The driver for the overall telescope configuration is the need for a large, diffraction limited field-of-view for the Star Formation Camera. Figure 5 shows a trace of the light paths to the various instruments. The UVS instrument is fed a narrow on-axis beam near the Cassegrain-like focus with reflections limited to the primary and secondary mirrors. The SFC and XPC instruments are fed off-axis beams and include additional powered and aberration-correcting optics.

The relatively slow f1.5 Primary Mirror (PM) is a stiff, lightweight, closed-back design constructed of Corning Ultra Low Expansion (ULE[®]) glass with an Al/MgF₂ coating. The segmented lightweight honeycomb core is joined to the lightweighted pocket-milled mirror facesheets using a low temperature fusion process. The PM is polished and final ion beam figured to a rms wavefront error less than 15 nm, only slightly better than Hubble's primary mirror (~ 20 nm). All PM processes have heritage from smaller mirrors and will be demonstrated on a sub-scale prototype. Areal density is conservatively specified at 50 kg/m², a safe progression from the current state of art.

The Secondary Mirror (SM) mounts to a hexapod actuator that enables calibration of pointing and focus, though, due to the precision composite metering structures, SM re-alignments will be very infrequent. A global correction is applied with additional corrections in the SFC and XPC instruments so that all instruments can be operated without adjusting the SM. The secondary mirror is Al/LiF coated for high reflectivity in the Far-UV. A dry nitrogen purge is applied to the SM throughout ground operations to avoid moisture degradation.

The instruments are kinematically mounted to the PM backing structure. The OTA precision metering structures coupled with a fairly simple thermal control system are able to keep the optics in alignment to the required tolerances. The composite metering structures are fabricated using fibers and a state-of-the-art cyanate siloxane resin system (co-patented by ITT). ITT's experience in using these materials result in metering structures that have thermal stability of the same order of magnitude as ULE[®]glass with nearly negligible hygroscopic effects. The integrated payload mounts to the spacecraft with piezo-actuated struts that provide vibration isolation and precision pointing of the bore sight. Active struts are conservatively included to simplify spacecraft pointing, but may not be necessary (HST achieves our specification without them). Active struts have been demonstrated on ITT testbeds and have a TRL of 6 or better.

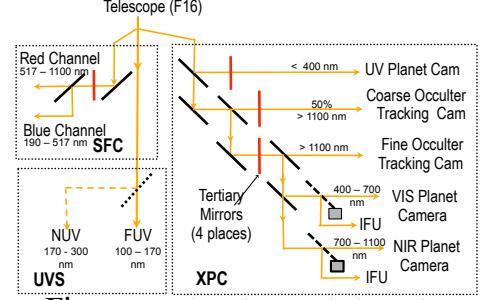


Figure 5: The telescope light paths.

Star Formation Camera (SFC)

The SFC instrument, shown in Figure 6, is a wide-field imager with an unprecedented combination of FOV ($19' \times 15'$) and resolution (18 mas). Final resolution is diffraction limited at 300 nm, but camera size is reduced by under-sampling at the diffraction limit. Critical sampling is reconstructed on the ground from multiple images with dithered pointing, using fast steering mirrors (FSMs) within the instrument.

A dichroic splits the beam at 517 nm into simultaneously operated red and blue channels, for efficient observing. Each channel includes a tailored set of band-pass filters and a shutter.

The SFC uses Lawrence Berkeley Laboratory's CCD detectors, with 10.5 micron pixels and a 3.5K square form-factor. A tertiary mirror within SFC produces an f/30 beam to match the plate scale. Each focal plane array (FPA) consists of 18×15 detectors and is 66×55 cm in size. They are passively cooled to 170 K and use thermal baffles to limit parasitic heating. Each detector is packaged with modular electronics for fault isolation and rapid change out. Detectors are extensively processed (thinning, AR coating, delta-doping, etc.) to optimize photometric efficiency.[15] JPL's Giga-pixel Initiative is developing techniques that could be applied to the production and test of the SFC flight detectors.

Exoplanet Characterizer (XPC)

The XPC instrument suite consists of UV, Visible, and NIR science cameras, coarse and fine occulter tracking cameras (FOTC), and two Integral Field Unit Spectrometers. They are all fed by a 0.1 deg off-axis beam and picked off just before the Cassegrain focus. The optics operate at room temperature while the detectors are cooled to 150 K. Figure 7 shows a schematic of the instrument without the visible light channel for clarity. A series of dichroic mirrors split the light as shown. The Ozone Camera uses 2 aspheric optics to form an f/90 beam, corrected over a 10" field. The total number of reflections in this instrument, including the primary and secondary telescope mirrors, is five. The beam is Nyquist sampled on the detector at a wavelength of 250 nm. IR light up to $2 \mu\text{m}$ is passed to the f/6.5 COCT which has a 3' field and 1" pointing precision to locate the occulter laser beacon and feedback position information for handoff to the FOTC (f/60, 20" field, 4 mas resolution). Visible and NIR light is split between two science channels (400-700 and 700-1000 nm), each with a filter wheel for spectrophotometry, a fine guiding mirror for beam stabilization, and a flip-in mirror to fit the IFUs. These science channels are identically designed to form an f/60 beam with a diffraction-limited 10" field and > 80% throughput on e2V Technologies L₃CCD™. The visible/IR cameras will be the exoplanet detection workhorses. They each have 8 reflections including the PM, SM, dichroic, two OAPs, 2 folds, and an el-

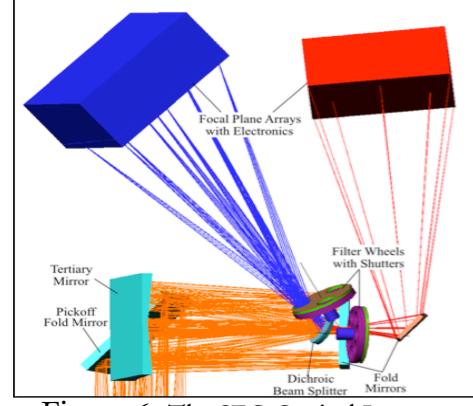


Figure 6: The SFC Optical Layout.

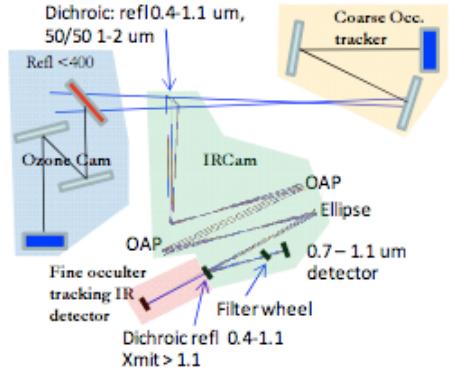


Figure 7: The XPC Optical Layout.

lipse, all easily fabricated. Based on the TPF-C CorSpec design,[13] the IFSs have a 134 x 134 microlens array to obtain an R~70 spectrum, again using L3 CCDs. We note that while all of our DRM studies were performed with conventional CCDs, the planet characterization science would greatly benefit from development of radiation hardened, zero read noise, high QE photon counting detectors in the NIR (700 to 1000 nm).

Ultraviolet Spectrograph (UVS)[12]

The ultraviolet spectrograph (UVS), shown in Figure 8, performs studies of gas ionization, composition, and dynamics in systems ranging from cosmological scales (the intergalactic medium) to planetary scales (exoplanet and solar system bodies). UVS is optimized for high sensitivity observations of faint astronomical sources at spectral resolutions, $\lambda/\Delta\lambda$, of 30,000 to 100,000 in the 100-300 nm wavelength range. The UVS has a single instrument enclosure, which includes all necessary subsystems (heaters, electronics, calibration platform, etc.) in addition to optics, detectors, and mechanisms. The spectrograph is located on-axis and receives light directly from the telescope secondary mirror through an entrance aperture and slit mechanism. Light can enter one of two channels. Light entering the far-ultraviolet (FUV; 100-170 nm) channel encounters a single Al/LiF coated, holographically ruled, 1st-order diffraction grating that focuses and disperses the light onto a long, curved, photon-counting microchannel plate detector array. Light entering the near-ultraviolet (NUV; 170-300 nm) channel is collimated by an optic behind the slit wheel that is placed into the incoming beam. The collimated light is then reflected to one of several echelle gratings, followed by a selectable cross-disperser and a camera mirror before being recorded by a flat 8K x 8K photon-counting CCD array. For both channels, the entire spectral bandpass of the channel is recorded in each exposure. Spectral dithering is available for high S/N observations. Selectable slits and apertures are available for both channels, including long slits for spatially resolved spectroscopy.

The UVS instrument design was refined and costed by the Integrated Design Center at GSFC. The UVS could be built today with existing technology (all at TRL 6), but would benefit significantly from technology development in the following areas: large-format photon-counting UV detectors (MCPs and CCDs) with quantum efficiencies > 60-80%; better UV reflective coatings with > 65-70% reflectivities between 100 and 300 nm; and large, efficient, aberration-correcting gratings with low scatter.

Occulter System

Starlight suppression for THEIA is accomplished via a large external starshade with an optimized shape[14] that results in a diffraction pattern at the telescope sufficiently dark for planet detection and characterization, as shown in Figure 9. A modular construction approach employing petals deployed around a fabric core was developed by study partner Lockheed Martin Space Systems leveraging past experience in large deployable space structures. The starshade is comprised of 2 major subsections, a 19.46 m diameter inner core composed of 3 layers of Kapton and an outer section of twenty 10.27 meter tall and 3.7 meter wide petals. Together, when deployed they form an occulting mask 40 meters in diameter from tip-to-tip.

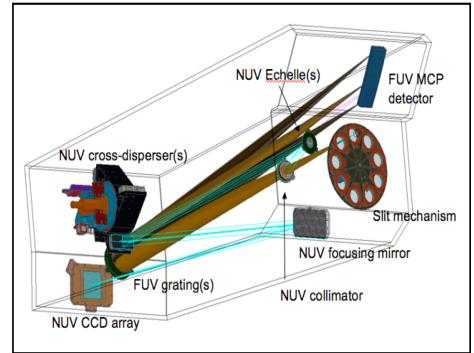


Figure 8: The UVS Optical Layout.

The precision shaped petal edge, defined for maximum light suppression, is machined into an extremely low CTE graphite epoxy sheet. The sheet is bonded to a petal perimeter graphite epoxy box frame to provide structural support. In the stowed configuration, the central core and petals mount to a graphite composite deployment deck, which in turn mounts to the spacecraft. A central opening accommodates the recessed mounting of propulsive thrusters, antennas and laser beacons. The stowed configuration fits inside a 5 m launch fairing with margin. A truss structure supports the stowed petals and is jettisoned after launch. Deployment is initiated by extending the entire stowed petal stack on two deployable booms. This linear action unfolds the center-blanket assembly. Once fully extended, the booms begin a rotation that initiates sequential deployment of the petals. All petal hinge lines are controlled by redundantly actuated, passively damped, high accuracy hinges. A simple sequencing cam between the primary hinge-lines of the petals also controls deployment. As the booms rotate, the petals unfold. The final position is controlled by stops designed into each hinge line. Careful optical analysis was used to design the hinges and gaps to maintain the needed starlight suppression.

The occulter design effort was based on the use of flight proven mechanisms for implementation of a precision deployment sequence using the ADAMS code in an interactive mode to define precision damping and torque rates to verify petal contact is avoided during unfurling. Manufacturing methods have been defined including tooling and facilities needed for component fabrication.

Meeting the science requirements for planet characterization requires an occulter design with starlight suppression of 1×10^{-11} and scattered light calibration to a contrast of 6×10^{-12} . Using new modeling tools developed by NASA's Exoplanet Exploration Program, we have analyzed the occulter starlight suppression performance and find that it is robust against motions and deformations. Our modeling approach combines an analytic solution for the occulter field at the telescope with a near-field diffraction model of the optical system. Performance is evaluated at the inner working angle in the telescope focal plane. We considered the likely petal manufacturing, deployment, and deformation modes, as well as the star-occulter-telescope line-of-site requirement. Table 2 shows the tolerances needed to meet the contrast stability goals at the inner working angle of 75 mas. The manufacturing tolerance can be relaxed if the deployment accuracy exceeds the indicated values. A careful thermal-mechanical analysis is in progress, coupled with the optical propagation code, to confirm contrast is maintained during expected dynamic and thermal environments.

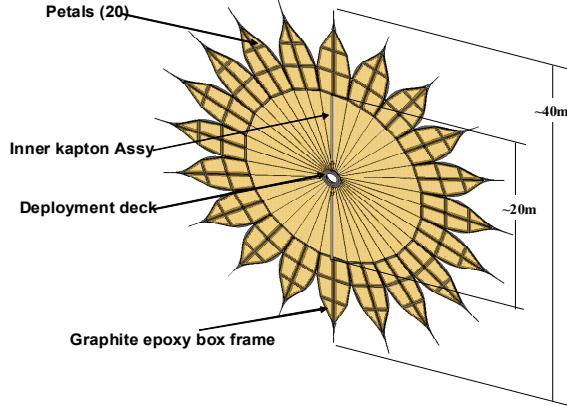


Figure 9: The Occulter Starshade

Petal Position or Shape Error	Allocation
r.m.s shape ($1/f^2$ power law)	100 μm
Proportional shape	80 μm at max width
Length clipping at tip	1 cm
Azimuthal position	0.003 deg (1 mm at tip)
Radial position	1 mm
In-plane rotation about base	0.06 deg (1 cm at tip)
In-plane bending (r^2 deviation)	5 cm
Out-plane bending (r^2 deviation)	50 cm
Cross-track occulter position	75 cm

Table 2: Starshade Tolerances.

4. Three Most Significant Technology Challenges for THEIA

Large Telescope Optics

THEIA's primary mirror (PM) is a 4m on-axis monolith with an areal density of 50 kg/m² and less than 15 nm of wavefront error, r.m.s. By comparison, Hubble's PM is a 2.4 m on-axis monolith with an areal density of 160 kg/m² and about 20 nm of wavefront error, r.m.s. By this comparison, the THEIA PM appears to represent a large technological challenge. However, significant advancements have been made since the Hubble PM was fabricated in the areas of mirror design, fabrication, and polishing which significantly reduce technology risk, and essentially turns the task of fabricating the THEIA PM from one of pure technology development to one of a challenging engineering exercise. These existing developments include:

1. Abrasive Water Jet (AWJ) cutting to aggressively lightweight a mirrors' core.
2. The invention of Low Temperature Fused (LTF) Corning ULE® mirror blanks.
3. Segmented core fabrication that reduces manufacturing time and risk of breaking a full-sized fragile core.
4. Pocket milled face-sheets that significantly reduces overall mirror weight.
5. Computer controlled active laps polishing of highly aspheric optics.
6. The combination of pocket-milling and deep segmented AWJ cores.
7. Technology advancement in optic and telescope metrology.

Many of these new processes have already been employed on existing programs such as Ikonos, Nextview, AMSD, TDM, and AFRL DOT.

Nevertheless, because the THEIA PM is large, relatively expensive, and not completely without risk, the THEIA plan is to develop a sub-scale prototype to demonstrate all processes prior to entering Phase C. We have allocated \$50M for this technology development. A subscale polishing demonstration will be used to confirm that the THEIA PM smoothness requirements could be met on a mirror of comparable stiffness. Development of a full-scale blank was also considered but deemed not necessary by our study partner, ITT Space Systems Division, LLC. Rather, a proto-flight unit will be used to qualify the design, as is the case for most of the optical systems developed by ITT. Witness samples will be processed in parallel with the flight unit and certified by optical inspectors at multiple points in the process.

There are other mirror technologies that could be developed to lessen the risk, cost and schedule for the THEIA PM, but they are not deemed essential. These include:

1. ULE® welding could enable a large blank to be built up from smaller pieces.
2. ULE® large boule development would reduce the schedule required to produce all of the glass required for large monolithic mirrors.
3. ULE® Striae (visibly detectable layers in the glass) are developed as a result of non-uniformities in the distribution of titanium oxide molecules which are introduced into the material to minimize the materials coefficient of thermal expansion. When ULE® is polished, the non-uniformities in the striae layers can result in high spatial frequency surface errors that could adversely impact the system performance of a telescope.

Large Focal Plane Arrays[15]

Large focal planes are essential to achieving the SFC science program introduced in the science section and outlined in a series of white papers [6, 7, 15, 9, 10]. The SFC Team-X study has yielded invaluable insight into cost and yield, as well as the likely problems associated with the production and testing of the many CCD chips in the two SFC focal planes (~ 540 flight-rated devices).

This section outlines the technological challenges associated with building these large focal planes. The investment in low-risk, low-cost, high-fidelity assembly and integration of large focal plane arrays will benefit not only the THEIA mission but also other future imaging missions.

There are several issues associated with large chip production:

1. The need to mass produce large numbers of chips with low read noise, low dark current and high yield from modern lot run manufacture;
2. The requirement to test large numbers of detectors while preserving the fidelity of the product and mitigating the risk associated with fabricating the final array;
3. The need to develop new packaging designs to minimize interchip gaps when mosaicing large numbers of detectors;
4. The need to develop high-capacity data storage, compression and transmission technology.

As part of this development process, we advocate a critical assessment of specifications for flight-rated detectors appropriate for the era of mass production. We have outlined a technology development path that will enable a production line environment that will be capable of producing 540 separate flight-read detectors for the twin FPAs:

1. Complete the infrastructure for processes and facilities (detectors, readout, packaging) (1 year)
2. Fabricate and validate prototype detector modules (SCA) - procure ASIC readout chips, procure detector fabrication run at foundry, process wafers at JPL, design packaging. Development and fabrication of 10 units, testing and qualification of the module (2 years)
3. Fabricate, validate and demonstrate at a ground observatory a prototype 3x3 raft module (SCA) - procure ASIC readout chips second iterative lot, procure detector fab run, process wafers at JPL, design packaging. Development and fabrication of 2 units, cold flatness test, shake and bake, radiation, observation including dewar, thermal, miscellaneous additional instrumentation, (two years)
4. Fabrication and validate prototype FPA by assembling two rafts (SCA) (1 year)
5. Fly a balloon demonstration (parallel with above steps 2-4). Overall schedule is four years for first flight with a second flight in the fifth year. Overall ROM cost is \$40M.

Occulter Technology Challenges and Test Program

One of the major technology challenges of THEIA is verifying the starlight suppression models and confirming that the occulter can be manufactured and deployed to the required tolerances. While optical models predict the desired contrast, verification that the scalar theory and other modeling steps are sufficient is necessary. Current work is underway at Princeton and elsewhere to perform laboratory scale tests of occulting masks and to determine their sensitivity. Work such as this at varying scales needs to continue.

The occulter starshade design employs existing materials and mechanical components but the petal deployment system as a whole is currently considered to be at TRL 3. Note however that a recent successful deployment testing of a 37.5 x 37.5 m panel demonstrated damping and spring rates comparable to THEIA's starshade. Our planned technology development program includes subscale deployment testing of a 3 petal set, a full compliment of subscale petals and characterization testing of thermal and dynamic responses used to validate analytical models that are used to predict the behavior of a full-scale system. Material testing will also be performed, including verification of CTE performance (a critical parameter for the graphite epoxy edges). The technology program will include the development of test equipment for gravity off-loading and an interferometric system to measure petal positions.

The sub-scale 1g development program consists of constructing and deploying three, 1/4-scale petals. Full scale, high accuracy hinges will be used to obtain deployed geometry and alignment measurements consistent with a full-scale design. This test program will be conducted in ambient and thermal vacuum conditions, and will be used to develop manufacturing, tooling, handling, deployment precision, deployed geometric stability, and measurement methods.

The KC135 og deployment program will consist of deploying eight, 1/20-scale petals in an airplane flying parabolic arcs in order to simulate a og environment. This development program will focus on evaluating deployment sequence, deployment repeatability, and deployment times. Adjustments to sequence timing, damp rates, and torque rates will be evaluated over the course of several deployments. Video measurements of deploy time and character will be used to correlate dynamic modeling.

A 1/5-scale occulter with a full complement of petals and blankets, full scale high accuracy hinges, and 1/5-scale precision deployable masts will be deployed on a sounding rocket in a near o-g, vacuum environment. Hinges will be instrumented to provide deployment telemetry. Retro-reflective targets will be video-taped during deployment providing additional telemetry to evaluate deployed alignments. This same 1/5-scale starshade system is deployed in a thermal vacuum chamber for more accurate measurements and performance verification over the operating temperature range. This test will also provide experience with the gravity off-loading test that will be scaled up for testing a full scale occulter. The total cost estimate for our starshade development to TRL 6 is \$40M.

We also plan to prepare a full-scale qualification unit. In addition to environmental qualification testing, we will use this qualification unit to deploy a 3 petal set in a thermal vacuum chamber for further verification of analytical models. We have also defined a test plan for deploying the full-scale qualification unit with full compliment of petals in an available hanger facility. This latter test is proposed but is not included in our current cost estimates.

5. Activity Organization, Partnerships, and Current Status

This project grew out of an NASA Advanced Strategic Mission Concept Study (ASMCS). Our team consists of scientists and engineers at Princeton University, The Space Telescope Science Institute (STScI), Arizona State University (ASU) and many other partner universities, NASA centers (JPL/Caltech, GSFC), and industry partners (Lockheed Martin Missiles and Space, Ball Aerospace, and ITT Space Systems LLC).

The chart in Figure 10 shows the projected schedule for mission development with a launch at the beginning of 2021. The three tall pole technology items are emphasized. An immediate investment in technology development is essential to meet this schedule.

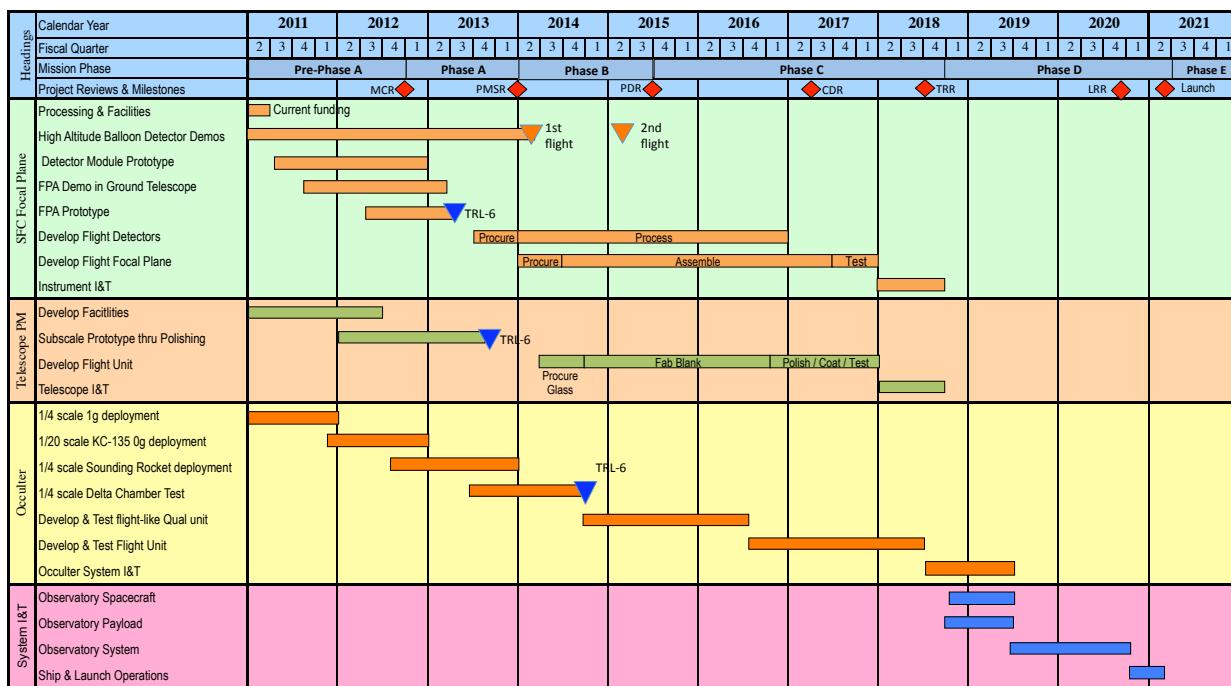


Figure 10: The THEIA development schedule

6. THEIA Costs

We estimate THEIA's total life cycle cost between \$5 and \$6 billion in FY09 dollars, including reserves. Table 3 shows the cost breakdown for 2 bounding cases. First is the JPL Team-X estimate (\$6B), arrived at after a series of instrument and mission level studies. Second is the THEIA team's estimate (\$5B) arrived at by making 4 adjustments to the Team-X estimate. Three of these adjustments are explained in Table 3 while the 4th, the telescope adjustment, is detailed below. Figure 11 shows an approximate cost profile through Phase D not including launch vehicle and operations costs.

The Team X cost estimates were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation or cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. Team X typically adds 30% reserves for development (Phases A-D) and 15% for operations

(Phase E). Team-X studies were conducted at the instrument, spacecraft and mission levels between July of 2008 and February 2009. Cost estimates for technology development and Pre-Phase-A Mission Concept development are from the THEIA study team and have been added to the Team-X estimate to enable direct comparison.

The telescope (OTA) has the largest impact on the final cost as it is both the most costly single line item and has the largest uncertainty. We have strived to establish a reasonably conservative cost estimate as there is no precedence for a 4m space science telescope. Using JWST as a comparison is not practical as THEIA's 4 m telescope is not deployed, has a passive monolithic primary mirror constructed of ULE® glass, is heated to room temperature on-orbit, and is optimized to operate from the near UV to the near IR (and is diffraction limited at 300 nm). By comparison, JWST's 6 m telescope is deployed, utilizing a segmented and actuated (active) beryllium primary mirror, is cryogenically cooled, and is operated in the near to mid- IR. As a result, we report the cost using two different approaches, a data based extrapolation from

Cost Element	Team-X	THEIA Team	Comments
Pre-Phase A Mission Concept	15	15	THEIA team estimate
Total Technology Development	150	150	THEIA team estimates
Occulter Starshield	40	40	
Primary Mirror	50	50	
SFC Focal Plane	40	40	
NEXT Ion thruster testing	20	20	
Management, Sys Engr, Mission Design and Mission Assurance	160	140	Derived from other changes
Science and Science Data Center	250	250	
Payload System	3000	2200	
Exoplanet Characterizer	150	150	
Star Formation Camera	400	400	
UV Spectrometer	200	200	Goddard IDC estimate
Fine Guidance Sensors	80	80	
Occulter Starshield	100	100	
Other	25	20	Derived from other changes
Telescope	2000	1200	See Text
Flight Systems (Observatory & Occulter)	560	500	THEIA est. uses screened MIL 883B parts versus Class S (do not need extra rad hardness)
System Level I&T (ATLO)	40	100	THEIA est. adds I&T of instruments with telescope & a complex shipping container
Mission Operations & Ground Data Systems	190	130	THEIA est. removes DSN cost, per assumption that THEIA will be an assigned mission
Education and Public Outreach	40	35	Derived from other changes
Reserves	1200	1000	Derived from other changes
Launch Services	440	440	2 Atlas V 551s
Total Mission	6000	5000	

Table 3: Team-X and THEIA Team Cost Estimates.

existing telescopes (Team-X) and a bottom-up estimate based on projections of manufacturing, integration, and test capabilities (THEIA).

Team-X's telescope cost estimate (\$2B) was derived from a family of cost versus aperture size curves that represent varying complexity levels. These curves are significantly divergent at 4 m and the Team-X cost estimate for THEIA lies near the mid-range of these curves. This extrapolation introduces enormous uncertainty but is believed to conservatively bound the telescope cost.

Using a bottom-up approach, the THEIA team established a preliminary telescope cost estimate of \$1.2B, which conservatively accounts for all non-standard features (e.g., 300nm diffraction limit, active mounting struts, LiF coated secondary mirror, plus miscellaneous issues). We subsequently received a grass-root cost ROM from ITT that confirmed our preliminary estimate as conservative. While this estimate certainly establishes a believable lower bound, we also believe that it accurately reflects a conservative prediction of the expected cost with reasonable contingency.

We also carry 30% in cost reserves for the telescope. There are \$50M in technology development costs to upgrade primary mirror processing facilities and advance primary mirror technology to TRL 6 with a subscale prototype.

Another area of relatively high cost uncertainty is the occulter starshade. Both the starshade technology development cost (\$40M) and the flight development cost (\$100M) derive from very detailed grass root estimates by our industrial partner, Lockheed Martin Missiles and Space. Estimates include all required manpower, materials and component procurements, assembly and test and test equipment. We also carry 30% in reserves for the starshade.

Our cost estimate for system level integration and test also derives from a detailed grass root estimate by Lockheed Martin Missiles and Space that leverages off experience on past programs including HST. This activity includes integration and testing of fully tested science instruments with a fully tested telescope. We also include the cost of a complex shipping container to maintain the required cleanliness, with the estimate based on analogy to a recent study.

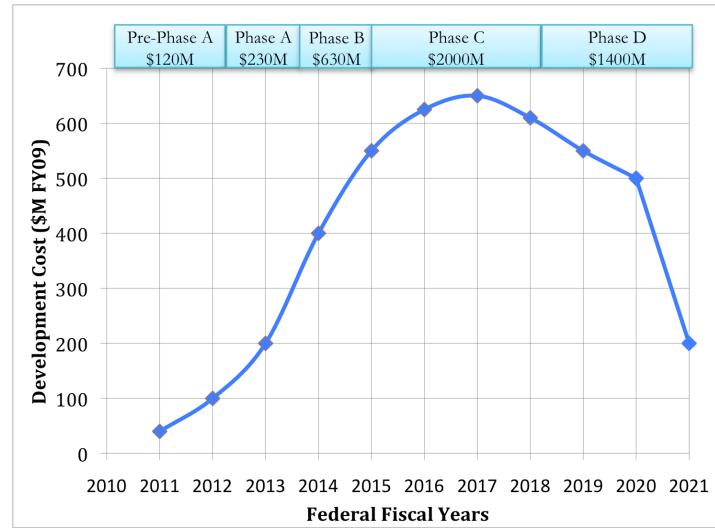


Figure 11: Representative THEIA Cost Profile.

Acknowledgments

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