Final Report
Astrophysics Strategic Mission Concept Study
The New Worlds Observer
Principal Investigator: Webster Cash

April 24, 2009

If habitable planets are common, NWO will discover them.
If life in the Universe is abundant, NWO will find it.

SUMMARY

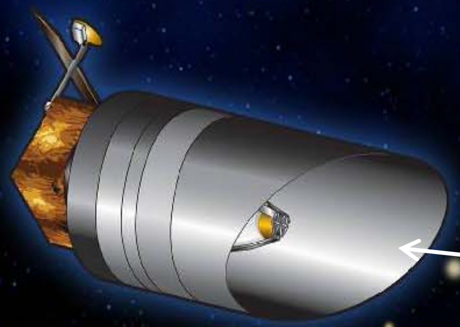
We present the results of the Astrophysics Strategic Mission Concept Study (ASMCS) for the New Worlds Observer (NWO). We show that the use of starshades is the most effective and affordable path to mapping and understanding our neighboring planetary systems, to opening the search for life outside our solar system, while serving the needs of the greater astronomy community. A starshade-based mission can be implemented immediately with a near term program of technology demonstration. The mission foldout is on the following page.

Co-author	Institution	Study Role	Co-author	Institution	Study Role
Brooks Atkinson	Ball	Telescope s/c system engineer	Aki Roberge	GSFC	Science Team
Wayne Davis	Ball	Telescope comm system lead	Steve Tompkins	GSFC	Ground Systems/Mission Ops
Jim DeCino	Ball	Telescope mechanical design	June Tveekrem	GSFC	Optics, Stray Light
Bill Deininger	Ball	Telescope s/c system engineer	Bruce Woodgate	GSFC	Instruments
Rand Donohoo	Ball	Telescope mechanical design	Maggie Turnbull	GSI	Science Team Lead
Steve Kendrick	Ball	Optics and Telescope Design	Dean Dailey	NGC	Mechanism and Structures Lead
Charley Noecker	Ball	Mission Design/Telescope Lead	Kent Decker	NGC	Power Subsystem Lead
John Bally	CU	Science Team	Reza Dehmohseni	NGC	ACS/GN&C Lead
Julia DeMarines	CU	Outreach/Education	Brian Gaugh	NGC	Thermal Control Subsystem Lead
James Green	CU	Science, Instrument Design	Tiffany Glassman	NGC	Science team/ Starshade Analysis
Phil Oakley	CU	Science Team	Mickey Haney	NGC	Comm System Lead
Ann Shipley	CU	Starshade Laboratory Testing	Reem Hejal	NGC	Dynamics Lead
Scott Benson	GRC	NEXT Propulsion System Lead	Chuck Lillie	NGC	Senior Advisor
Steve Oleson	GRC	NEXT Propulsion System	Amy Lo	NGC	Deputy PI, Mission Design
David Content	GSFC	Laboratory Testing	David O'Conner	NGC	Starshade ACS Lead
Dave Folta	GSFC	Flight Dynamics	Gina Oleas	NGC	System Engineer
Sharon Garrison	GSFC	Study Management	Ron Polidan	NGC	Senior Advisor
Keith Gendreau	GSFC	Science System Engineer	Rocco Samuele	NGC	Starshade Laboratory Testing
Kate Hartman	GSFC	Study Manager	Stephen Shields	NGC	Mechanical Design Integration
Joe Howard	GSFC	Optical Design	James Shirvanian	NGC	Formation Flying Conops
Tupper Hyde	GSFC	Technology Lead	David SooHoo	NGC	Propulsion
Darryl Lakins	GSFC	Lead System Engineer	Giovanna Tinetti	UCL	Science Team
Jesse Leitner	GSFC	Formation Flying Systems	Bryan Dorland	USNO	JMAP Instrument PI
Doug Leviton	GSFC	Optics, Instrument, Lab Testing	Rachel Dudik	USNO	JMAPS Instrument, Astrometry
Rich Luquette	GSFC	Formation Flying Systems	Ralph Gaume	USNO	Astrometry
Bill Oegerle	GSFC	Science Team	Brian Mason	USNO	Science Team, Astrometry
Karen Richon	GSFC	Orbits, Navigation Lead			

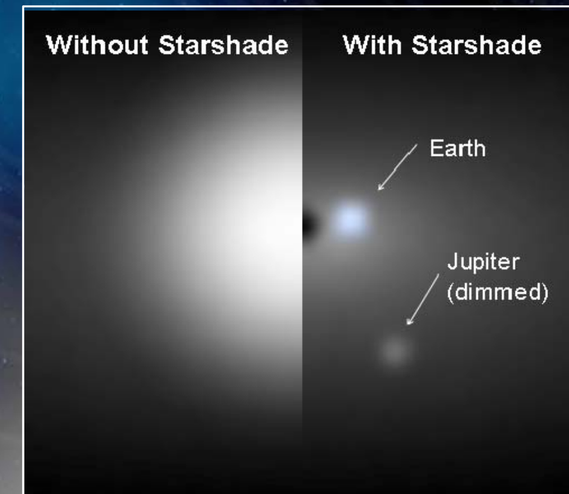
New Worlds Observer: an Affordable and Efficient Way to Revolutionize Exoplanet Science

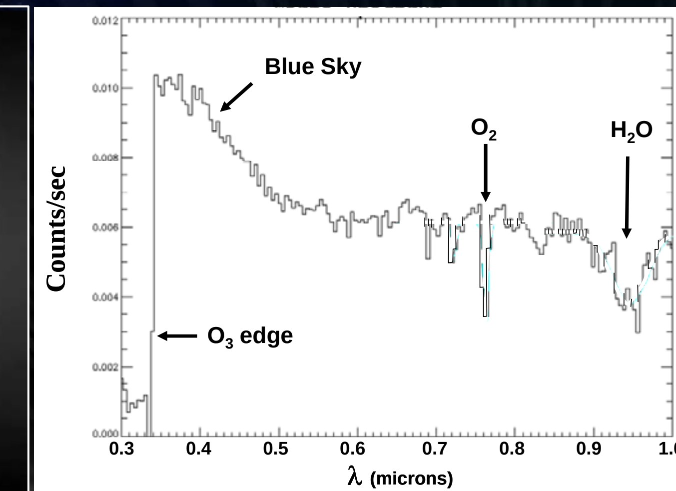
NASA Themes Addressed with Starshade:
- Is there life elsewhere in the universe?
- Are there other planetary systems like our own?
- How do planetary systems form and evolve?
- How are stars and stellar system formed?

NASA Themes Addressed with Telescope:
- What is the dark energy pulling the universe apart?
- How did the first stars, galaxies and quasars form?
- What are the ultimate fates of stars?



~80,000 km





NWO's primary science: discovery and characterization of terrestrial exoplanets

4m UV-Visible TELESCOPE

Provides large collecting area and high resolution for both exoplanet science and general astrophysics. Carries 5 instruments to enable a wide array of UV and Visible astrophysics

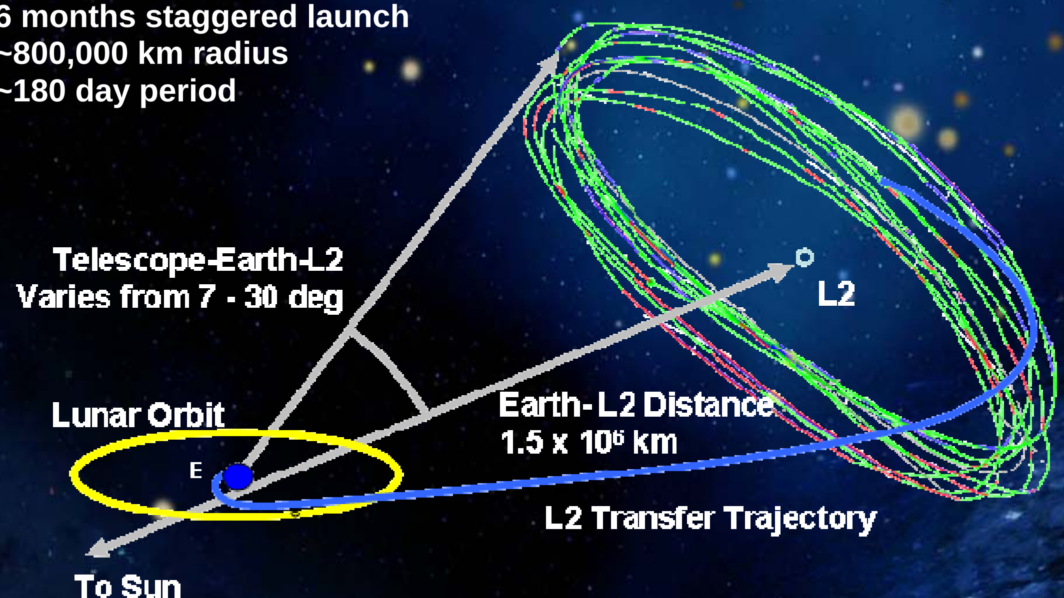
Instrument	Primary Use	FOV	Bandpass
ExoCam	Detecting/ Imaging Exoplanets	26″ x 26″	0.25-1.7 mm
ExoSpec	Spectroscopy of Exoplanets	10″ x 3″	0.25-1.7 mm
Shadow Sensor	Fine alignment control	N/A	1.7-3 mm
WF Camera	GA, Fine Guider	10′×20′	0.4-0.9 mm
UVSpec	GA UV Spectroscopy	< 1″	0.12-0.5 mm

Deployable Apodized STARSHADE

Provides 10^{10} starlight suppression to enable exoplanet imaging starting at IWA 50 mas, with 100% planet light throughput. Can be used with astrophysics objects like AGNs

L2 Orbit

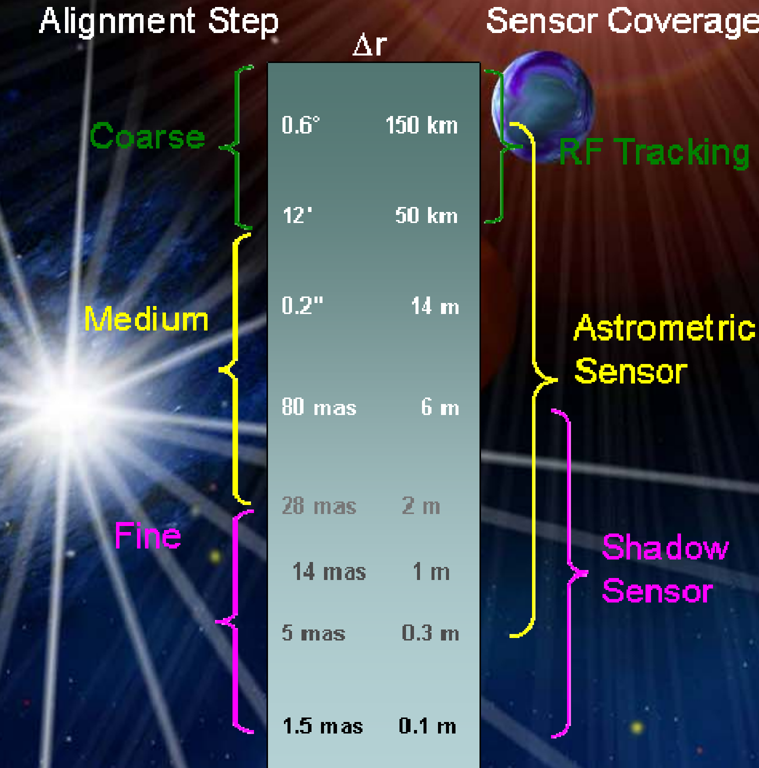
6 months staggered launch
~800,000 km radius
~180 day period



NWO Observatory Mass

All mass in kg	Telescope Spacecraft			Starshade Spacecraft		
	CBE	Cont.	Alloc.	CBE	Cont.	Alloc.
Spacecraft dry mass	4077	30%	5300	2710	30%	3523
Propellant Mass (bi prop)	448	0%	448	476	0%	476
Propellant Mass (Xenon)	n/a	n/a	n/a	1220	0%	1220
Spacecraft Wet Mass	4525	27%	5748	4406	16%	5219
Payload Adapter Fairing	114	5%	120	114	5%	120
Separation System	49	5%	51	49	5%	51
Total Launch Mass	4688	26%	5919	4570	26%	5390

NWO uses a 3-step alignment process to center the starshade and telescope to within 1 m.



Background by Mary Pat Hybrk-Keith

I. INTRODUCTION

Is Earth a unique outpost of life in a vast and empty Universe? How did planets come into being and why are they in their current state? What are the circumstances under which life arises, and how common is it? NASA can definitively address these questions in the coming decade with the New Worlds Observer (NWO).

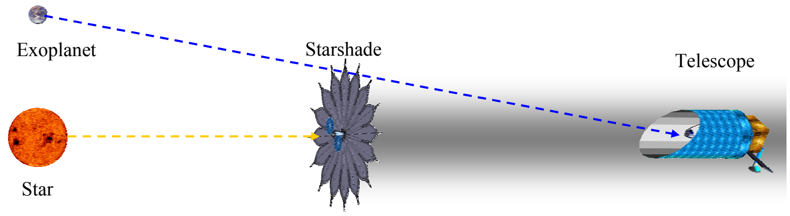


Figure 1: NWO's cost-effective starshade shadows the telescope from the star, while light from a terrestrial exoplanet passes the edge of the starshade unimpeded.

Hundreds of giant exoplanets have now been detected and improvements in technology are moving the detection limits to smaller and smaller masses. NWO can discover Earth-like planets and, detecting their existence is just the beginning: NWO will perform spectroscopy of planets in the habitable zones of dozens of stars to answer the question of how common life is in the Universe. A facility capable of finding and characterizing terrestrial planets requires that the starlight be suppressed by a factor of at least 10^{10} to enable the planet's light to be seen against the light of its host sun. This suppression needs to be confined within tens of milliarcseconds (mas) so that the planet's light is not blocked. Direct imaging with NWO will reveal most of the planets in an extrasolar system in just a single exposure. Through spectroscopy, we can determine the nature of each planet discovered.

The NWO mission concept (Fig. 1) can do all of this and more. Full suppression of the starlight by the starshade before it enters the aperture relieves the telescope of demanding requirements such as ultra-high quality wave front correction and stray light control. The NWO telescope requires only diffraction-limited wavefront quality. This design results in a clean separation of light suppression and light collection. The starshade is a passive mechanical structure that only has mm-level requirements on the edge, not over the surface. Integrated development of NWO could start today.

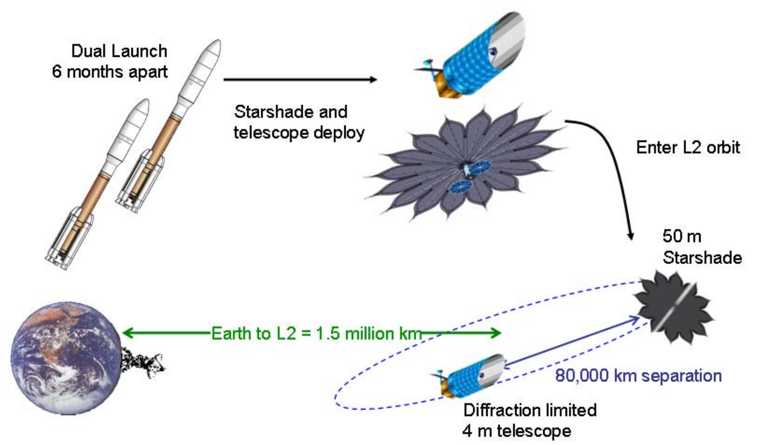


Figure 2: Employing existing technology, NWO uses a 4m telescope and a 50m starshade orbiting around the Sun-Earth L2 point to image and characterize terrestrial planets.

The NWO mission is illustrated in Fig. 2. Two launch vehicles take the 50m starshade and the 4m telescope to L2, where they enter a halo orbit. The two spacecraft are separated by ~80,000km. The starshade moves relative to the telescope to occult target stars. The average exoplanet observing cycle is ~2 weeks per star, with the capability of more than 100 cycles over a 5-year mission.

The study has shown, in part through collaboration with the ATLAST ASMCS study group, that starshades are an extendable technology. Larger starshades can accommodate successively larger telescopes, freeing the telescope to adopt architectures such as segmented mirrors and central obstructions that are not available to other direct-imaging techniques. We took a detailed look at the technology necessary to make the New Worlds Observer a reality: most of this technology already exists. What is new for NWO is that these existing technologies have not been combined in this particular way before. Technology development for NWO can be rapidly implemented to lead to a flight program within a few years, with well-understood and controlled risks. The launch of a starshade could be envisioned in as little as six years. The cost of a starshade-only mission is in the medium cost category. The cost of a 4m UV-Visible observatory is, unsurprisingly, in the flagship range.

II. SUMMARY OF FINDINGS:

Our findings from the Astrophysics Strategic Mission Concept Study are summarized below:

- NWO is capable of effectively searching thirty total habitable zones, with a contrast limit of 10^{-11} and inner working angle of 50mas.
- Spectra of all major planets in a Solar system twin at 10pc can be obtained in less than 24 hours at R ~100 over a wavelength range of 0.1 to 1.1µm, due to the high throughput of the NWO system.
- The wavelength range of NWO covers the ozone edge, water lines, and some methane lines, making detection of life possible.
- The design of the telescope is independent of the design of the starshade. A diffraction-limited UV/O/IR telescope like HST can be used with no additional constraints from the starshade. 70% of the telescope time is available for general astrophysics during the time that the starshade is traveling to the next target star.
- NWO does not require invention of new technology: all the elements of the technologies used exist including the deployment and telescope-to-starshade alignment systems. Currently these technologies need to be integrated into a full-scale working system.
- Starshades provide a versatile architecture. They may be expanded, extended, and upgraded for future missions.

III. ASMCS STUDY AND REPORT

The technology associated with starshades represents an all-new approach to the problem of starlight suppression. The starshade concept was developed with funding from a NASA Institute for Advanced Concepts (NIAC) phase 1 and 2 architecture studies and contributions from academic and industry partners up until April 2008, when we were awarded a one million dollar ASMCS study for a flagship mission deemed appropriate for the coming decade. In this document we report the results of the study.

Our diverse study team included approximately 50 people from nine institutions with Goddard Space Flight Center responsible for management. It brought together a wide range of expertise in all the crucial areas to address this unique design and study mission concept. We believe the study has been a resounding success, and we provide a summary of our results.

Table 1: Appendices

A.	MDL Outputs
B.	IDL Outputs
C.	Science
D.	Mission Requirements
E.	Starshade
F.	Telescope
G.	Trajectory and Alignment
H.	JMAPS
I.	NEXT
J.	Orbits
K.	Launch
L.	Operations
M.	Management
N.	Servicing
O.	Technology Roadmap
P.	Relevance to NASA
Q.	Alternative Telescopes
R.	Bibliography
S.	TAR Final Report

Conveying the full range of scientific and engineering results generated from this study is limited by the size of this 20-page Final Report requested by NASA. Therefore, we have included numerous appendices with this report. This document is designed as a stand-alone summary that conveys the main points. We refer the reader to the appendices listed in Table 1 for more thorough reporting and explanation. We reference the appendices as needed throughout. The required Mission Design Lab study final report is included as Appendix A. We chose to use an Instrument Design Lab study to investigate our Trajectory and Alignment sensors, and that report is included in Appendix B.

IV. RELEVANCE TO NASA NEEDS

We believe the New Worlds Observer is exactly the kind of mission NASA needs to fulfill its goals. It is exploratory in nature, inspiring to the public, and provides unparalleled scientific data.

To summarize relevance, we reviewed the nine grand science themes from the 2006 Astrophysics Roadmap. Of these, NWO can address seven. The four shown in green are related to the use of the starshade. Three more in blue can be addressed by the telescope without use of the starshade. More details are included in Appendix P.

Themes Addressed with Starshade

- **Is there life elsewhere in the universe?**
- **Are there other planetary systems like our own?**
- **How do planetary systems form and evolve?**
- **How are the stars and stellar systems formed from the interstellar clouds of gas and dust?**

Themes Addressed with Telescope

- **What is the dark energy pulling the universe apart?**
- **How did the first stars, galaxies, and quasars form?**
- **What are the ultimate fate of stars, and the origin of the elements essential for life?**

V. KEY SCIENCE GOALS

The science enabled by the New Worlds Observer is extensive and groundbreaking. With current and near-term technology, we can make great strides in finding and characterizing planets in the habitable zones of nearby stars. The key science goals of NWO are: 1. discover dozens of Earth-like planets in the Habitable Zones (HZ) of nearby stars with a total search completeness of 30; 2. characterize the planets we find using time-resolved photometry, spectroscopy, and polarimetry, giving us information such as atmospheric conditions, internal structure, mass estimates, and signs of life; 3. study other aspects of the extrasolar system including giant planets, planetesimal belts, and exozodiacal dust; and 4) conduct a large range of astronomical research ~70% of the time, while the NWO starshade is moving from target to target. Appendix C addresses these areas in more detail.

1) Discovery

Because a star's HZ is located so near to the star itself, NWO must provide extremely high-contrast imaging at very small star-planet angular separations. The starshade does this by suppressing the starlight by many orders of magnitude while allowing light from all planets beyond the Inner Working Angle (IWA) to pass to the telescope with 100% throughput. We make the distinction between the starlight suppression, which is the fraction of incident starlight that enters the telescope, and the planet contrast limit, which is the faintest planet that can be seen by NWO near a given star. Because the residual starlight that does enter the telescope is not imaged onto the same pixels as the planet, the planet contrast limit is 10-100 lower than the starlight suppres-

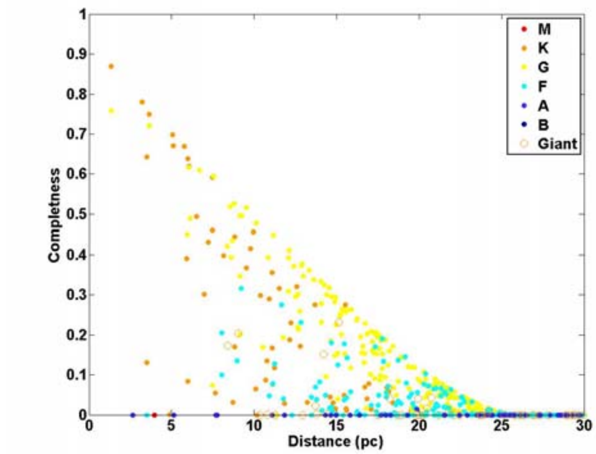


Figure 3: The completeness for the NWO target stars versus their distance. There are ~100 stars with an appreciable chance of finding a HZ-resident planet, most of which are early-K to F stars.

sion. That is, if the starlight is suppressed to 10^{-10}, we can see planets that are 10^{-11} to 10^{-12} of the stellar brightness.

We created a simple model of the size of the HZ around other stars by scaling the size of our own HZ (0.7 to 1.5AU) by the square root of the stellar luminosity: HZ (AU) = 0.7 - 1.5 $\times \sqrt{L_* / L_{sun}}$. Translating the linear HZ size in AU into an angular size, we find that the angular HZ size can be expressed in terms of the apparent magnitude alone. For a separation scaled to 1AU, this means:

$$\theta_{HZ}('') = a_{HZ}(AU)/d(pc) = \sqrt{(L_* / L_{sun})} \Big/ d(pc) = \sqrt{10^{-(M_V-4.8)/5}} / d(pc) \approx 10^{-V/5}$$

Our list of prime target stars extends to V~7, which translates to HZ=30 - 60mas. Thus NWO must have an IWA in this range to be able to see the majority of the HZ planets for these stars.

As well as being very near to the star, a habitable terrestrial planet is very small in size, and thus reflects only a tiny fraction of the star's light. By definition, the “habitable zone” is where an Earth-like planet receives the right amount of energy to have liquid water on its surface; therefore, the luminosity of a planet in the HZ does not depend on the luminosity of the star. For planets of a given size and albedo, planet contrast depends only on $1/L_*$. This brings home the challenge for planet-imaging missions: it is easier to observe large values of both angular HZ size and fractional planet brightness, but the former varies as $L_*^{1/2}$ while the latter varies as $1/L_*$.

With IWA~50mas and planet contrast limit of ~10^{-11} there are ~500 stars whose habitable zone is at least partly visible. Most of these stars are F, G, and K type since the system was tuned to find extrasolar systems like our own, which are most likely to harbor Earth-like planets.

We can model the probability of finding a HZ planet around each target star with NWO, which is known as the completeness for that star (Fig. 3; see e.g. Brown 2005). If there is one planet per HZ on average (η_{HZ}=1), then the completeness is the expected number of HZ planets detected. We sum the completeness for each observed star to get the total completeness for the mission.

We created sample mission schedules to determine the total number of planets NWO can discover and found that we can easily achieve a total completeness of 30 for a wide range of mission configurations. If η_{HZ} is high (close to 1), the total completeness of 30 translates to tens of HZ planets discovered. This seems likely to be the case; the number for our Solar System is 3 since Venus, Mars, and Earth all reside in the HZ as defined by Kasting et al. (1993). There is mounting evidence that planets like the Earth are common; “Super Earths” are already being found and the incidence of planets seems to be rising to lower mass. It is likely that η_{HZ} is near unity and Kepler will measure that number within a few more years. Even if this turns out to not be the case, NWO is robust against a wide range of η_{HZ} values since the size of the starshade and its operation can easily be adapted for different situations.

The total number of systems searched is limited by the scarcity of good target stars, not by NWO’s ability to make enough observations. This is thanks to both the unique ability of NWO to observe the entire extrasolar system at once and the high throughput of the telescope. The high efficiency and sensitivity offset the time required for re-pointing.

The idea that a direct-detection method has a poor efficiency for discovering planets is simply not true for NWO; knowing the "addresses" of planets beforehand is useful but not necessary. NWO can start taking spectra of any exoplanets very quickly after arriving at a target star, even if we know nothing about the system. Within 24 to 48 hours, NWO can image and take spectra of every planet from the HZ outward.

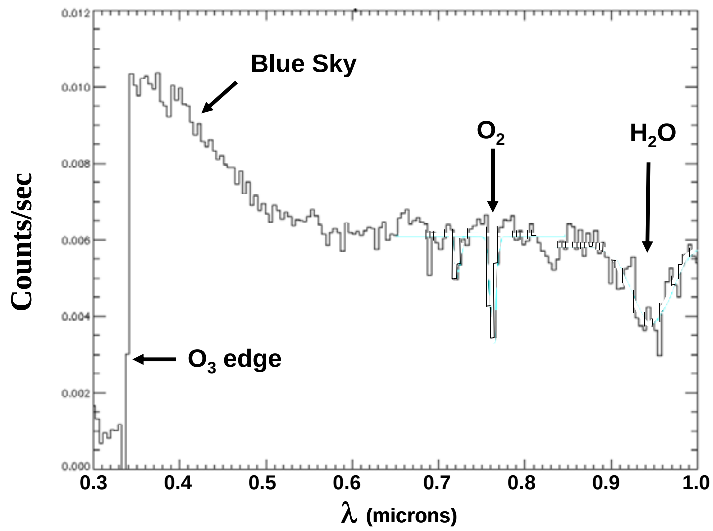


Figure 4: The spectrum of the Earth at 10 pc as seen by NWO. Note the prominent water and oxygen absorption lines and the ozone edge in the near UV.

2) Characterization

Once exoplanets have been discovered, detailed observations such as time-resolved photometry, spectroscopy, and polarimetry will reveal the true nature of these planets and the systems in which they were born. The physical properties of exoplanets can be characterized using visible-band, reflected starlight which depends attributes including the size of the planet, the distance between the planet and the star, the composition and structure of the planet's atmosphere and surface, and the wavelength of the observation.

Spectroscopy of terrestrial exoplanets will quickly reveal a wealth of information about the planet's atmospheric and surface conditions including habitability or even the presence of life. Water, carbon dioxide, oxygen, methane, ozone, and ammonia give the key signatures. Water is the necessary ingredient for the types of life found on Earth and it has played an intimate, if not fully understood, role in the origin and development of life on Earth. The presence of carbon-dioxide would indicate (1) that carbon is available for the biosphere, (2) a greenhouse effect, and (3) the possibility of climate regulation via carbon cycling between the atmosphere and hydro/geosphere. A large amount of oxygen in a terrestrial atmosphere would be extremely interesting; oxygen is so chemically reactive that it must be continuously produced at enormous rates to persist. O_2 in the Earth's atmosphere is the result of continuous input from the biosphere (Lovelock 1979).

A simulated spectrum of the Earth at 10pc, viewed for 50 hours by NWO, is shown in Fig. 4. All known sources of noise are included. Clearly visible in the spectrum is the rise to short wavelength, indicating Rayleigh scattering. Toward the red end are strong absorption features of water, indicative of oceans and clouds. Most exciting is the presence of biomarkers such as absorption lines from molecular oxygen and an absorption edge from ozone in the near ultraviolet. These features in the spectrum of the Earth arise solely as a byproduct of plant life.

An analysis of a planet's color, brightness variability, and spectrum provides an estimate of the planet's reflectivity, or albedo. From this, the planetary radius can possibly be derived as well as an estimate of its density (rocky planets tend to have much lower albedo than gas giants). This classification system provides a method to estimate planetary mass. While measuring the mass of the planet is an important parameter for detailed modeling, the most important information regarding habitability is gained through direct observation. Measurement of mass should follow planet detection and classification, as opposed to being a necessary first step.

The full suite of astrophysical techniques will be available for exoplanet observations. We can make rough measurements of atmospheric density from Raleigh scattering. Photometric monitoring could reveal surface variations for planets with relatively transparent atmospheres (Oakley, Cash, & Turnbull 2008). A high-resolution spectrometer might be used to capture a detailed spectrum of a particularly interesting planet. Similarly, other general astrophysics (GA) instruments might be used to characterize planets in special circumstances.

3) Planetary Systems

Since NWO will have a large field of view of ~0.2 square arcminutes, we will discover outer planets and diffuse emission while searching the HZ of the star. The detection, characterization, and orbit determinations of gas and ice giants in the outer parts of planetary systems will provide important clues about the system's long-term dynamical evolution. NWO will provide reliable statistics on, for example, the presence of ice and gas giants in long-period orbits in mature planetary systems, and estimates of disk lifetimes. Given the parameters observable with NWO, it will be possible to differentiate between and constrain models of planet formation and evolution.

We must also carefully consider diffuse emission from interplanetary dust in the extrasolar systems. This exozodiacal dust (or "exozodi") is crucial, both for its science return and as a source of background noise.

The amount of exozodi is typically quantified by the fractional infrared luminosity (L_{IR}/L_*) which is proportional to the dust mass, though other factors like grain properties affect it. Currently known exozodi disks (better known as debris disks) have fractional infrared luminosity (L_{IR}/L_*) ≈ 10^{-3} - 10^{-5} (e.g. Bryden et al. 2006). The zodiacal dust interior to our asteroid belt has $L_{IR}/L_* \cong 10^{-7}$, which we call 1 "zodi". We are not currently able to detect this amount of dust around other stars; this can only be done with high-contrast direct imaging. Since NWO has no outer working angle and produces zero distortions in the field, exozodiacal light and debris disks will be optimally imaged by this system.

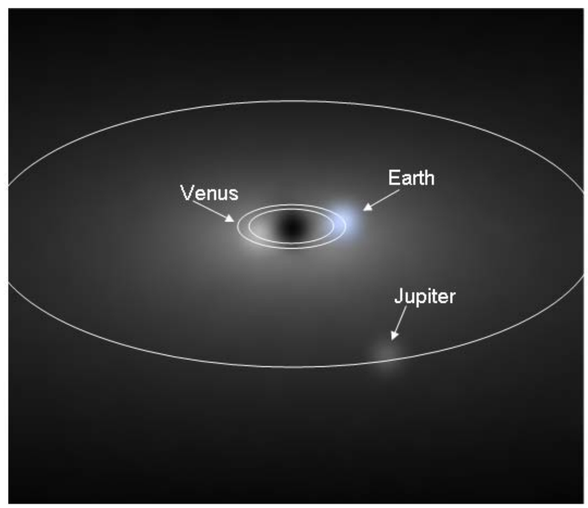


Figure 5: The exozodiacal light can help estimate the inclination of the system and therefore constrain planet orbits. This image shows a simulation of a hypothetical system with three planets – Venus, Earth and Jupiter. The exozodiacal light has total brightness equal to our own, but is more spatially extended.

The distribution of exozodiacal light is a sensitive tracer of the system's orbital dynamics. Planetary orbital resonances will be displayed as gaps and enhancements in the dust. Tiny planets, too small to be seen directly, should leave distinct marks. The observed dust distribution gives us critical information like the inclination of the system's ecliptic plane (Fig. 5). By eye, one can place an ellipse over the system, estimating the orientation of the plane. Then, concentric ellipses may be drawn about the central star and those that pass through a planet show the orbit of that planet under the assumption of circularity. Exozodiacal light has the potential to give us a first estimate of the orbit of each planet from a single image. Revisits will determine other planet orbit parameters.

Zodiacal and exozodiacal dust also create a background flux that is mixed with the planet signal in both images and spectra. Even if nearby systems have exozodi levels no greater than the Solar System level, the zodiacal and exozodiacal background will be the largest source of noise for most terrestrial planet targets, assuming the starlight is suppressed to ~10^{-10}. The surface brightness of the exozodi is the main factor controlling how long it takes to detect an exoplanet buried in it. We know very little about exozodi levels in nearby stellar systems. However, NWO is quite robust against the presence of many zodis of dust in the extrasolar system (Fig. 6). A useful benchmark goal is S/N = 10 on an Earth-like planet in a Solar System twin at 10pc viewed at a 60° inclination, which NWO can achieve in 3.3 hours. Even if there is 10 zodi in this system (~19 mag/arcsec^2 at the planet location), NWO can image the Earth twin in less than a day.

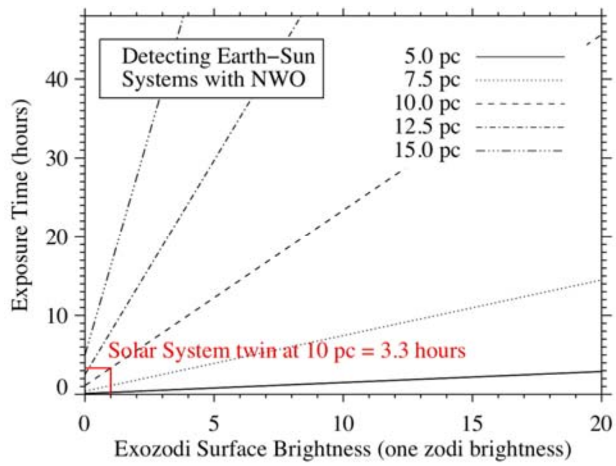


Figure 6: Time to detect an Earth-like planet in the HZ at S/N=10 vs. exozodi surface brightness (in units of zodi). Time to detect an Earth-like planet in a Solar System twin is in red.

4) General Astrophysics

Up to 70% of the telescope observing time will be dedicated to astrophysical observations of interest to the larger community. The telescope is similar to HST, but nearly twice the diameter, covering the same waveband (from Lyman-α to the near IR). Compared to HST, the resolution will improve by a factor of two over much of the visible and the ultraviolet. It will have over four times the collecting area, higher observing efficiency, wider field of view, and better detectors yielding an order of magnitude more data.

Sample GA projects to be conducted with a 4m NWO include:

- Probing the distant Universe by searching for and analyzing the light of distant supernovae (SNe) and gamma-ray bursts (GRBs)
- Investigation of the cosmic evolution of galaxies and galaxy clusters
- Tracing the cosmic evolution of dark energy
- Mapping the distribution of dark matter
- Characterization of the stellar populations in the Milky Way and Local Group Galaxies
- Probing the cradle-to-grave evolution of stars and planetary systems of all masses
- Indirect searches for extrasolar planets by means of transits, gravitational micro-lensing, and astrometry
- Studies of the “Galactic Ecology”, the cycling of the interstellar medium (ISM) into stars back into the ISM using UV, visual, and near-IR tracers

General Astrophysics observations can be conducted both while the starshade is moving to the next target (stand-alone mode) and during planet finding and characterization (parallel observations). While the telescope is observing a nearby target star being occulted by the starshade, the wide-field camera can be used to obtain deep images of the background field. When NWO targets high Galactic latitude fields, the background will primarily consist of distant galaxies. Deep imaging of these fields will be used to map the distribution of dark matter using the distortions of galaxy images produced by weak gravitational lensing (Tyson, Wenk, & Valdes 1990; Fischer et al. 2000) and can be analyzed for transient events such as supernovae and GRBs. When NWO targets low Galactic latitude fields, the background will primarily consist of stars. Deep imaging and photometry will characterize the stellar populations along these lines-of-sight and synoptic monitoring will identify all variable stars.

The 4m aperture of the NWO telescope will out-perform 2m-class facilities being considered for missions dedicated to specific science goals such as mapping dark matter, tracing dark energy, or probing star formation in the local Universe. In the diffraction limit, the point-source sensitivity increases as telescope diameter to the fourth power. Thus, each of the major science objectives can be met by NWO in a fraction of the time required by a smaller aperture.

VI. TECHNICAL OVERVIEW

<u>The Starshade</u>

The idea of a starshade is not new (Spitzer 1962), but eliminating light diffracting around an external occulter for imaging Earth-like planets has been impractical (Marchal 1985; Copi & Starkman 2000). Recently, Cash (2006) found an apodization function that made such a system practical with today's technology. Shown in Fig. 7, the starshade is an opaque screen that sits in the line of sight from the telescope to the star. If the starshade is sufficiently distant, it will subtend a small angle, allowing it to blot out the star's light while allowing the exoplanet light to pass unobscured past the edge. A detailed requirements document for the Starshade is in Appendix D. Our science goals are taken from the TPF STDT report, and the NWO mission is designed to fulfill and exceed those requirements.

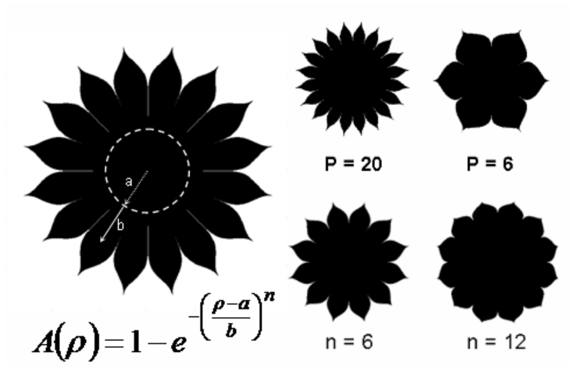


Figure 7: The apodization function, A(ρ), describes the shape of the starshade and can be optimized for suppression level, wavelength range, shadow size, and IWA.

Cash's offset hyper-Gaussian apodization function reduces diffraction by many orders of magnitude; Fig. 7 shows the parameters of this apodization function. A starshade with 2(a+b) = 50m (the effective diameter), operating ~80,000 km from a 4m telescope is capable of 10^{10} starlight suppression within 50mas for wavelengths from 0.1 to 1μm. Our studies of the starshade in the past four years have shown that the optimal petal number for NWO is P = 16, a balance between starshade mass and shadow diameter. The hypergaussian parameter is optimized at n = 6 over the wavelength range. Four independent software codes have been developed to simulate starshade performance. Fig. 8 shows the suppression efficiency of the baseline starshade design as a function of both shadow radius and angular offset for two representative wave-

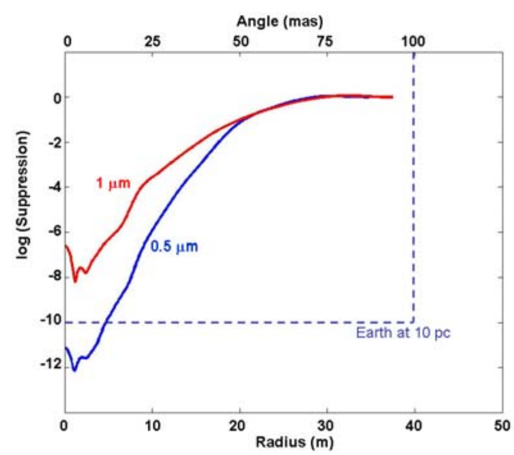


Figure 8: Light suppression falls by >ten orders of magnitude across a shadow radius of just 20m, allowing observations of planets as close as 50 mas.

lengths.

Deriving the requirements and tolerances for the starshade has been a challenge. Never before has anyone set tolerances on an occulting screen that must be understood to the 10ppm level. In response to this need, two codes were used extensively and cross-checked for agreement and accuracy. One code, written at Caltech under contract to Northrop Grumman Aerospace Systems (NGAS), is based on a Fourier propagation technique. The other, written at the University of Colorado, relies on an edge integral technique. Via these codes, we have derived more detailed requirements on the starshade shape (Fig. 9), which drive the design of the starshade. The requirements include parameters such as petal number and tip and valley truncation radii. This is one of the key areas that we will continue to mature in the next year.

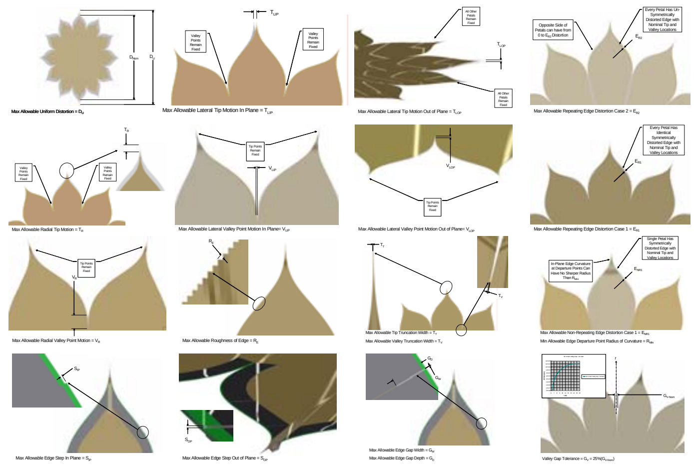


Figure 9: The starshade is tolerant to many distortions. Distortions on the shape of the starshade have been modeled using diffractive simulations and fall within the capability of existing technology. More details can be found on the NWO website.

The starshade payload must be folded up for launch due to its large diameter. NGAS, world leader in space deployables, provided the engineering that went into designing a mechanism to reliably deploy the starshade and lock it into its final shape. The payload is a passive device that only needs to maintain a specified outline. Telescoping booms constitute the only moving deployment mechanism for the starshade, while a passive, rigid edge provides the necessary shape precision for high starlight suppression. The Astro Telescoping Boom Assembly would be tailored to provide the necessary stowed/deployed lengths as well as needed stem-drive force. The boom design uses eight or nine stages; each made of thin-wall glass fiber reinforced plastic (GFRP) tubing. Tube overlap sections have doubled wall thickness for strength. At the base would be a spring-driven root hinge assembly using eddy current damper resistance to slow deployment if needed.

The edges of the starshade need to be held to a tight tolerance; this tolerance error budget is the subject of an intensive on-going study. Our preliminary findings indicate that using a fixed, solid edge gives us the best shape control. The NWO edge uses lightweight, graphite wrapped, honeycomb aluminum members that fold up on hinges to fit inside the launch vehicle. The edges ride out with the telescoping booms, as shown in Fig. 10,

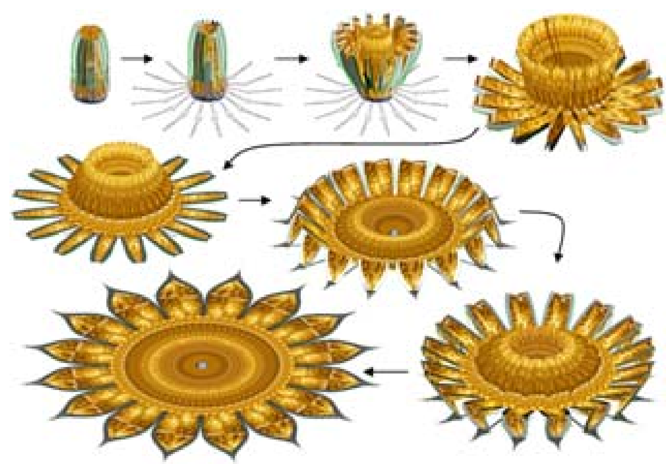


Figure 10: The stowed starshade has a high compaction ratio to fit inside the 5m EELVs. The starshade deployment uses a single powered mechanism for each petal.

and are not actively controlled; their shape is precision manufactured and assembled on the ground. The edge pieces take very little tension during launch and deployment and retain their shape on station. The thin edge (<100 micron radius of curvature) minimizes scattered light to mitigate concerns regarding sunlight scatter during an observation. The interior of the starshade is three layers of Kapton, untensioned to avoid thermal expansion issues. The three layers provide opacity and protect against micro-meteorite holes.

The three major pieces of the deployment system—telescoping tubes, thin edge, and membrane—are of high heritage. The main uncertainty is using these parts together and on a much larger scale. However, we believe we can bring the starshade deployment to TRL 6 with a very cost-effective technology demonstration program, in ~30 months. Starting with understanding the deployed starshade tolerances, we will create a design that can accommodate these tolerances. We will test each component individually and build subscale starshades to be tested in a thermal vacuum chamber. Full-scale single or multiple petal sections of the starshade may then be constructed to test for deployment precision. We will correlate these with models of the optical performance, currently being validated with laboratory testing, to ensure that the starshade will deploy, remain stable, and provide the necessary suppression for finding Earth-like planets.

The starshade space vehicle baseline design is shown in Fig. 11. The main function of the spacecraft is to move the starshade from target to target and maintain alignment during observations. The spacecraft is characterized by having a large and very capable propulsion system to provide ΔV for retargeting maneuvers. The NEXT ion propulsion system from Glenn Research Center is used for its high total lifetime fuel throughput and efficiency, enabling the greatest number of targets searched for the least mass. A 16 kW power system is used to provide power to the NEXT system (for comparison, the HST solar arrays provide 6kW). The solar arrays are deployed on a boom which has one axis degree of freedom. Due to solar array shadowing, the travel direction cannot be within 30 degrees of the sun. Fortunately, this happens less than 9% of the time and we carry an extra 3% of fuel to account for the additional travel.

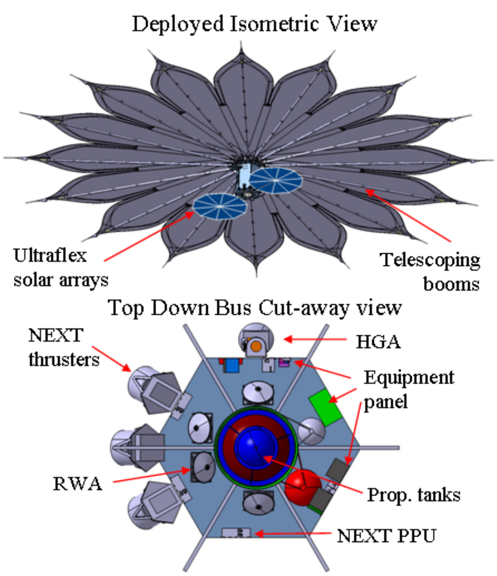


Figure 11: The starshade is a passive payload. The spacecraft bus provides high ΔV with the NEXT electric propulsion system.

Verification and validation of this large deployable is one of the main challenges of NWO. Our top-level plan is to perform unit-wise design and validation, integrated into the technology development process. Starting with the perimeter, for example, we will design and validate a tenth-scale rigid edge section to the necessary requirements. We will build on the success of this edge test by designing and validating critical edge components such as tips and valleys, and then integrate the pieces by producing full-scale pathfinders of a petal or a quarter section of the starshade, which can be environmentally tested and validated in existing, large thermal vacuum chambers. The starshade and its spacecraft are described in more detail in Appendix E, along with the NWO verification and validation strategy.

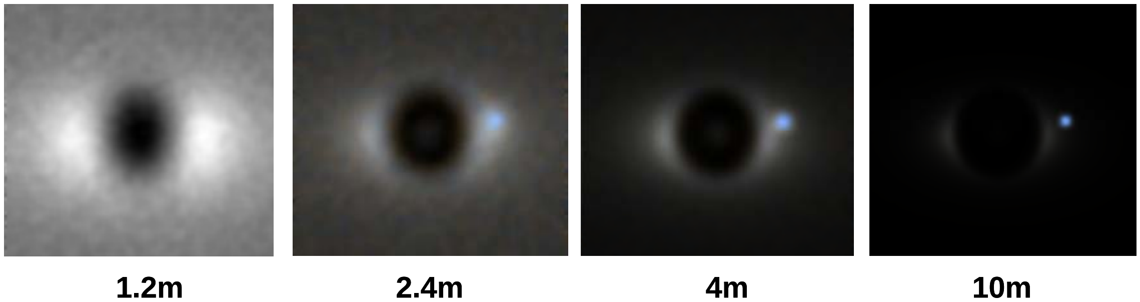


Figure 12: The use of a starshade decouples inner working angle from aperture diameter. The extended light in these images is due to exozodiacal dust, distributed as in our Solar System, and is not residual stellar light. As the aperture of the telescope increases, the image of the Earth emerges from the glow.

<u>The Telescope</u>

Fig. 12 shows a series of simulations of our Solar System viewed pole-on from 10pc using NWO. As the diameter of the telescope increases, the exoplanets emerge from the confusion. The diffraction limit on a telescope determines its resolution and hence the quality of observations of a distant system.

The baseline is a 4m telescope, sufficient to resolve the exoplanet from the background, and at the size limit for a monolithic mirror to fit inside existing launch vehicles and be fabricated in existing facilities. The whole telescope spacecraft is shown in Fig. 13. While it is larger than HST, this telescope has roughly the same tolerances. The optical design of the telescope is straightforward. This is primarily because the starlight from the target stars will be fully suppressed, so there are no special requirements on the optical train as there are for internal coronagraphic techniques. For example, segmented mirrors and any mirror coating may be used. The primary mirror configuration is still being studied (monolith vs. segmented) but our current baseline is a monolith. A 4m UV-Visible/near-IR telescope is within the state of the art for space telescopes.

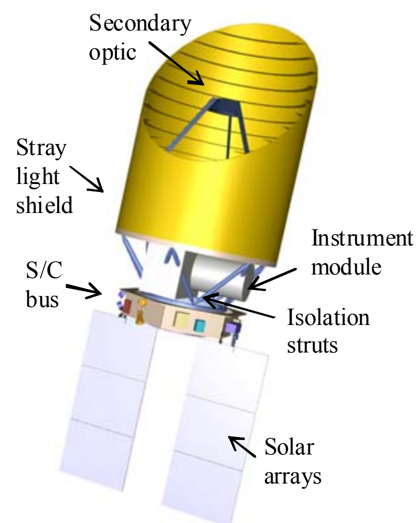


Figure 13: The starshade eliminates the need for specialized optics for high-contrast imaging in the telescope. This allows the telescope to be a true general astrophysics instrument.

Table 2: NWO Science Instruments

Name	**Primary Use**	**FOV**	**# pixels**	**Bandpass**	**Focus**	**Notes**
ExoCam	Detecting/ Imaging Exoplanets	26″ x 26″	4 x 2k x 2k	0.25-1.7 μm	Cass.	photon-counting CCDs, 6 bands simultaneously
ExoSpec	Spectroscopy of Exoplanets	10″ x 3″	500 x 150 x 728	0.25-1.7 μm	Cass.	R=100, integral field
Shadow Sensor	Fine alignment control	N/A	256 x 256	1.7-3 μm	Cass.	Pupil plane mapping
WF Camera	GA, Fine Guider	10′×20′	92k x 46k	0.4-0.9 μm	TMA	3′×3′ req. for FG
UVSpec	GA UV Spectroscopy	< 1″	16k x 256	0.12-0.5 μm	Cass.	R=30,000 – 100,000

The instruments that are carried on the telescope are described in Table 2. These include instruments that are necessary for the primary exoplanet science as well as instruments that enhance the general astrophysics capabilities of the telescope.

The baseline optical design is a modified Three Mirror Anastigmat (TMA). This design allows wide-field imaging for General Astrophysics applications and a high-quality narrow field at the Cassegrain focus (after only two mirrors). The various instrument apertures are spread around the focal plane and the light is sent into a given instrument by steering the telescope in the manner of HST. Details of the telescope instruments and the telescope spacecraft are provided in Appendix F.

Trajectory and Orbit

NWO requires two spacecraft aligned within ±1m along the line-of-sight. This is most easily accomplished if these spacecraft are in a low-acceleration environment such as the Sun-Earth L2 point, the future home of a fleet of astronomical instruments. NWO will have a six-month halo orbit around L2 as shown in Fig. 14. The baseline orbit and trajectory trade selection are in Appendix J.

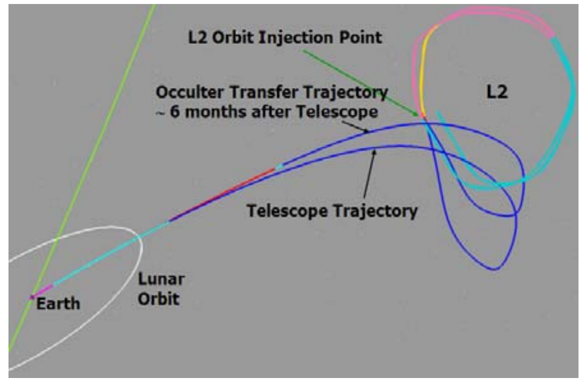


Figure 14: The benign environment of the Earth-Sun L2 point enables NWO to efficiently slew between targets and align the two spacecraft.

The telescope will follow its nominal orbit around the L2 point, performing orbit maintenance once or twice every 6 months, as usual. Due to the large separation, the starshade will have to travel many thousands of km to align with each target star. The starshade is constantly moving about the telescope; thus it is not a typical L2 orbit. We have developed a mission planner that simulates the L2 environment, includes completeness and imaging and spectroscopy exposure times for each star, and optimizes these trajectories. We find that the NEXT system can enable observations of more than 150 targets in 5 years, including imaging more than 75 stars to achieve a total completeness of 30 and taking spectra of the planets found. Typical starshade travel time between targets is 5-10 days and typical observation times range from 24 hours for imaging to 14 days for spectroscopy. Currently, we look only at first visits; we are upgrading our mission planner this year to consider revisits. Configuration of the NEXT system, performance, and trades are in Appendix I.

Obtaining and maintaining alignment of the starshade and telescope is a multi-stage process and is one of our technology tall poles. The three trajectory and alignment control (TAC) phases are: Step 1 (Coarse): maneuver the starshade to be collinear with the telescope and target star to ±50km in absolute position, guided by conventional deep space navigation techniques. For routine operations, we may switch to guidance by the optical astrometric sensor mounted on the starshade. Step 2 (Medium): the astrometric sensor on the starshade guides it closer to its required position until the starshade shadow begins to fall on the telescope – requiring ~50m accuracy at 80,000km

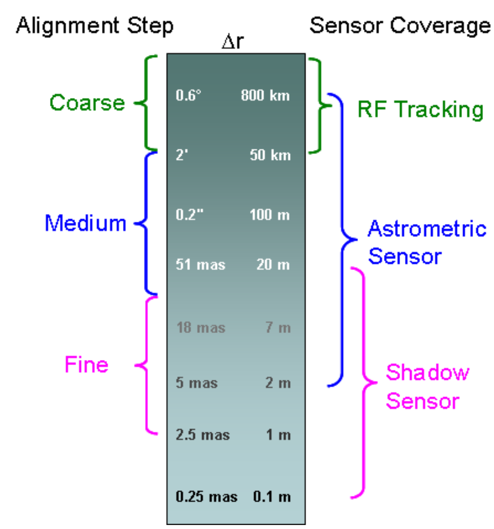


Figure 15: The three-step trajectory and alignment system provides overlapping sensor ranges to facilitate handoff.

separation. Step 3 (Fine), after that, a "shadow sensor" on the telescope measures the center of the starshade shadow and guides the starshade to keep the shadow centered on the telescope. The three phases of our TAC system are outlined in Fig. 15.

We have developed a low-risk approach for controlling starshade alignment and slewing (Noecker 2007). The astrometric sensor assembly (Fig. 16) has a small astrometric telescope at its core. This instrument observes the science telescope and measures its sky position relative to the background stars to determine its relative bearing in celestial coordinates. With astrometric catalogs, we can correlate the target star to its antipodal stars and compute where the telescope should appear among the antipodal stars. The addition of corner-cube retroreflectors turns the astrometric instrument into a sextant, which can greatly improve accuracy and efficiency. An in depth overview of the TAC system is in Appendix G.

We have adopted the Joint Milli-Arcsecond Pathfinder Survey (JMAPS) instrument as our baseline astrometric instrument. JMAPS is sensitive down to 15^{th} mag., with a single-measurement accuracy of 5mas. Combined with inter-spacecraft RF ranging, NWO's 3-D relative position will be known to a few meters laterally and a few tens of km in distance. This is enough to guide the coarse slew between stars all the way to the onset of shadowing. Details of JMAPS are in Appendix H.

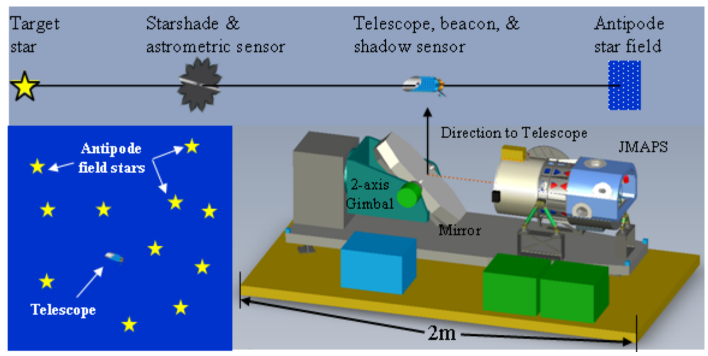


Figure 16: The astrometric sensor on the starshade observes an optical beacon on the telescope to find the telescope's location against antipodal stars for medium alignment.

At NIR wavelengths, just beyond the science bandpasses, the starshade suppression is greatly reduced and the Spot of Arago reemerges. At $\lambda = 2\mu m$, the spot is about 3m across, less than the size of the mirror. The shadow sensor, a small instrument in the telescope, examines an image of the telescope pupil at these long wavelengths, centroids on the Spot of Arago, and determines the telescope's location relative to the spot (Fig. 17). This technique can achieve a sensitivity of a few cm or less in 1sec of integration time. We find that the alignment control accuracy is limited by noise in this sensor.

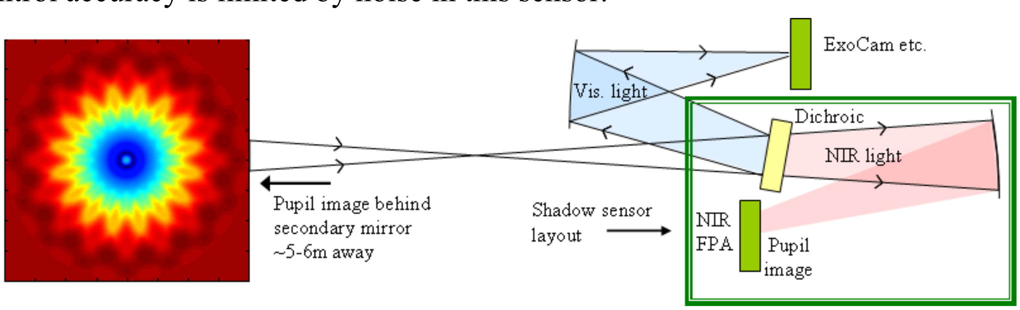


Figure 17: The shadow sensor, a pupil-plane sensor on the telescope, measures the near-IR shadow profile and determines the starshade's offset relative to the telescope.

<u>Launch and Operations</u>

We expect the NWO program to require two launch vehicles. Our current baseline is two 5m class EELVs for the telescope and starshade. We have calculated the total launch mass for each of the spacecraft, and our current NWO spacecraft design masses include a 30% margin to comply with the NASA Gold Rule GSFC–STD-1000 for Pre-Phase A. The option of launching both the starshade and the telescope on the same LV has been investigated, but we found it to be too risky. It requires stacking the two space vehicles inside the same fairing and a significant decrease in launch mass margin. Furthermore, only the Delta IV Heavy could be used, which is almost as expensive as two EELV (specifically, the Atlas) launch vehicles. We are therefore using two launch vehicles. The current spacecraft total launch masses with margin for both Science Telescope and Starshade Spacecraft are listed in Table 3. The power budget is listed in Table 4. Our launch vehicle margin, trades, and selection is detailed in Appendix K.

The starshade is scheduled to launch 6 months after the telescope, which ensures that the telescope has been properly commissioned and that, should any failures occur with the telescope, investment in the starshade is not lost and its operation can be postponed until needed. As a further risk reduction, the additional mass margin on each launch vehicle may potentially reduce the design cost of the two space vehicles, as we have a significant mass margin to be parceled out.

The NWO system comprises the following segments: 1) the Starshade Spacecraft; 2) the Science Telescope Spacecraft; 3) the Ground Segment, composed of the Science Operations Center

Table 3: NWO Observatory Mass

NWO Observatory Mass						
	Telescope Spacecraft			Starshade Spacecraft		
	CBE (kg)	Cont.	Allocation (kg)	CBE (kg)	Cont.	Allocation (kg)
Spacecraft Dry Mass	4077	30%	5300	2710	30%	3523
Propellant Mass (bi prop)	448	0%	448	476	0%	476
Propellant Mass (Xenon)	n/a	n/a	n/a	1220	0%	1220
Spacecraft Wet Mass	4525	27%	5748	4406	16%	5219
Payload Adapter Fairing	114	5%	120	114	5%	120
Separation System	49	5%	51	49	5%	51
Total Launch Mass	4688	26%	5919	4570	26%	5390

Table 4: NWO Power Budget by Phase

NWO Power by phase (W)	Launch		Commission		Science Ops		Comm. Down-link		Comm. Cross-link		Safehold		Peak			
	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.		
Telescope Payload	565.0	734.5	955.0	1241.5	1090.0	1417.0	1090.0	1417.0	400.0	520.0	565.0	734.5	1270.0	1651.0		
Telescope S/C	137.5	178.8	614.4	798.7	648.7	843.3	664.1	863.3	848.6	1103.2	473.8	615.9	342.7	445.5		
Totals (W)	702.5	913.3	1569.4	2040.2	1738.7	2260.3	1754.1	2280.3	1248.6	1623.2	1038.8	1350.4	1612.7	2096.5		
	Launch		Commission		Science Ops		Retargetting		Comm. Down-link		Comm. Cross-link		Safehold		Peak	
	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.	Estimate	Alloc.
Starshade Payload	0.0	0.0	73.0	94.9	73.0	94.9	73.0	94.9	54.0	70.2	7.0	9.1	21.9	28.5	112.0	145.6
Starshade S/C	93.1	121.0	282.9	367.8	267.9	348.3	14923.9	16468.9	507.9	660.3	267.9	348.3	298.4	387.9	15878.4	20641.9
Totals (W)	93.1	121.0	355.9	462.7	340.9	443.2	14996.9	16563.8	561.9	730.5	274.9	357.4	320.3	416.4	15990.4	20787.5

(SOC), the Mission Operations Center (MOC), the Flight Dynamics Facility (FDF); and 4) the Deep Space Network (DSN). Coordinated operation for exoplanet science requires a single operations team to operate the two spacecraft as a single instrument. Each spacecraft will have its own operations team at launch; these teams may be consolidated into a single team during the exoplanet-observation commissioning phase. NWO has the potential to downlink large volumes of data – up to 2.5Tbits per day from the wide-field camera in the most ambitious scenario. This drove the architecture to include the DSN Ka-band capability, which can receive data at rates up to 150Mbps. The general astrophysics operations phase of the mission is expected to be similar to HST and JWST. The science operations for NWO are located at the Space Telescope Science Institute (STScI), which is eminently capable of supporting a world-class space observatory. Because of the tight connection between science and mission operations, the mission operations are also located at the STScI. More details of the operations of the starshade can be found in

Appendix L.

VII. TECHNOLOGY DRIVERS

We have reviewed the status of the technology needed to build and fly NWO in the coming decade with well-controlled risks. Our technology development roadmap is shown in Fig. 18, and is the subject of another Astro2010 white paper (Starshade Technology Development). The development of the NEXT thrusters is not shown on our roadmap, as it is funded already. NWO only needs potential lifetime extension testing.

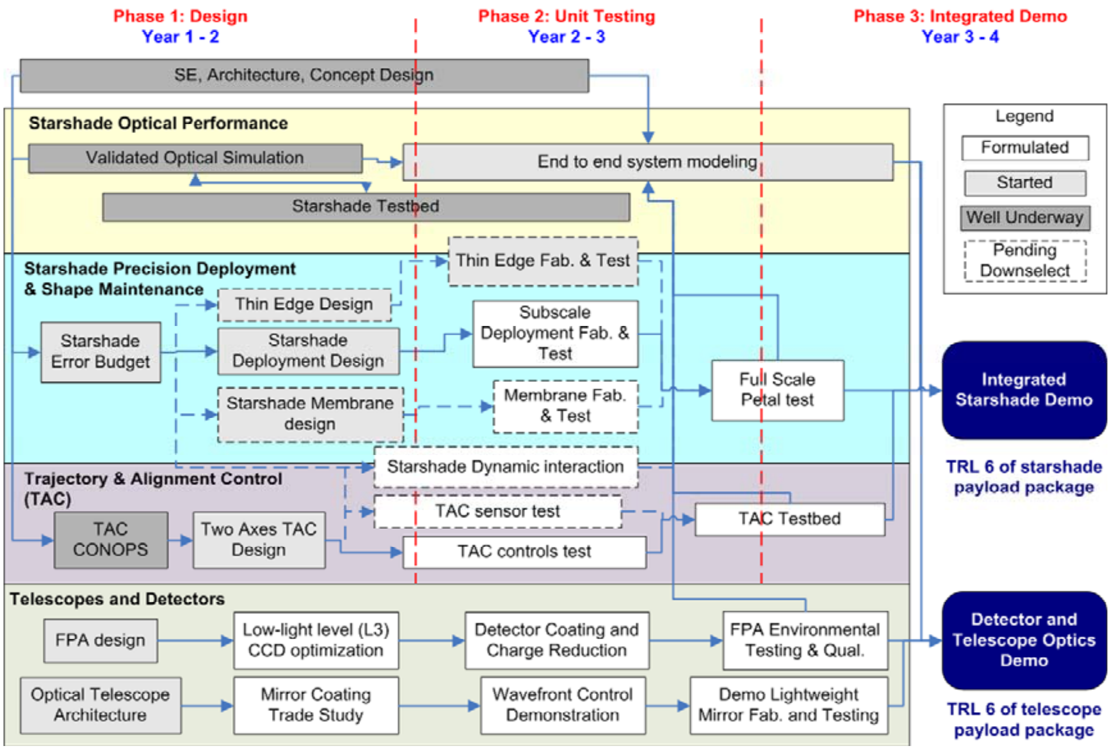


Figure 18: Many of these elements in this technology roadmap have been started. We expect the bulk of this development to be finished within 3 years from start.

Of these, only 'Starshade Deployment and Shape Maintenance' is both crucial to the success of the mission and new, in that nothing of a similar shape and precision has been built before. All the other tall poles have alternatives – technical offramps that would still allow the mission to go forward, albeit at modified performance or cost. We estimate the development of the necessary technology for NWO to TRL 6 can be achieved within 3 years, with a budget of ~$65M. Further details of the Technology Development for NWO are in Appendix O.

VIII. MANAGEMENT

We have shown in this document that the New Worlds Observer is in good shape technologically and scientifically and is ready to go in the near term. The management plan is written in Appendix M with this direct implementation in mind. We have provided a summary of the costing exercises in Appendix M as well. Our main costing efforts were centered on a full-up baseline mission in the manner of HST and JWST. We have also provided some scaled-down numbers for reduced cost that can still address much of the core science (see Appendix M).

For the proposed NWO facility-class mission implementation, we would expect the management structure to follow a NASA "top-down" approach where the mission goals are identified and delineated by the Science Mission Directorate Exoplanet Program Office based on community input from National Academies studies, such as this Decadal Survey, as well as other advisory groups. A proposed organization is shown in Figure 19. Some or all of the individual instruments on NWO would be competed. Industry partners would be competed for selection of other mission components, for example, the telescope, spacecraft, and starshade developments, with some mission elements developed in-house or managed by NASA Centers. The overall project management would be assigned to a NASA Center. A project scientist would oversee the NWO science program with the science working group and science team.

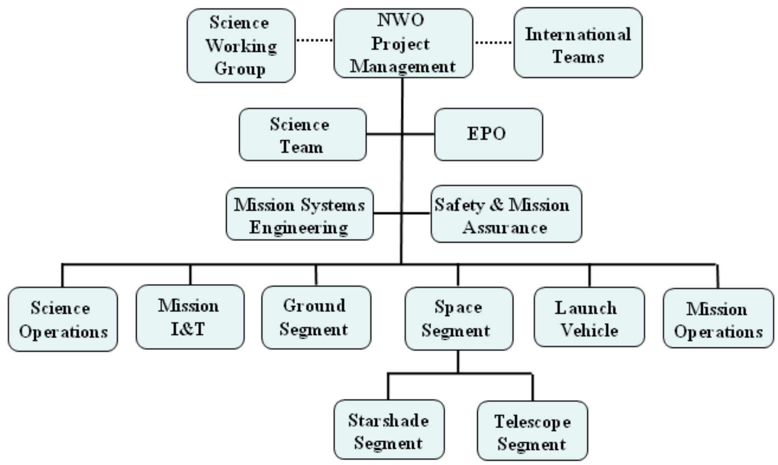


Figure 19: New Worlds Observer Proposed Project Organization

IX. COST

New Worlds Observer is in good shape technologically and scientifically and is ready to start development in the near term. Our main costing efforts were centered on a full-up baseline mission in the manner of HST and JWST.

Costing is particularly difficult and yet is crucial to the success of the NASA science program. We have studied the cost in several independent ways: NWO team grassroots, GSFC Integrated Design Center (IDC) PRICE-H parametric and grassroots, and GSFC 70% confidence level estimates, all developed in 2008 during the study. The GSFC Science Directorate also generated a parametric and 70% confidence level cost estimate that are included near the end of this section. We have attempted to use

Table 5: Mission Cost Element Summary in 2008 fixed year M$.

Cost Elements	Base	With contingency
Total for Telescope	**1082**	**1406**
telescope	384	499
exocam	100	130
exospec	100	130
COS	80	104
IFS	80	104
spacecraft	198	257
beacons	4	5
GA instrument (WFC)	136	177
Total for Starshade	**474**	**617**
starshade	140	182
spacecraft	236	307
astrometric sensor	59	77
astrometric system	39	51
Total Science and Technology	**156**	**203**
Science Algorithms	91	118
Technology	65	85
Total Mission Ops, Ground Development, System I&T	**120**	**155**
Mission Operations	41	53
Ground System Development	44	57
System I&T	35	46
Mission Wrappers	**244**	**466**
PM,SE,SMA	240	312
Funded Schedule Slack	0	150
EPO	4	4
Total Phase A-D	**2076**	**2847**
Launch Vehicle	**380**	**380**
Phase E (Nominal OPS for 5 years)	**400**	**459**
Science	325	374
Ground Development	1	1
Mission Operations	65	75
EPO	9	9
Grand Total	**2856**	**3686**

Table 6: NWO Baseline Cost Summary

		Phase A				Phase B				Phase C/D								Phase E								TOTALS	
WBS #	WBS Element	FY2010	FY2011	Total	Total RY	FY2012	FY2013	Total	Total RY	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	Total	Total RY	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	Total	Total RY	FY$	RY$
1.0	Project Management	4	3	7	8	4	5	9	10	10	12	14	13	12	4	64	79							0	0	80	97
2.0	System Engineering	4	3	7	8	4	5	9	10	10	12	14	13	12	4	64	79							0	0	80	97
3.0	Safety & Mission Assurance	4	3	7	8	4	5	9	10	10	12	14	13	12	4	64	79							0	0	80	97
4.0	Science /Technology	9	26	35	38	30	13	43	48	15	12	12	12	12	15	78	98	35	65	65	65	65	30	325	467	481	631
5.0	Payload	48	48	96	103	61	71	133	150	158	189	180	165	161	40	893	1112							0	0	1122	1365
6.0	Spacecraft	27	19	46	49	21	21	42	47	35	38	92	85	69	27	346	436	0	0					0	0	434	532
7.0	Mission Ops	2	2	4	4	4	4	8	9	5	5	5	6	6	2	29	37	15	15	15	8	8	4	65	92	106	142
8.0	Launch Vehicle	11	7	18	19	12	12	24	27	241	30	30	20	10	7	338	405	0	0	0	0	0	0	0	0	380	451
9.0	Ground Dev	1	1	1	1	1	1	1	1	7	8	9	8	6	5	42	52	0	0	0	0	0	0	1	2	45	56
10.0	System I&T			0	0		3	3	4	4	5	6	6	7	5	33	41	0						0	0	33	44
11.0	EPO			0	0			0	0						4	4	5	2	2	2	2	2	2	9	13	13	18
	Subtotal SMD Mission Cost	109	112	221	237	141	139	280	316	495	321	376	341	306	114	1954	2424	52	82	82	74	74	35	400	573	2856	3530
	Reserves (30% A-D; 15% E)	29	32	61	65	39	38	77	87	76	87	104	96	89	31	483	604	8	12	12	11	11	5	59	84	680	840
	Funded Schedule Slack					5	5	10	11	5	10	28	41	38	18	140	179							0		150	190
	Total SMD Mission Cost	138	144	282	302	184	182	366	414	576	419	508	478	433	163	2577	3206	60	94	94	85	85	41	439	657	3686	4580

the most conservative path when in doubt, and the relatively advanced state of the key technologies gives us lower cost risk than is often encountered. We were not surprised to find that a flagship mission costs are high like those of predecessor missions. Further into the development of NWO we would expect to invite international participants, for example ESA and JAXA. Their contributions would reduce the total cost to NASA.

The following assumptions were made in developing the baseline mission cost. The Project start is in fiscal year 2010, with a Phase A duration of 18 months, Phase B duration of 24 months, Phase C/D duration of 60 months, and a Phase E duration of 60 months. Two spacecraft vendors will build separate spacecraft in parallel. Specialized test facilities at NGC are required for the starshade. Two Atlas launch vehicles are needed with the telescope launch in June 2019 and the starshade launch in February 2020. Funded schedule reserve is included in the budget: 14.3 months of reserve on the critical path. Costing reserves include 30% applied at the mission level (Phase A-D) excluding EPO and LV, and 15% applied to Phase E.

In order to provide a simple way to see why NWO numbers are as they are, we present Table 5 which is a breakout of our baseline mission cost by cost elements. We have broken out separate costs for the telescope and starshade, science and technology, total mission operations, ground development and systems I&T, and mission wrappers (PM, SE, SMA). We delineate the Phase A-D and Phase E costs with and without contingency. The Phase A-D costs without contingency: the total telescope/instrument cost with spacecraft is $1.1B, including costs for the general astrophysics (GA) instruments; the total starshade system with spacecraft cost is $474M; total science and technology is $156M; the total mission operations, ground system development and I&T costs are $120M, PM/MSE/SMA costs are $240M, and EPO at $4M. The subtotal cost for Phases A-D is $2.1B without contingency. The cost for two EELV (Atlas launch vehicles) is $380M. The total Phase E cost is $400M and includes science, ground system support, mission operations and

EPO. One can see that the total price for the mission is in the vicinity of $3.7 Billion, significantly less than JWST.

The baseline mission detailed cost summary for the 4-meter telescope with a 50-meter starshade in fixed year 2008 dollars is shown in Table 6, with and without reserves and shows the funded schedule reserve. The table also includes totals in fixed year 2008 and real year dollars. These cost estimates were developed using results from the GSFC IDC, NWO team grassroots, parametric, and ROM cost methods. Some particulars of the 2008 fixed year dollar budget are discussed next. The total science cost estimate is $416M and includes developing science algorithms and executing the science program during the operations phase. The science budget for development of science requirements, etc., during Phases A-D is $91M. The Phase E science operations budget is $325M. The Phase E science operations cost breakdown is as follows: $200M ($40M per year) for mission scheduling, data processing operations, calibration and hardware support, computing facilities and IT needs, science management and GA program management: $125M for the science community (roughly $25M per year). The technology development budget is $65M to bring technologies to TRL 6 prior to mission PDR in 2013.

The Science Directorate at GSFC also generated a mission-level S-curve cost estimate for comparison. A parametric point estimate and 70% confidence level (CL) estimate were generated for NWO in March of 2009. Launch vehicle and grassroots instrument costs were used in the model. Information on the NWO hardware from the IDC studies was used. Mission wrappers (percent of flight hardware) and 30% reserves were applied. The parametric cost estimate with reserves is $3.4B in 2008 fixed year dollars. The 50% CL estimate is $3.7B and the 70% CL estimate is $4.0B.

The NWO mission baseline cost with contingency is $3.7B which matches the 50% CL estimate generated by the GSFC Space Sciences Directorate. This result means that there is a 50% chance that NWO will cost $3.7B or less. NASA Headquarters prefers the cost risk to be more in line with the 70% CL.

X. Project Schedule

Figure 20 shows the NWO baseline mission schedule. The planned operational lifetime of the NWO mission is 5 years, project start in 2010, Phase A duration of 18 months, Phase B duration of 24 months, 60 month development period, two spacecraft vendors building separate spacecraft in parallel, specialized test facilities for the starshade development, separate launch vehicles for both spacecraft (telescope launch June 2018 and the starshade launch February 2019), 60 months of operations (i.e., Phase E primary mission), and 14.3 months of funded schedule reserve on the critical path.

Reviews will be conducted according to the NASA Procedural Requirements (NPR) document 7120.5D. Integrated Independent Reviews (IIRs) and Critical Milestone Reviews of the NWO project will be conducted. The IIRs are used to evaluate the status of a flight project at the mission system level and at the major system element level (i.e., spacecraft, instrument(s), and ground system). The results of the EPRs constitute a key input to the IIRs. Milestones and key decision points (KDPs) consistent with NPR 7120.5D will be implemented. Project-level reviews include the mission definition review (MDR), system definition review (SDR), preliminary design review/confirmation review (PDR/CR), critical design review (CDR), system integration review (SIR), mission operations review (MOR), pre-environmental review (PER), flight operations review (FOR), pre-ship review (PSR), and launch readiness review (LRR).

The schedule critical path lies along the telescope/payloads/spacecraft part of the schedule.

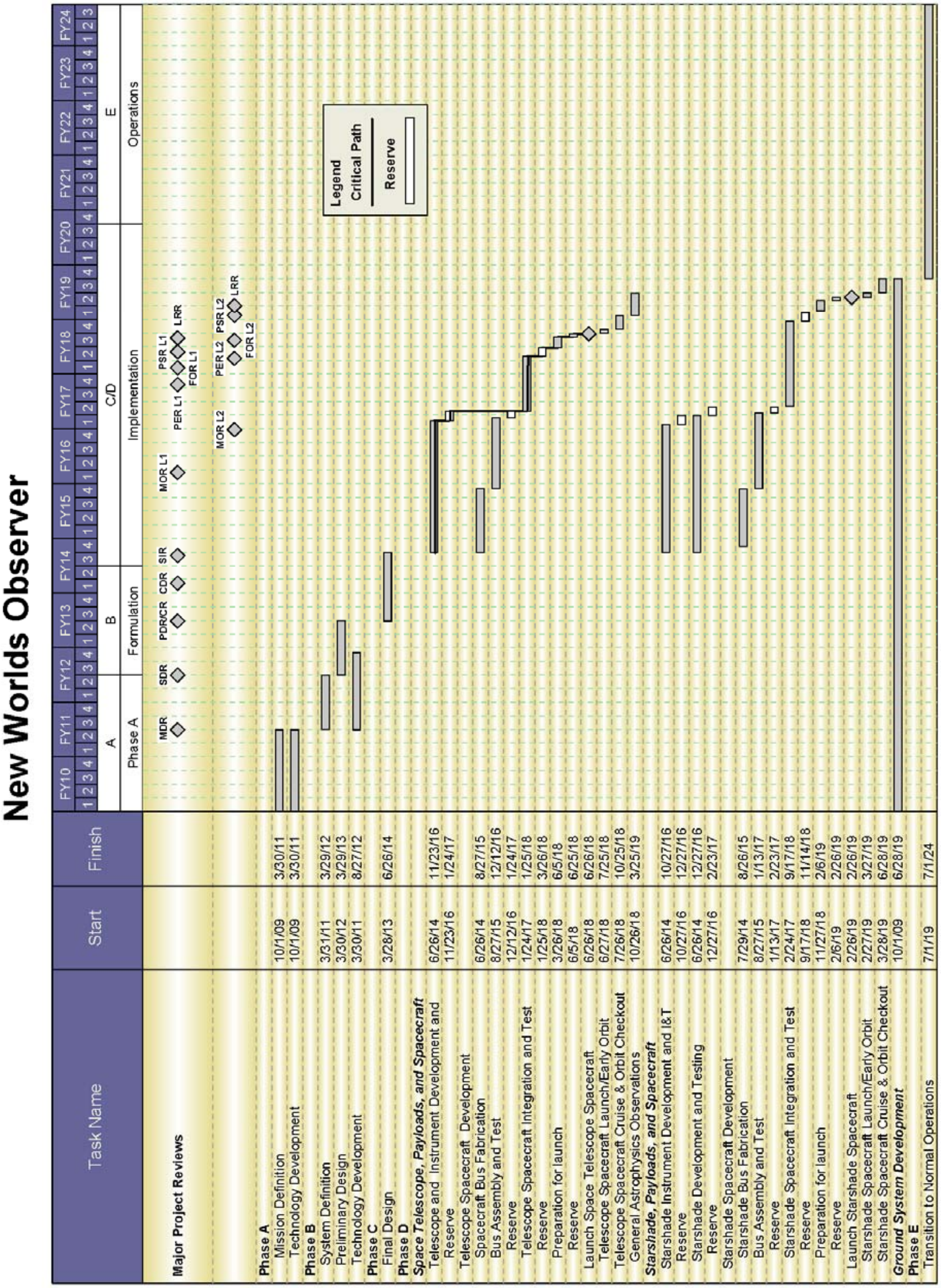


Figure 20. New Worlds Observer Baseline Mission Schedule

The telescope and instrument development and integration and test (I&T) are allocated 630 days. The telescope spacecraft development is 644 days. The telescope spacecraft integration and test is 263 days. The telescope spacecraft launch and early orbit checkout is 21 days, and cruise to the L2 orbit and checkout is 66 days. During this time general astrophysics observations can be conducted.

The starshade/payloads/spacecraft will be developed by a separate vendor from the telescope/payloads/spacecraft but will be developed in parallel. The starshade instrument development and I&T is 611 days. Starshade development and testing is 654 days. The starshade spacecraft development/testing is 644 days. Starshade spacecraft I&T is 407 days. Starshade spacecraft launch/early orbit checkout is 21 days and the cruise to L2 orbit and checkout is 67 days. The starshade launch is approximately 8 months after the telescope launch. The transition to normal operations is July 2019 with the mission operating five years.

The NWO schedule includes a total of 14.3 months of schedule reserve along the critical path, and exceeds the GSFC recommendations (GPR 7120.7) by about 3 months. There is 6.2 months of reserve on the critical path for the telescope and instrument development and integration and test, spacecraft bus assembly and test, and telescope spacecraft integration and test, and preparation for launch. The starshade, payloads and spacecraft have 8.1 months of reserve. The NWO budget includes funding for this schedule reserve and is $150M in 2008 fixed year dollars.

The NWO mission concept was reviewed by a panel convened for a Technical Assessment Review (TAR). The panel was chaired by Dennis Andrucyk, and chosen to cover the technical areas pertinent for NWO. The NWO team presented the mission concept to them over a 3-day period in November of 2008. The TAR panel's final report is included in Appendix S.

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The NWO ASMCS Study Report & Appendices are at: http://newworlds.colorado.edu/