Astro2010 PPP RFI Response

THE NEW WORLDS OBSERVER

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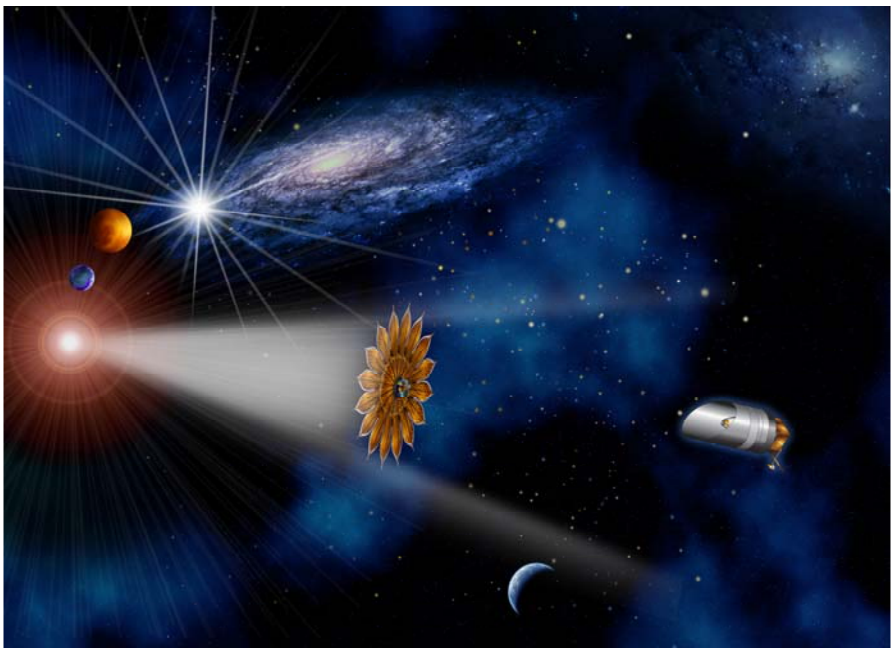
If habitable planets are common, NWO will discover them.
If life in the Universe is abundant, NWO will find it.



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I. SUMMARY

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).

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, but detecting their existence is just the beginning: only spectroscopy of planets in the habitable zones of dozens of stars can 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 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.

The NWO mission is illustrated in Fig. 2. Two launch vehicles take the 50 m starshade and the 4 m telescope to L2, where they enter a halo orbit. The two spacecraft are separated by ~80,000 km. 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 150 cycles over a 5 year mission.

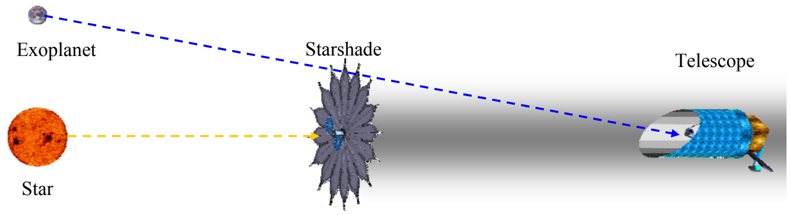

Figure 1: NWO's cost-effective starshade shadows the telescope from the star, while light from a terrestrial exoplanet passes the edge of the starshade unimpeded.

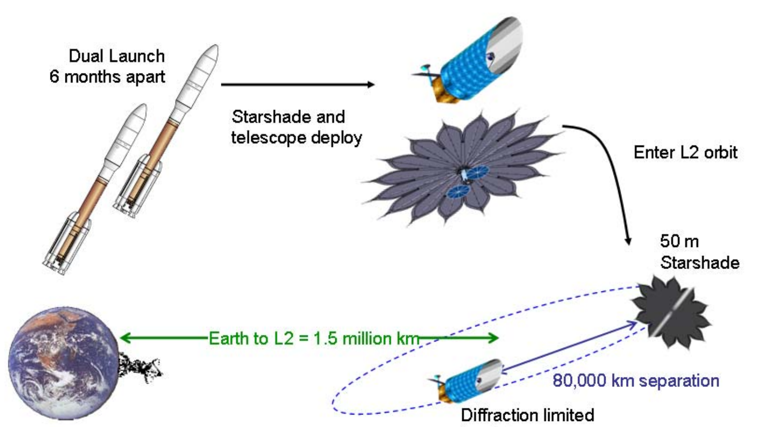

Figure 2: Employing existing technology, NWO uses a 4 m telescope and a 50 m starshade orbiting around the Sun-Earth L2 point to image and characterize terrestrial planets.

This whitepaper is based on the results of the Astrophysics Strategic Mission Concept Study for New Worlds Observer. Reports giving extensive details on the mission can be found at http://newworlds.colorado.edu

II. 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.

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 suppression. 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 1.5 AU) 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 1 AU, 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 - 60 mas. 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 to 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 goes as $L_*^{1/2}$ while the latter goes as $1/L_*$.

With IWA~50 mas 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.

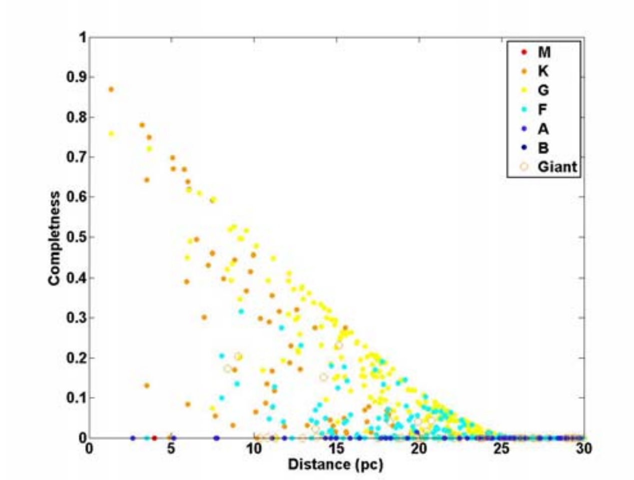

Figure 3: The completeness for the NWO target stars versus their distance. There are ~100 stars with an appreciable chance of finding a HZ-resident planet, most of which are early-K to F stars.

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.

<u>2) Characterization</u>

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 on the size of the planet, the distance between the planet and the star, the composition and structure of the planet's atmosphere and surface, the wavelength of the observation, etc.

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).

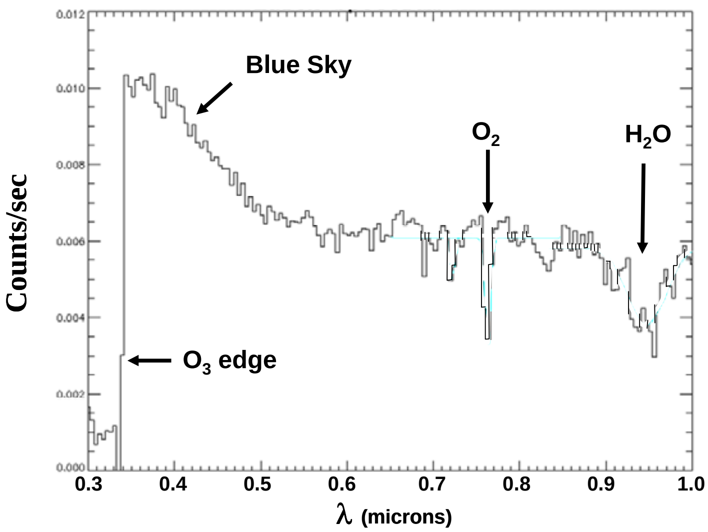

Figure 4: The spectrum of the Earth at 10 pc as seen by NWO. Note the prominent water and oxygen absorption lines and the ozone edge in the near UV.

A simulated spectrum of the Earth at 10 pc, 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 the presence of ice and gas giants in long-period orbits in mature planetary systems, estimates of disk lifetimes, etc. 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.

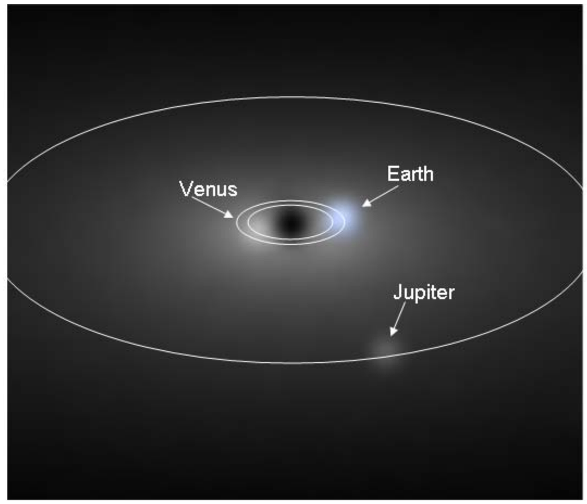

Figure 5: The exozodiacal light can help estimate the inclination of the system and therefore constrain planet orbits. This image shows a simulation of a hypothetical system with three planets – Venus, Earth and Jupiter. The exozodiacal light has total brightness equal to our own, but is more spatially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

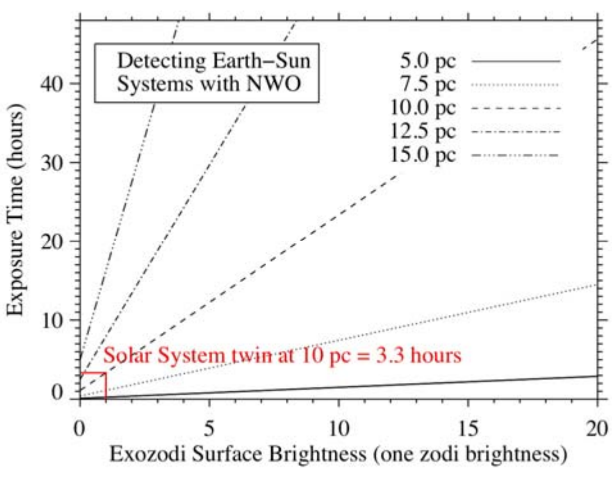

Figure 6: Time to detect an Earth-like planet in the HZ at S/N=10 vs. exozodi surface brightness (in units of zodi). Time to detect an Earth-like planet in a Solar System twin is in red.

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 in 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 10 pc viewed at a 60^o 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.

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 4 m 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 2 m-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.

III. TECHNICAL OVERVIEW

The Starshade

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.

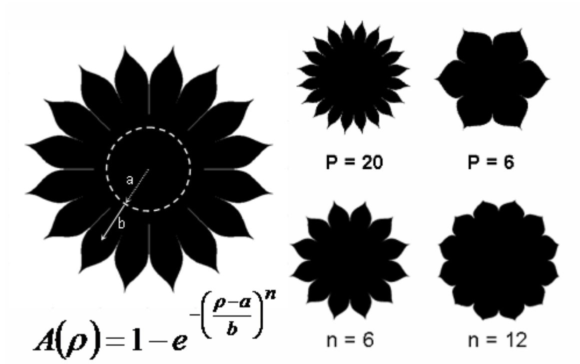

Figure 7: The apodization function, A(ρ), describes the shape of the starshade and can be optimized for suppression level, wavelength range, shadow size, and IWA.

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) = 50 m (the effective diameter), operating ~80,000 km from a 4 m telescope is capable of 10^{10} starlight suppression within 50 mas for wavelengths from 0.1 to 1 µm. 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 wavelengths.

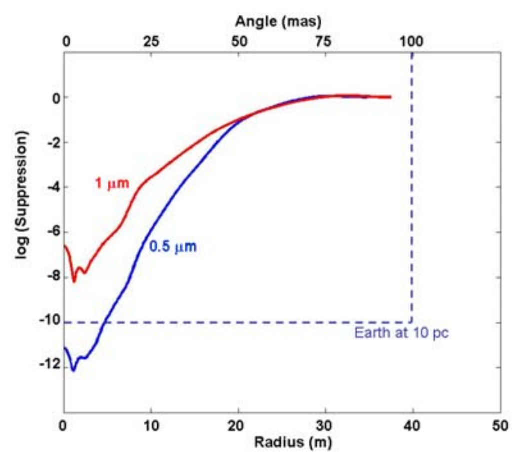

Figure 8: Light suppression falls by >ten orders of magnitude across a shadow radius of just 20 m, allowing observations of planets as close as 50 mas.

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 10 ppm 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.

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. Deployment and shape maintenance of the starshade is one of our technology tall poles and is described in the next section.

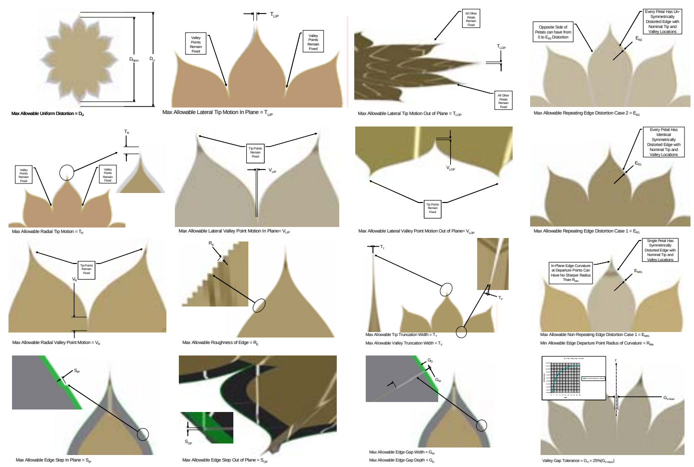

Figure 9: The starshade is tolerant to many distortions. Distortions on the shape of the starshade have been modeled using diffractive simulations and fall within the capability of existing technology. More details can be found on the NWO website.

The starshade space vehicle baseline design is shown in Fig. 10. 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 6 kW). 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.

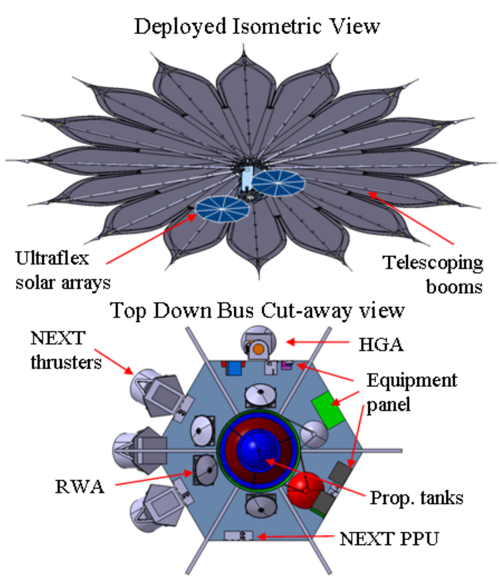

Figure 10: The starshade is a passive payload. The spacecraft bus provides high ΔV with the NEXT electric propulsion system.

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.

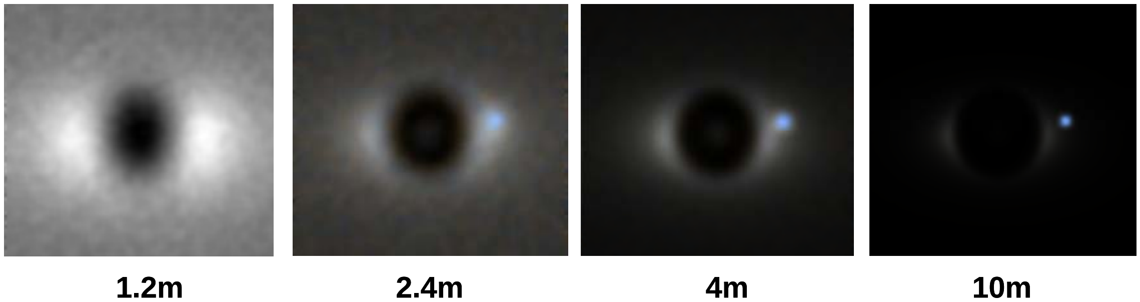

Figure 11: The use of a starshade decouples inner working angle from aperture diameter. The extended light in these images is due to exozodiacal dust, distributed as in our Solar System, and is not residual stellar light. As the aperture of the telescope increases, the image of the Earth emerges from the glow.

The Telescope

Fig. 11 shows a series of simulations of our Solar System viewed pole-on from 10 pc 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.

We have chosen to baseline a 4 m telescope for its ability to resolve the exoplanet from the background, and because it is the breakpoint for a monolithic mirror fitting inside existing launch vehicles and using existing facilities. The whole telescope spacecraft is shown in Fig. 12. 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 4 m UV/Optical/near-IR telescope is within the state of the art for space telescopes.

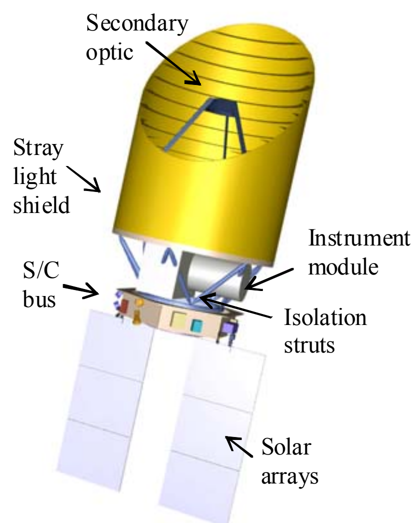

Figure 12: The starshade eliminates the need for specialized optics for high-contrast imaging in the telescope. This allows the telescope to be a true general astrophysics instrument.

The instruments that are carried on the telescope are described in Table 1. These include instruments that are necessary for the primary exoplanet science as well as instruments that enhance the general astrophysics capabilities of the telescope.

Table 1: 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

We chose a modified Three Mirror Anastigmat (TMA) as the baseline optical design. This design allows wide-field imaging for General Astrophysics applications and a high-quality narrow field at the Cassegrain focus. 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

Trajectory and Orbit

NWO requires two spacecraft aligned within ±1 m 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. 13.

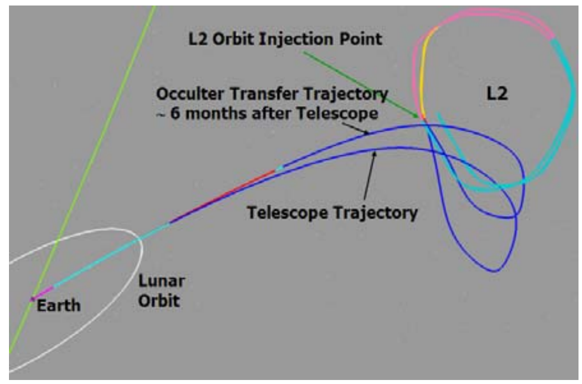

Figure 13: The benign environment of the Earth-Sun L2 point enables NWO to efficiently slew between targets and align the two spacecraft.

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. In essence, the starshade is constantly moving about its orbit at L2, 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.

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: maneuver the starshade to be collinear with the telescope and target star to ±50 km 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: the astrometric sensor on the starshade guides it closer to its required position until the starshade shadow begins to fall on the telescope – requiring ~50 m accuracy at 80,000 km separation. Step 3, at this point, 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. Development of the sensors and algorithms for the TAC system is one of the technology tall poles of NWO and is discussed in more detail in the next section.

Launch and Operations

We expect the NWO program to require two launch vehicles. Our current baseline is two 5 m 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 2. The power budget is listed in Table 3.

Table 2: 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 3: 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

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 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 (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 2.5 Tbits 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 150 Mbps. 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.

IV. 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. 14, 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.

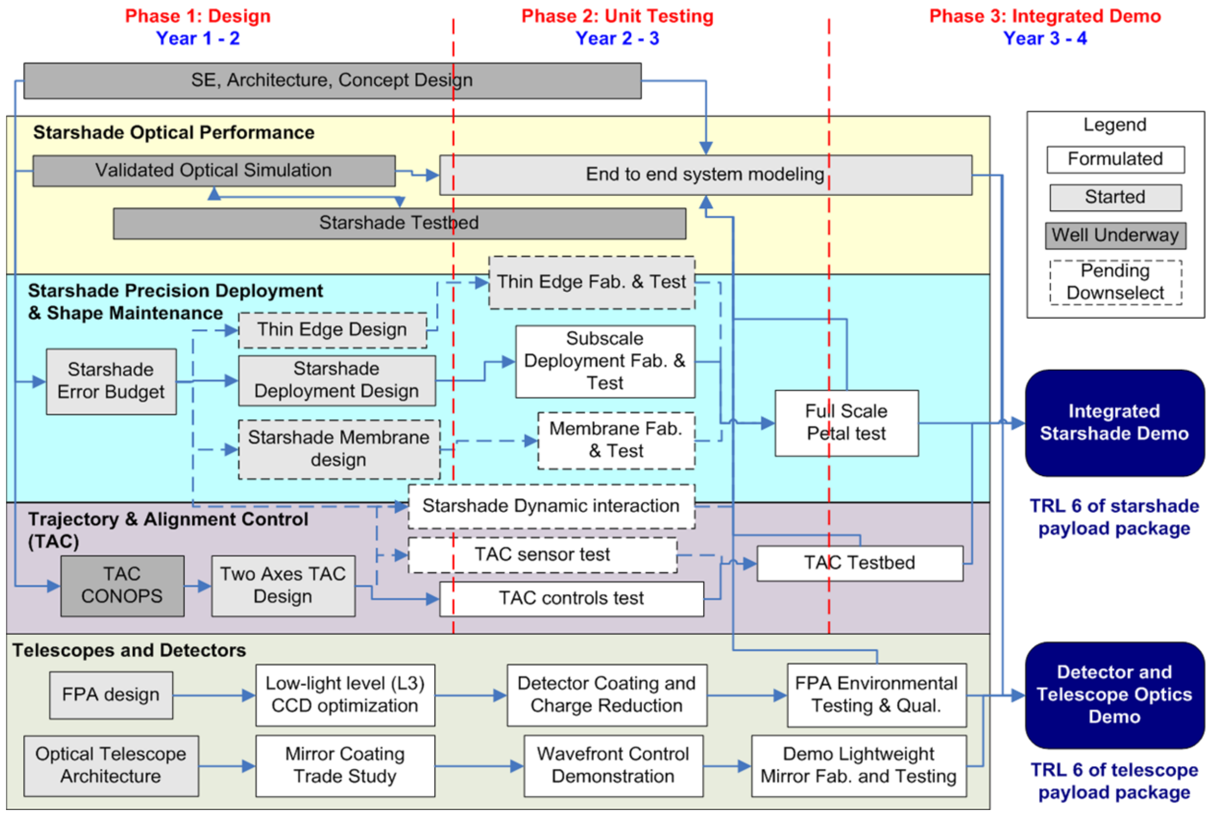

Figure 14: Many of these elements in this technology roadmap have been started. We expect the bulk of this development to be finished within 3 years from start.

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 (see Starshade Technology Development white paper). A top-level budget for NWO technology development is shown in Table 4.

Table 4: NWO Technology Development: Current TRL Level, Budget, and Top-Level Schedule in $M

	TRL	2011	2012	2013	Total
1. Starshade Optical Performance	*4*	2	3		**5**
2. Starshade Deployment & Shape Maintenance	*4*	3	10	14	**27**
3. Trajectory and Alignment Control	*5*	1	4	5	**10**
4. Photon Counting Detectors	*4*	2	4	6	**12**
5. 4m Telescope	*5*	1	3	5	**9**
6. Electric Propulsion	*5*		2		**2**
Total		**$9M**	**$26M**	**$30M**	**$65M**

Starshade Precision Deployment and Shape Maintenance

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 is shown in Fig. 15 and 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.

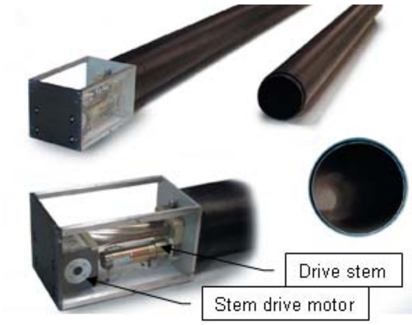

Figure 15: TRL 9 stem-driven booms enable reliable starshade deployment.

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. 16, 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.

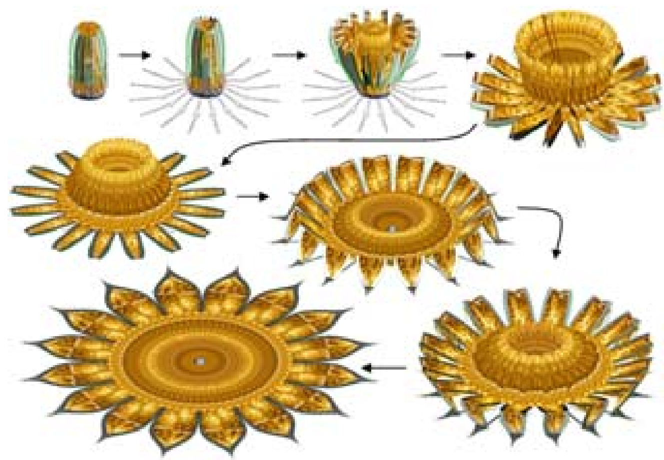
Figure 16: The stowed starshade has a high compaction ratio to fit inside the 5 m EELVs. The starshade deployment uses a single powered mechanism for each petal.

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, lasting ~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.

Trajectory and Alignment Control

We have developed a low-risk approach for controlling starshade alignment and slewing (Noecker 2007). The three phases of our TAC system are outlined in Fig. 17. The astrometric sensor assembly (Fig. 18) 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.

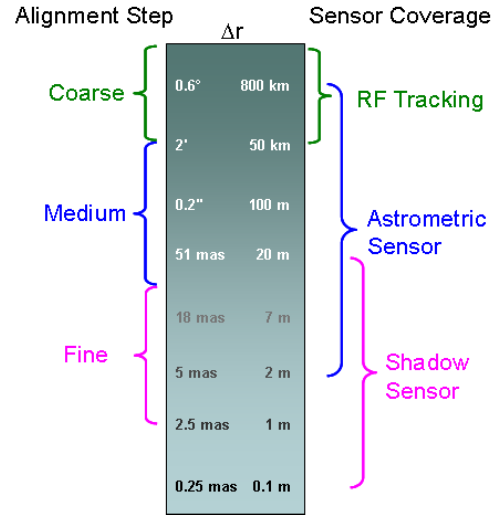

Figure 17: The three-step trajectory and alignment system provides overlapping sensor ranges to facilitate handoff.

We have adopted the Joint Milli-Arcsecond Pathfinder Survey (JMAPS) instrument as our baseline astrometric instrument. JMAPS is sensitive down to 15th mag, with a single-measurement accuracy of 5 mas. 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.

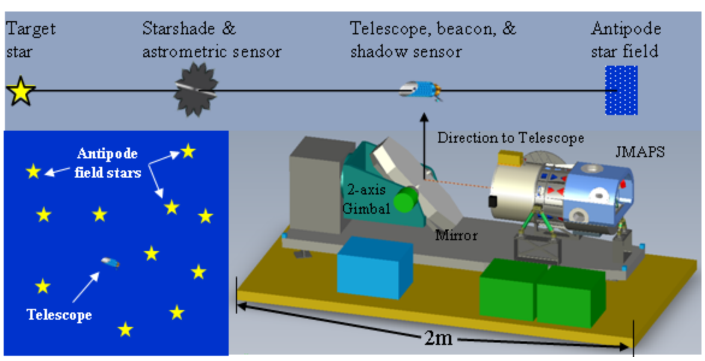

Figure 18: The astrometric sensor on the starshade observes an optical beacon on the telescope to find the telescope's location against antipodal stars for medium alignment.

At NIR wavelengths, just beyond the science bandpasses, the starshade suppression is greatly reduced and the Spot of Arago reemerges. At $\lambda = 2$ μm, the spot is about 3 m 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. 19). This technique can achieve a sensitivity of a few cm or less in 1 sec of integration time. We find that the alignment control accuracy is limited by noise in this sensor.

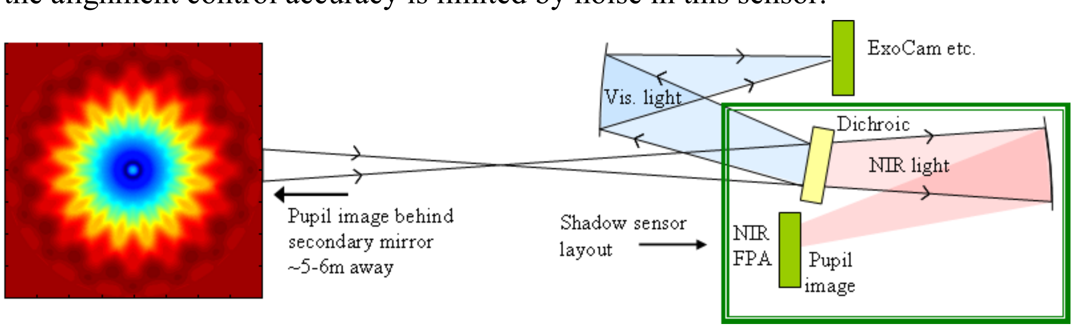

Figure 19: The shadow sensor, a pupil-plane sensor on the telescope, measures the near-IR shadow profile and determines the starshade's offset relative to the telescope.

V. ORGANIZATION, PARTNERSHIPS, CURRENT STATUS

The concept discussed in this paper was originally developed in 2004 as the New Worlds Explorer, with funding from the NASA Institute for Advanced Concepts (NIAC). The concept was matured further through a NIAC Phase II follow-on award and donated contributions from team member organizations through April 2008, when NWO was awarded the NASA Astrophysics Strategic Mission Concept Study (ASMCS) for a flagship mission deemed appropriate for the coming decade. The team that coalesced around the ASMCS includes approximately 43 people at eight institutions under the management of GSFC. It brought together a wide range of expertise in all the crucial areas to address this unique design and study problem.

Table 5: The NWO Team

Organization	NWO Responsibilities	Unique Capabilities	Relevant Experience
University of Colorado	▪ PI ▪ Science Operations ▪ Science Team ▪ Optical Design ▪ Systems Analysis ▪ EPO	▪ Space Science Mission Development	▪ PI for HST Cosmic Origins Spectrograph (COS) ▪ Optical Design for Far Ultraviolet Spectrographic Explorer (FUSE) ▪ Cassini, Gallileo ▪ MESSENGER
GSI	▪ Lead Scientist		
NASA Goddard Space Flight Center	▪ Science Team ▪ Project Management ▪ Mission Systems Engineer ▪ Safety & Mission Assurance ▪ Space & Ground Segment Manager ▪ Mission Operations Manager ▪ Flight Dynamics ▪ Instruments ▪ Telescope	▪ Space Science Program Management ▪ Space Flight Mission Operations ▪ Space Flight Project Management ▪ Instrument Dev. and Management	▪ HST ▪ GLAST ▪ JWST ▪ SWIFT ▪ WMAP ▪ SDO ▪ EOS ▪ GOES ▪ JDEM ▪ Many more
NASA Glenn Research Center	▪ Propulsion Systems	▪ Advanced Propulsion Technology Dev.	▪ NEXT Development Program
Northrop Grumman Aerospace Systems	▪ Deployable Occulter Mission Design ▪ Deputy PI ▪ Starshade Manager ▪ Launch System Manager ▪ Science Team	▪ Large Scale Deployable Space Structures	▪ Chandra ▪ TDRSS ▪ EOS Aura/Aqua ▪ Classified Programs
Ball Aerospace	▪ Spacecraft Bus Trajectory and Alignment Control ▪ Telescope Manager ▪ Payload Manager ▪ Instruments	▪ Spacecraft Buses for Deep Space Missions	▪ Deep Impact ▪ Kepler ▪ Chandra Aspect Camera
USNO	▪ Alignment Sensor	▪ Astrometry ▪ Instrumentation	▪ Joint Milliarcsecond Pathfinder Survey Mission
University College of London	▪ Science Team	▪ Exoplanet spectral modeling	▪ ESA ExoPlanet Roadmap Advisory Team ▪ Group coordinator for ExoPlanet atmospheres ▪ Co-I for ExoPlanet obs on VLT-Crires, IRTF, Spitzer, Hubble ▪ TPF-C, TPF-I/Darwin, SEE-Coast Concepts Working Groups; Co-I THESIS concept

The NWO team is shown in Table 5. The ASMCS for NASA HQ is due April 24th and the team will continue to work on refining the concept, developing technology, creating verification & validation plans, and conducting research with our testbeds. Particular attention will be given to addressing the higher priority technology development and mission risk items identified, with the goal of better understanding the technical issues, through both modeling and prototype hardware. These efforts will establish a more reliable assessment of risk than could be achieved during our concept study. The PI, lead scientist, and team continue to work on furthering collaborations, partnerships and increasing the science community support for NWO, both domestically and internationally. Discussions continue with ESA and JAXA in particular.

For the proposed NWO facility-class mission described in this white paper we expect the management structure to follow a NASA “top-down” approach where the mission goals are identified 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. Some or all of the individual instruments on NWO will be competed. Industry partners will be selected competitively for other mission components, such as the telescope, spacecraft, and starshade developments. Some mission elements will be developed in house or managed by NASA Centers. The overall project management would be assigned to a NASA Center and would also coordinate any NASA HQ negotiated international participation. A project scientist would oversee the NWO science program with the science working group and team.

VI. ACTIVITY SCHEDULE

The planned operational lifetime of the NWO mission is 5 years with a goal for an extended mission of an additional five years. The NWO project will start in 2011, with a Phase A duration of 18 months, Phase B duration of 24 months, and a development period of 60 months. Two spacecraft vendors will build the two spacecraft, which will launch in separate launch vehicles (telescope launch June 2019 and starshade launch in February 2020). Specialized test facilities will be built for the starshade development. NWO will then have a planned operational lifetime of 60 months (i.e., Phase E primary mission).

Reviews will be conducted according to the NASA Procedural Requirements (NPR) document 7120.5D. The Goddard Integrated Independent Review (IIR) process fulfills the NASA imposed requirement within NPR 7120.5D for both Independent Reviews and Critical Milestone Reviews of projects. 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). IIRs are supported by project-conducted Engineering Peer Reviews (EPRs) which assess the status of subsystem or lower assembly levels. The results of the EPRs constitute a key input to the IIRs. The project-level reviews are shown on the mission schedule in Fig. 20.

The critical path lies along the telescope/payloads/spacecraft part of the schedule. Payload development includes two instruments needed for exoplanet research, a high resolution camera and spectrometer, along with two instruments for trajectory alignment and control, the astrometric sensor assembly (on the starshade) and shadow sensor assembly (on the telescope). The general astrophysics instruments include a high-throughput far-UV spectrometer, an integral field spectrograph and a wide-field camera/guider. 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 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 $154M.

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 June 2020 with the mission operating five years.

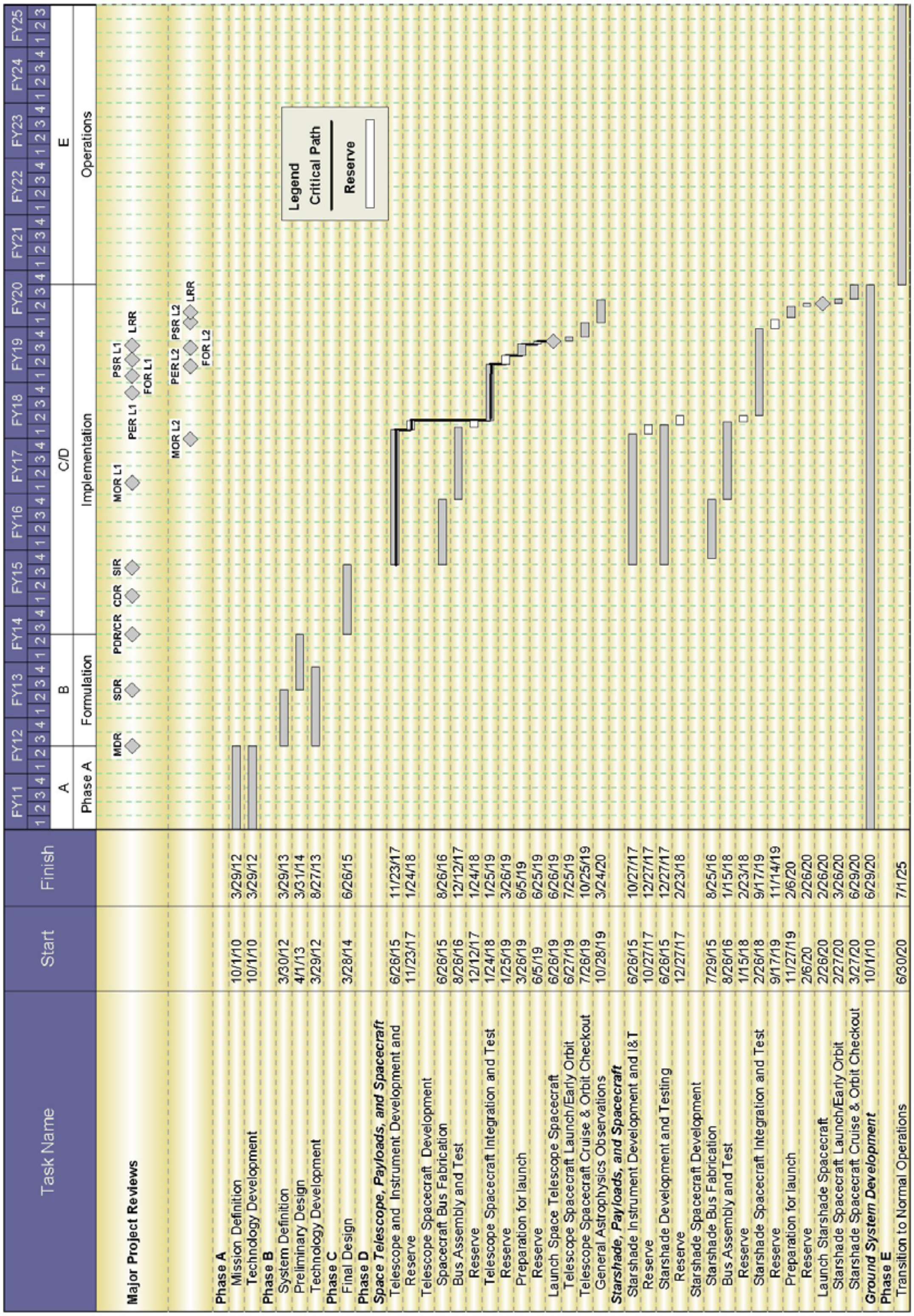

Figure 20: New Worlds Observer Integrated Baseline Mission Schedule

VII. COST ESTIMATE

Costing Assumptions and Details

The following assumptions were made in developing the baseline mission cost. The project start is in fiscal year 2011, with a Phase A duration of 18 months, Phase B duration of 24 months, Phase C/D duration of 60 months, and Phase E duration of 60 months of cooperative operation. Two spacecraft vendors will build separate spacecraft in parallel. Specialized test facilities at NGAS are required for the starshade. Two EELVs 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. Thirty percent costing reserves were applied during Phase A-D and fifteen percent were applied during Phase E to all cost elements except EPO and launch vehicle.

Table 6: Cost Estimating Methods by Work Breakdown Structure Element

WBS Element	Cost Methods
1.0 Project Management	ROM
2.0 Systems Engineering	ROM
3.0 Safety & Mission Assurance	ROM
4.0 Science/Technology	ROM
5.0 Payload	GR
6.0 Spacecraft	GR
7.0 Mission Operations	GR
8.0 Launch Vehicle	ROM
9.0 Ground System Development	GR
10.0 Systems I&T	GR
11.0 Education & Public Outreach	ROM

Cost Estimating Methodology

Our costing efforts were centered on achieving realistic estimates for a full-up flagship mission in the manner of HST or JWST. We have studied the cost in several independent ways: NWO team grassroots (GR), rough order of magnitude estimates (ROM), GSFC Integrated Design Center (IDC) PRICE-H parametric, grassroots, and 70% confidence level estimates, all developed in 2008 during the study and inflated to 2009 fixed year dollars. The GSFC Science Directorate also generated a parametric and 70% confidence level cost estimate that are included near the end of this section. The starshade cost estimate was generated by NGAS with grassroots estimates based on parts and drawing counts. Non-recurring engineering (NRE) incorporates design time estimates from the parts and drawing counts. The starshade cost includes one qualified and tested Astro telescoping boom assembly, one four-boom quarter circle qualification model of the starshade assembly, one 16-boom flight unit, and facilities costs. Costs for Project Management (PM), Mission Systems Engineering (MSE), and Safety and Mission Assurance (SMA) are percentages of spaceflight hardware costs. Education and Public Outreach cost is a ROM estimate at 0.5 percent of the total mission cost without the launch vehicle and before reserves and contingency are applied. Table 6 summarizes the cost methods by Work Breakdown Structure (WBS) cost element.

Cost Results

The baseline mission detailed cost summary for the 4-meter telescope with a 50-meter starshade in fixed year 2009 dollars is shown in Table 7 with and without reserves and shows the funded schedule reserve. This cost estimate was developed using results from the IDC, NWO team grassroots, parametric, and ROM cost methods. The total science cost estimate is $430M 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 $95.5M. The Phase E science operations budget is $334.3M. The Phase E science opera-

Table 7: NWO Mission Baseline Cost Summary

		Phase A			Phase B				Phase C/D								Phase E							TOTALS
	(FY and Total costs in fixed 2009$)	FY2011	FY2012	Total	FY2012	FY2013	FY2014	Total	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	Total	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	Total	($M)
WBS #	**WBS Element**																							
1.0	Project Management	3.5	2.0	5.5	1.6	5.2	2.8	9.6	4.6	12.5	15.3	12.9	11.9	9.9	2.1	69.1							0.0	84.2
2.0	System Engineering	3.5	2.0	5.5	1.6	5.2	2.8	9.6	4.6	12.5	15.3	12.9	11.9	9.9	2.1	69.1							0.0	84.2
3.0	Safety & Mission Assurance	3.5	2.0	5.5	1.6	5.2	2.8	9.6	4.6	12.5	15.3	12.9	11.9	9.9	2.1	69.1							0.0	84.2
4.0	Science /Technology	9.3	26.8	36.0	15.4	13.4	15.4	44.2	7.7	12.3	12.3	12.3	12.3	15.4	7.7	80.3	16.7	66.9	66.9	66.9	66.9	50.1	334.3	494.9
5.0	Payload	40.0	20.0	60.0	20.0	80.0	41.5	141.5	68.0	200.0	200.0	150.0	150.0	145.0	40.0	953.0							0.0	1154.5
6.0	Spacecraft	27.7	19.8	47.5	10.7	21.4	10.7	42.7	17.8	39.6	95.0	96.0	71.3	36.5	0.0	356.2							0.0	446.4
7.0	Mission Operations	2.4	1.6	4.0	2.0	4.0	2.0	7.9	2.8	4.7	5.5	6.3	6.3	1.6	2.8	30.1	3.3	13.5	13.5	13.5	13.5	10.0	67.3	109.3
8.0	Launch Vehicle	11.0	7.0	18.0	6.0	12.0	6.0	24.0	120.5	30.0	30.0	20.0	10.0	7.0	120.5	338.0	0	0.0	0.0	0.0	0.0	0.0	0.0	380.0
9.0	Ground System	0.5	0.5	1.0	0.3	0.5	0.3	1.0	3.6	8.2	8.2	8.6	6.2	4.1	3.6	42.6	0.1	0.2	0.2	0.2	0.2	0.2	1.1	45.8
10.0	System I&T			0.0		0.0	3.2	3.2	3.0	3.1	3.0	4.1	10.0	10.0	0.0	33.2	0.0						0.0	36.4
11.0	EPO			0.0				0.0						2.1	2.1	4.1	0.1	2.0	1.9	1.9	1.9	1.5	9.3	13.5
	Subtotal Mission Cost	101.3	81.8	183.1	59.1	146.9	87.6	293.6	237.1	335.5	400.1	336.0	301.8	251.3	182.8	2044.6	20.2	82.6	82.5	82.5	82.5	61.8	412.1	2933.4
	Reserves (30% A-D; 15% E)	27.1	22.4	49.5	15.9	40.5	24.5	80.9	35.0	91.6	111.0	94.8	87.5	72.7	34.0	510.8	3.0	12.1	12.1	12.1	12.1	9.0	60.4	701.6
	Funded Schedule Slack				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	49.3	30.0	154.3							0.0	154.3
	Total Mission Cost	128.4	104.2	232.6	75.0	187.3	112.1	374.4	272.1	427.1	511.1	430.8	464.4	373.3	246.8	2709.7	23.2	94.7	94.6	94.6	94.6	70.9	472.5	3789.2

tions cost breakdown is: $204.3M ($41M per year) for mission scheduling, data processing operations, calibration and hardware support, computing facilities and IT needs, science management and GA program management: $130M for the science community (roughly $26M per year). Technology development for NWO is already underway; by 2011 we expect to need less than 2 years for this activity. The technology development budget is $65M to bring technologies to TRL 6 prior to mission PDR in 2014.

In order to provide an easy way to see the cost breakout of specific flight/ground components, we present Table 8. We have broken out separate costs for the telescope and starshade, science/technology, total mission operations/ground development and systems I&T, and mission wrappers. We delineate the Phase A-D and Phase E costs with and without contingency. Phase A-D costs without contingency: the total telescope/instrument cost with spacecraft is $1.1B, including costs for the GA instruments; the total starshade system with spacecraft cost is $486M; total science and technology is $160.5M; the total mission operations/ground system development and I&T costs are $123M, PM/MSE/SMA costs are $253M, and EPO at $4M. The subtotal cost for Phases A-D is $2.1B without contingency. The cost for two EELV (specifically, one Atlas 541, and one Atlas 551) launch vehicles is $380M. The total Phase E cost is $412M and includes science, ground system support, mission operations and EPO. One can see that the total price for the mission is approximately $2.9 Billion (without contingency), significantly less than JWST.

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

NASA.

Baseline Price-H and 70% Cost Summary

The Science Directorate at GSFC also generated a cost estimate for comparison. A parametric point estimate and 70% confidence level (CL) estimate (NASA, 2007) were generated for NWO in March of 2009. Launch vehicle and grassroots instruments 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 $3.5B in 2009 fixed year dollars. The 50% CL estimate is $3.8B and the 70% CL estimate is $4.1B.

The NWO mission baseline cost with contingency is $3.8B 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 $3.8B or less. NASA Headquarters prefers that the cost risk is more in line with the 70% CL.

Table 8: Mission Cost Element Summary in 2009 fixed year M$.

Cost Element	Base	W/Contingency
Total for Telescope	**1114.9**	**1449.4**
Telescope	395.0	513.5
Exocam	103.0	133.9
Exospec	82.3	133.9
COS	82.3	107.0
IFS	205.3	107.0
spacecraft	205.3	266.9
beacons	4.1	5.4
GA Instrument (WFC)	139.9	181.9
Starshade	**486.0**	**631.9**
Starshade Payload	144.0	187.2
Spacecraft	241.1	313.4
Astrometric Sensor	60.8	79.1
Astrometric System	40.1	52.2
Total Science and Technology	**160.5**	**208.7**
Science Algorithms	95.5	124.2
Technology Development	65.0	84.5
Total Mission Ops, Ground Development System I&T	**123.0**	**159.9**
Mission operations	42.0	54.6
ground systems development	44.6	58.0
System I&T	36.4	47.3
Mission wrappers	**256.7**	**486.8**
PM, SE, SMA	252.6	328.4
Funded Schedule Slack	0.0	154.3
EPO	4.1	4.1
Total Phase A-D	**2141.1**	**2936.7**
Launch Vehicle	**380.0**	**380.0**
Phase E (Nominal Ops for 5 years)	**412.0**	**472.5**
Science	334.3	384.4
Ground Development	1.1	1.3
Mission Operations	67.3	77.4
EPO	9.3	9.4
Grand Total	**2933.1**	**3789.2**

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