Astro2010 PPP RFI Response

The New Worlds Probe: A Starshade with JWST

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NWP can do imaging and spectroscopy of terrestrial planets as early as 2016
This may be the fastest and most affordable path to the discovery of life.

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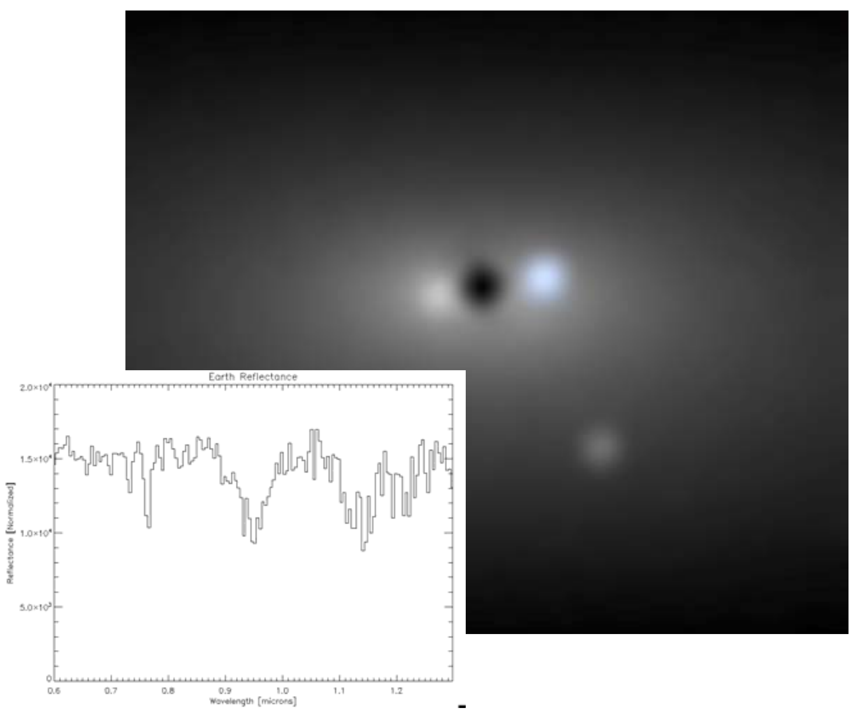

I. SUMMARY

The James Webb Space Telescope will be an extraordinary observatory, providing a huge range of exciting new astrophysics results. But it will not be able to directly observe planets in the Habitable Zone of nearby stars – perhaps the most important and tantalizing astronomy goal for the coming decade. In this paper, we discuss the New Worlds Probe (NWP), a concept whereby we send an external occulter, known as a starshade, on its own spacecraft to work in alignment with JWST, enabling JWST to reveal those elusive habitable planets and open the search for life (Fig. 1).

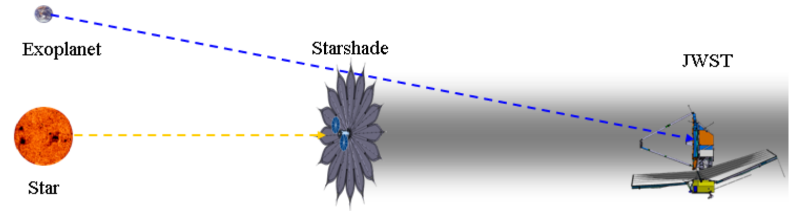

Figure 1: NWO's cost-effective starshade shadows the telescope from the star, while light from a terrestrial exoplanet passes the edge of the starshade unimpeded.

Recent advances in apodization functions have now enabled external occulters to be designed in a practical way for the direct detection of Earth-like planets (Cash, 2006). A starshade approximately 50 m in diameter, flying 55,000 km from a telescope can throw a sufficiently deep shadow over a telescope to reveal Earth-like planets at 10^{10} suppression, at as little as 75 milliarcseconds (mas) from the parent star. NWP will image planets from the habitable zones outward around nearby stars and immediately capture spectra to determine their natures. The search for water planets will be possible using the strong water absorption bands in the near infrared. Biomarkers like the O_2 line can be detected with sufficient observing time and can open a serious search for simple life.

The authors of this whitepaper are completing two Astrophysics Strategic Mission Concept Studies called the New Worlds Observer and THEIA. Both groups concluded that starshades working with a 4 m-class UV/Optical/near-IR telescope would enable detailed study of Earth-like planets at the price of a flagship mission. The teams joined with the Space Telescope Science Institute to discuss the faster, less expensive option of a starshade being used with an existing telescope, JWST. The NWP program can be executed quickly and efficiently for the price of a medium (or Probe) class Exoplanet mission. The starshade can be launched up to 3 years after JWST and rendezvous with the telescope in orbit around L2 (Fig. 2). The starshade structure was designed using high-heritage components – integrated development of NWP could start today. NASA can image terrestrial planets by 2016.

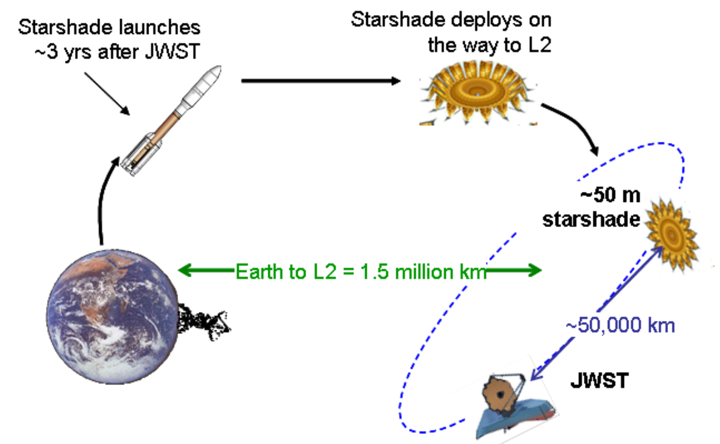

Figure 2: Employing existing technology, NWP uses a 50 m starshade with JWST to image and characterize extrasolar planets.

II. KEY SCIENCE GOALS

NWP is the fastest and cheapest way to make progress on many of NASA's grand themes, such as finding planetary systems like our own and discovering life in the universe. With current and near-term technologies, we can make great strides in finding and characterizing planets around nearby stars. By the middle of the next decade, NWP will enable us to find terrestrial planets around other stars and determine their habitability. This is a valuable addition to JWST's science program.

The science program of NWP uses the extensive capabilities of JWST's instruments. We assume a total available exposure time for the starshade of 7-9% of the total exposure time on JWST (or 10^7 sec for a 5 year mission). This time budget is smaller than the typical amount available for a dedicated mission like NWO or THEIA and the science goals are designed to make optimal use of this time by balancing the characterization of known objects with a reasonable survey of nearby stars. The key science goals for this mission are:

1. Find Terrestrial Planets: survey nearby stars for Earth-like planets to a completeness = 10.
2. Characterize Terrestrial Planet Habitability: conduct spectroscopic analysis on the planets found, searching specifically for water and determining the planets' temperature. Deeper spectroscopy can then be used to search for more challenging species such as oxygen.
3. Characterize Known RV Planets: find the size, temperature, and atmospheric composition of known radial velocity (RV) planets. These include mostly giant planets (Jupiter to Neptune mass) and potentially super Earths by the NWP launch date.
4. Characterize Exozodiacal and Debris Disks: determine the brightness, structure, and composition of exozodiacal and debris disks.

The starshade's starlight suppression works better at shorter wavelengths for a given starshade size. In the optimization of a starshade (Cash et al. 2006; Vanderbei et al. 2007) for JWST, the main requirement driving the design is starlight suppression at the longest wavelength. The increasing size of the starshade with increasing longest wavelength must be balanced with the need to maintain a reasonable starshade size. The operating wavelengths chosen for flagship missions such as NWO and THEIA are ~0.4 to ~1.1 μm and ~0.25 to ~1.1 μm, respectively. JWST is optimized to work in the near- to mid-IR (λ>0.6 μm). This provides access to an oxygen band (0.76 μm) and offers the advantage of expanding the sensitivity to the near-IR, which is a rich area for exoplanet science (TPF STDT report).

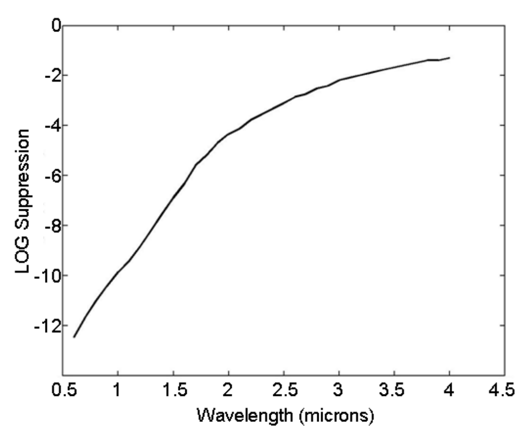

Figure 3: Starlight suppression with the NWP starshade versus wavelength for a spacecraft separation of 55,000 km.

Fig. 3 shows an example of starlight suppression at the JWST aperture versus wavelength for a 50 m starshade operating 55,000 km from JWST, which provides an IWA of 75 mas. We can adjust the separation between the starshade and telescope while on orbit to select the optimal performance. For example, at a distance of 40,000 km, the IWA increases to ~100 mas, but the starlight suppression at long wavelengths improves to

$\sim 10^{10}$ at 1.5 μm and $\sim 10^{8}$ at 2 μm.

1) Find Terrestrial Planets

The detection of terrestrial planets by NWP is done using imaging with NIRCam on JWST at the shortest wavelengths. The filters of interest are the F070W, F090W, and F115W bands, covering 0.6-0.8 μm, 0.8-1 μm, and 1-1.3 μm, respectively. In addition, there are a number of medium band filters that can be used (F140M, F162M, F182M, and F210M) with applications for the detection of water vapor or methane absorption bands.

We can detect an M = 30 point source at S/N=10 with both the F070W and F090W filters in ~66 hours given a exozodiacal background equal to our own (see below). This will take ~34 hours with the F070W filter and ~22 hours with the F090W filter. Detecting planets against the exozodiacal background lengthens the exposure, though advanced signal extraction can help mitigate this problem. One of the difficulties is that the JWST PSF is significantly undersampled at these wavelengths.

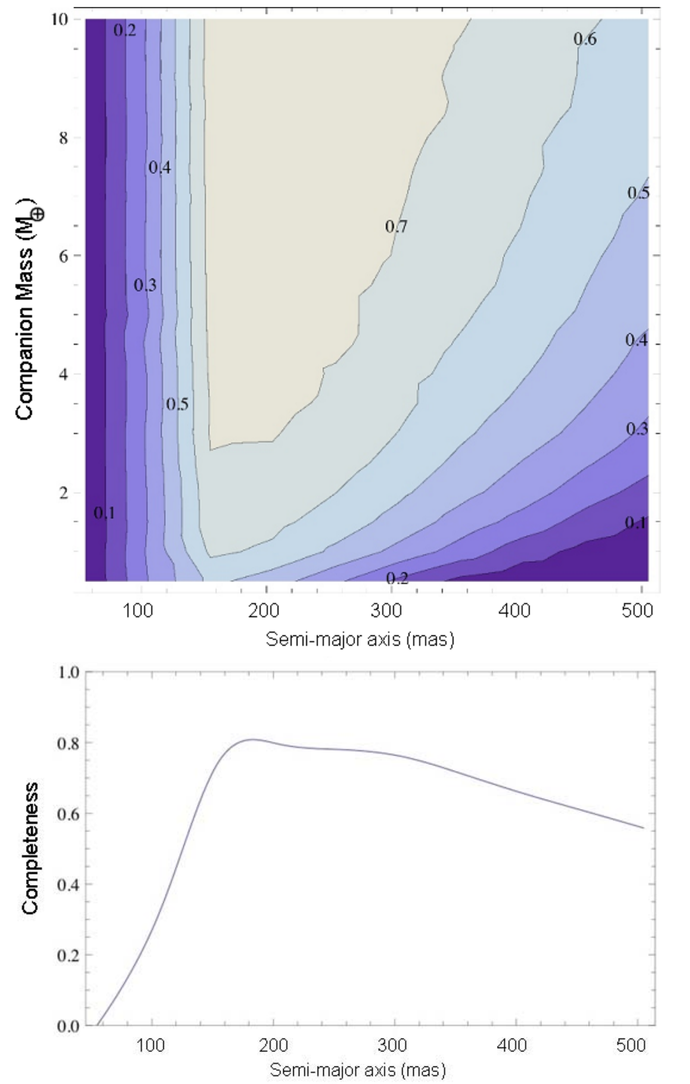

Figure 4: Top: The completeness (discovery probability) contours for a single-visit completeness of planets around a solar-type star at 10 pc. The contrast limit is Δm = 26, with a conservative 100mas IWA. **Bottom**: a slice of the contour for Jupiter mass planets.

In any single observation of a planetary system there is a probability that a planet will be detected. For example, the planet could be in transit and hidden behind the shade. Or, it might be at quadrature and easy to see. In the upper diagram of Fig. 4, we show probability contours for the single visit discovery of a planet as a function of its mass and distance from the star for the case of 10 pc. NWP will have probability of planet detection in the 20-50% range for planets in the habitable zone and larger planets, farther out, can have probabilities of discovery in excess of 70%. The lower diagram shows the probability of finding Jupiter-sized planets as a function of semi-major axis. The NWP system will have better performance that shown in the plots due to a smaller system IWA.

2) Characterize Terrestrial-Planet Habitability

Photometry and spectroscopy will reveal the true nature of these planets and the systems in which they were born. Spectroscopy of terrestrial exoplanets will quickly reveal a wealth of information about the planet's atmospheric and surface conditions, most notable the detection of water which can be seen even in fairly low resolution spectra. Further characterization may be possible in the most favorable cases including the search for oxygen and a number of other species that could potentially be detected in the near infrared (e.g., carbon dioxide, methane, or ammonia). Spectroscopy of giant planets at a resolution comparable to what is nowadays achieved on brown dwarfs will constrain the surface gravity of these objects and open the possibility of a complete characterization including mass, temperature, radius, and major atmospheric absorbers.

We have calculated the exposure times needed to get an S/N=10 spectrum of an Earth twin and of giant planets at 10 pc. We will use the prism in NIRSpec to get low-resolution spectra (R~40) and the gratings to get high-resolution spectra (R=1000 or 2700). The high-resolution spectra can be binned down to get R~100 spectra of terrestrial planets at the cost of additional detector noise. This results in observations with the grating being detector limited while observations with the prism are background limited.

Spectra of an Earth-like planet at 10 pc obtained with NIRSpec and NWP is shown in Fig. 5. The strong absorption features of water, indicative of oceans and clouds, are readily detectable even in the low-resolution spectra. More exciting is the presence of biomarkers such as absorption lines from molecular oxygen in the higher-resolution spectra. These features are in the spectrum of the Earth solely as a byproduct of plant life.

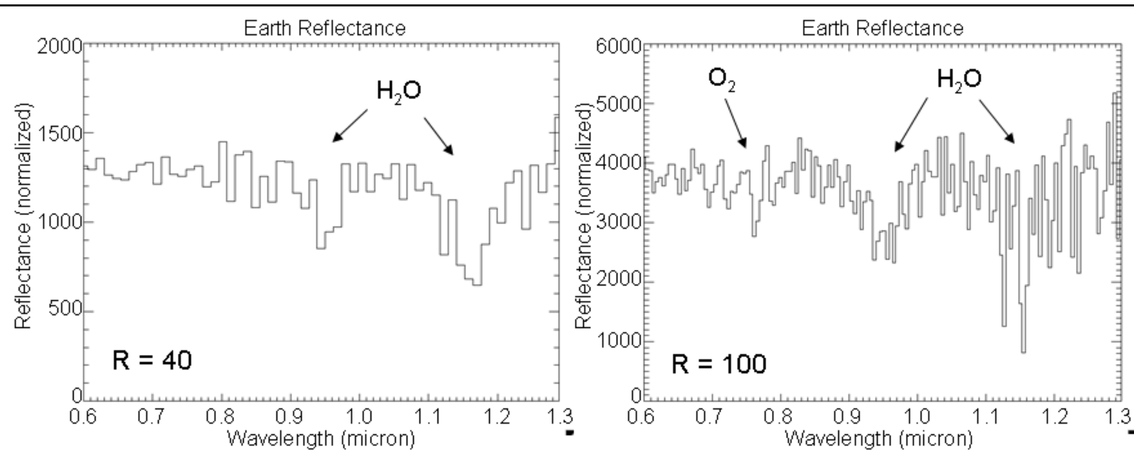

Figure 5: Simulation of the Earth spectrum with NWP and NIRSpec. Left, resolution of R=40 with the prism in (10^5 sec). Right: R=100 obtained with R=1000 grating in $1x10^6$ sec. The water bands are easily detectable in a low-resolution spectrum and would give the proof of existence of a habitable planet. The oxygen A band is detectable in the R=100 spectrum in a reasonable amount of time with S/N<10 in the continuum.

For a terrestrial planet at 10 pc, we estimate the time to get an R=40 spectrum with the prism is 10^5 sec, assuming an exozodical dust level of equivalent to that in our Solar System and a slit width of 0.1″ with the Integral Field Unit (IFU). This calculation includes an additional 1 zodi of background to account for scattered-light contamination. The observation is background-limited and the exposure time doubles with the long slit of width 0.2″. The oxygen line cannot be seen in the R ~ 40 spectra due to spectral line confusion, and is not a function of S/N. The same amount of time will be necessary to obtain an R=1000 spectrum of a Jupiter analog or an R=2700 spectrum of a more massive giant planet. A spectrum of an Earth-like planet using the

R=1000 grating (1.0-1.8 μm) and binning down to R=100 can be obtained with S/N ~5 in 10^6 sec, making the crucial oxygen A band visible.

Using the Integral Field Unit (IFU) or the micro-shutter array (MSA), it is potentially possible to simultaneously obtain spectra of several planets. The IFU provides a 3″ × 3″ field of view with spatial resolution of 0.1″. This will be particularly interesting for multiple-planet systems and interplanetary dust. However, slit and MSA spectroscopy have higher efficiency than the IFU and would be preferable for the faintest targets. MSA spectroscopy can also be used to image multiple objects in the field although the apertures are larger than the IFU (0.2″ x 0.45″).

3) Characterize Known RV Planets

The third goal focuses on the characterization of planets that are already known to exist. As of today, there are 24 giant planets with projected semi-major axes larger than 100 mas (Exoplanet Community Report Chap. 3), many more planets are expected in the coming 5 to 10 years before NWP's launch. This will be a target rich area of discovery. These planets typically have $\sim 10^{-9}$ contrast and are readily accessible to NWP, both for imaging and spectroscopy. Combining RV and imaging can break the m*sin*i degeneracy and provide the planet's mass. Spectroscopy at R=40 with JWST's NIRSpec prism and even R=1000 is within reach for Jupiter twins, enabling better measurements of surface gravity and atmospheric constituents. With access to giant planet masses, temperatures, gravities, radii, and the main atmospheric absorbers, NWP will open new areas in understanding planet formation and diversity. We will use NIRSpec to get spectra of both the known planets and any additional planets that we may discover in each system.

4) Characterize Exozodi and Disks

NWP's fourth goal is to study exozodiacal dust (or "exozodi") in planetary systems, which is generated by comet and asteroid collisions. Observing exozodi is crucial, both for its science return and as a source of background noise for exoplanet observations. Currently known exozodi disks (better known as debris disks) have L_{IR}/L_* values in the range of 10^{-3} to 10^{-5} (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 NWP has no outer working angle and produces zero distortions in the field, exozodiacal light and debris disks will be optimally imaged by this system.

Exozodiacal light also provides a treasure trove of scientific discovery. Just as NASA's Deep Impact mission probed a Solar System comet by studying material generated in a man-made collision, exozodiacal dust provides information on the composition of extrasolar asteroids and comets. Furthermore, the distribution of the exozodi 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. Imaging the exozodi gives us the inclination of the system's ecliptic plane, which can help us make a first estimate of a planet's orbit from a single image.

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, zodiacal and exozodiacal background will be largest source of noise for most targets, assuming the starlight is suppressed to $\sim 10^{-10}$. 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, NWP is quite robust against the presence of many zodis of dust in the extrasolar system.

Starshade Red Leak

Although it is possible to optimize the starshade to work for the entire JWST short-wavelength bandpass, the size of the starshade becomes large and the separation between the starshade and JWST becomes too distant. We can use filters to limit the bandpass, but the question of the out-of-band quality of these filters becomes important; on the red side of the band the starshade's suppression drops as the wavelength increases. In the case of NIRCam, the filters have out-of-band rejection of 10^4 to 10^5, which requires a starshade suppression of at least 10^4 to 10^5 over the entire sensitivity band of the NIRCam detector (up to 2.4 μm).

For spectroscopy with NIRSpec, this problem is relaxed because the light is spectrally dispersed. The only concern is long-wavelength light scattered into the short-wavelength pixels. Moreover, any combination of filter and dispersive element is possible and we have identified two useful target acquisition filters: F110W (1.0 to 1.2 μm) and F140X (0.8 to 2.0 μm). The latter is the most interesting for exoplanet science in general, including potential access to the bands of H_20, CH_4, CO_2, O_2 (1.27 μm), CH_4, water ice, and NH_3. However it misses the oxygen A band at 0.76 μm. The current filter has a red leak of ~ 8% at 3 μm which may limit spectroscopic performance for the faintest objects because of scattered light. We suggest an optional upgrade of this filter (see the technology development section below) to improve the out-of-band rejection. Another optional filter modification would be to replace two existing long-pass filters (F070LP and F100LP) with band-pass filters. These filters are intended for use with the gratings in the wavelength range 0.7 to ~1.4 μm and 1 to ~2 μm, respectively, because of combined effect of the grating efficiency and second-order contamination. These filters might be replaced with minimal impact on the JWST science, especially the shorter wavelength filter (F070LP).

III. TECHNIAL OVERVIEW

The Starshade

Recently, Cash (2006) found an apodization function that makes external occulter systems practical with today's technology. The starshade has been realized in the New Worlds Observer mission concept, where a 50m starshade is flown with a dedicated, 4m telescope. Because the starlight does not enter the telescope, there are not particular constraints on the telescope optical quality: the telescope can be on-axis, segmented and even with modest optical quality without significant loss of performance. All these reasons enable the starshade design to work with JWST, even at the shortest wavelengths.

Shown in Fig. 1, the starshade is an opaque screen that flies in the line of sight from JWST to the target star. If the starshade is sufficiently distant it will subtend a small angle to blot out the star while allowing the exoplanet light to pass unobscured over the edge.

Cash's offset hyper-Gaussian apodization function reduces diffraction by many orders of magnitude. A starshade with 2(a+b) = 50 m (the effective diameter), operating ~50,000 km from JWST is capable of 10^{-10} starlight suppression within 75 mas for wavelengths from 0.1 to 1 µm. This starshade has 16 petals, with hypergaussian parameter n = 6. This is essentially the same starshade as the NWO flagship, and so can reuse all the learning and design we have developed for that mission concept.

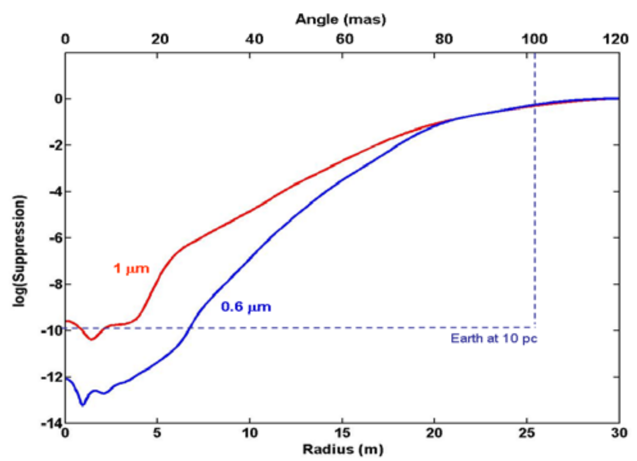

Figure 6: Residual starlight falls by >10 orders of magnitude across a shadow radius of <20 m, allowing observations of planets as close as 75 mas.

Four independent software codes have been developed to simulate starshade performance. Fig. 6 shows the suppression efficiency of the baseline starshade design as a function of both radius and angular offset for two representative wavelengths.

Deriving the requirements and tolerances on 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 Corporation (NGC), 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. 7), 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. NGC, world leader in space deployables, provided the engineering that went into designing a mechanism to reliably deploy the shade and lock it into its final shape. The payload is a passive device that 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.

The starshade space vehicle baseline design is shown in Fig. 8. The main function of the spacecraft needs to move the starshade from target to target and maintain alignment during observation. 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 are 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.

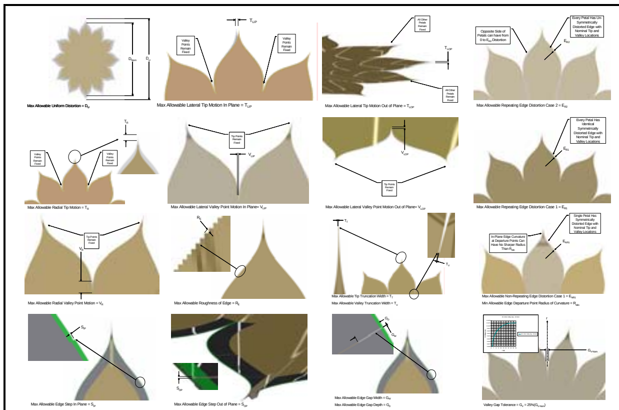

Figure 7: The starshade is tolerant to many distortions. Distortions on the shape of the starshade have been modeled using diffractive simulations and fall within the capability of existing technology.

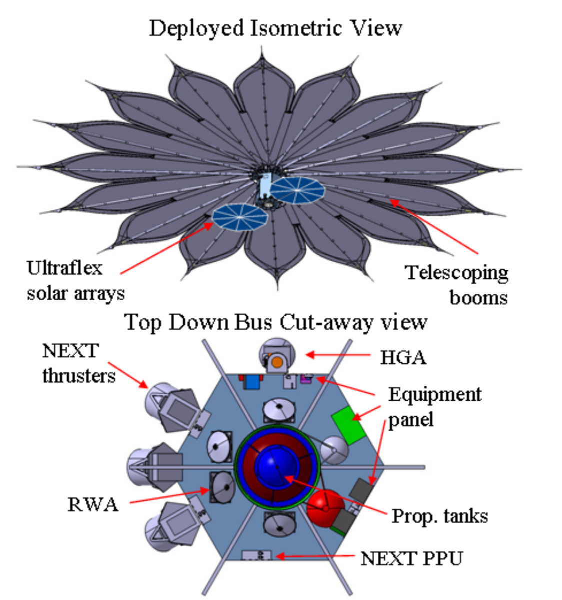

Figure 8: The starshade is a passive payload. The spacecraft bus provides high ΔV with the NEXT electric propulsion system.

Verification and validation of this large deployable is one of the main challenges of NWP. 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 design and validate a tenth-scale rigid edge section to the necessary requirements. We 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 to-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.

<u>JWST</u>

The JWST is a large, infrared-optimized space telescope designed to study the formation of the first stars and galaxies. JWST (Fig. 9) will have a large mirror, 6.5 meters in diameter and a sunshield the size of a tennis court. JWST is being launched in 2013 to the Sun-Earth L2 point, 1.5 million km from the Earth, where it will conduct its observations. The NWP project is primarily concerned with three systems on board JWST: two of the science instruments, NIRCam and NIRSpec, and the sunshield, which reflects sunlight towards the NWP starshade and can be used for an alignment signal.

The NIRCam design consists of two broad- and intermediate-band imaging modules, each with a 2.16' × 2.16' field of view. The modules will have a short and a long wavelength channel, taking images simultaneously with light split by a dichroic at about 2.35μm. The short wavelength channels will be sampled at 4096 × 4096 pixels (0.0317"/pixel), the long wavelength channels by 2048 × 2048 pixels (0.0648"/pixel). The short and long wavelength arms are Nyquist sampled at 2μm and 4μm respectively. NIRCam will also be used for wavefront sensing to assure perfect alignment and shape of the different primary mirror segments. Each imaging module has a pupil wheel with extra optics and pupil analyzers for wavefront sensing. The wavefront sensing capability is fully redundant in both imaging modules because the mission depends critically on its functionality. Although JWST is mainly optimized for the near- and mid-infrared, it has access to shorter wavelengths with modest optical quality down to 0.6~0.7 μm on NIRCam and NIRSpec.

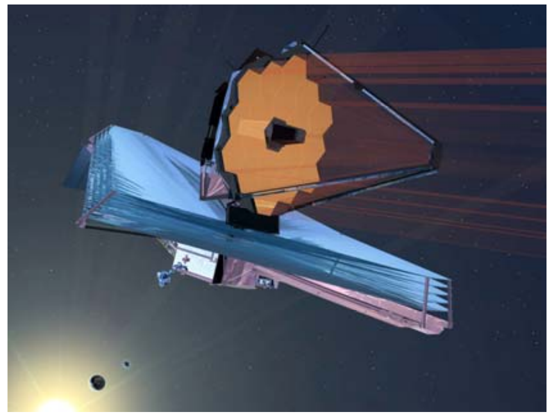
Figure 9: JWST will be able to image and characterize terrestrial planets in 2016 with the addition of the NWP starshade.

In the R~100 and R~1000 modes, NIRSpec provides the ability to obtain simultaneous spectra of more than 100 objects in a >9 sq. arcmin field of view. At R~100, one prism spectrum covers the full 0.7 μm - 5 μm wavelength range. However the resolution is a function of wavelength, and R is about 40 at the shortest wavelengths. At R~1000, three gratings cover the wavelength range from 1μm - 5μm. To improve sensitivity, the pixels will have a larger projected size on the sky (~0.1") than those on NIRCam.

The JWST sunshield is made of five-layers, consists of extremely thin, specially coated, reflective Kapton membranes and a supporting structure, and measures about 22 m × 12 m. The sunshield blocks solar heat, allowing the telescope's science instruments to operate at cryogenic temperatures.

Trajectory and Alignment Control

We will launch the NWP starshade to meet up with JWST in 2016. The launch window is 1 month occurring every 6 months. Fig. 10 shows an example starshade phasing orbit with JWST. It is also possible to rendezvous with JWST on the far side of L2. The launch window would then be 1 month wide, every 3 months, for an additional ~200 m/s of ΔV. Because the separation between the two spacecraft is large, there is no chance of collision even in the case of an error.

The ability of NWP to locate, track, and align itself to JWST is essential for mission success. However, the Trajectory and Alignment Control (TAC) system for NWP cannot rely on a “cooperative” telescope that is able to send data to the starshade; JWST is a passive partner in alignment. The NWP team intends to seamlessly integrate the exoplanet operation into the existing JWST operations architecture which means that the science observations enabled by NWP will be commanded on JWST just like any other observation.

A 50 m starshade, at a separation of 55,000 km from the telescope, must be aligned to the line-of-sight to a target star with a 3σ error of ~2 m in order for the telescope to stay in the deepest part of the shadow. Two meters at 55,000 km corresponds to ~8 mas. In order to achieve 8 mas position control, we must be able to measure the alignment to ~2 mas.

Achieving and maintaining alignment of the starshade and JWST involves major two steps. The first step, coarse alignment, is to move the starshade to within ±50 km of the line of sight from JWST to the target star. During early science operations, this slew can be guided by ground tracking and ephemeris modeling; the starshade will have daily downlinks to the ground, where it performs a position check against ground telemetry, obtains updates on JWST position, and obtains updates (if available) on the JWST visit file. Fifty km is a conservative estimate of the 3-D positional error relative to the commanded position for this technique. Alternatively, we could use a less ground-intensive method suggested by Beckman (2002). By obtaining a ranging measurement, with Doppler data from a ground station, and spacecraft attitude measurements, we can use CelNav (part of GSFC's Enhanced Onboard Navigation System software package) to obtain an accuracy of ±37 km without ground telemetry upload. For routine operations, guidance for this phase can be obtained from the optical astrometric sensor mounted on the starshade.

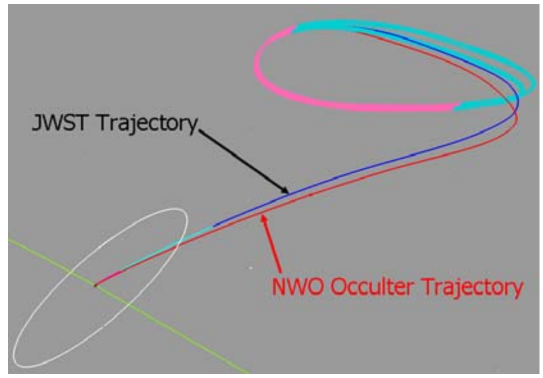

Figure 10: The NWP starshade is launched on a ~100 day trajectory to a position ~50,000 km away from JWST. Exoplanet observations can begin around Oct. 2016.

The astrometric sensor is also the primary source of alignment knowledge for the second, fine alignment step. For the second step of alignment, we use reflected light from the JWST sunshield as the guiding signal for the astrometric sensor (AS) mounted on the starshade. The AS is described in more detail below and each step in the process is outlined in Table 1. We present trades and further work required for the TAC in section IV.

The AS is a small camera mounted on the starshade that determines the alignment of the starshade to JWST and the target star. It must be able to find JWST when the starshade is up to 50km from its commanded position and move the starshade to within 2m of the line-of-sight to the target star. Fig. 11 shows the method of using reflected light from the JWST sunshield as a guiding signal for the AS. Candidate AS instruments are JMAPS and HRI (Table 2), both of

Table 1: Nominal NWP TAC Operations Events

Event	Timescale	Sensor	Position Precision		Details
			Dist.	Angle	
Starshade Retarget	5-30 days	Ground or AS	50km	3'	Slew to new target using NEXT thrusters Get alignment data once/day from ground or AS
Acquire JWST	2-12 hrs	AS	±4m	15mas	If the sunshield is not visible: wait until next JWST pointing maneuver (or ground can insert JWST roll maneuver to illuminate sunshield) Starshade maneuvers to final position Time depends on accuracy of previous step
Alignment Acq. & Calibration	1-2 hrs	AS & Ground	±2m	8mas	Start of JWST cooperative mode JWST maneuvers to ensure sunshield is visible Starshade AS + JWST WSC Mode calibrate alignment JWST acquires target star
Science Observation	1-5 days	AS (+ Ground)	±2m	8mas	JWST performs science observation Starshade maintains alignment using AS or JWST WSC Mode

which have high heritage from previous missions.

A 50 km position error corresponds to 3.4′ at 50,000 km, so the FOV is more than adequate to find the signal from JWST at the hand-off point. On average, 12 stars brighter than 15th magnitude will appear in the astrometric sensor's FOV which serve as references for relative motions, or, with astrometric calibration, for absolute bearing measurements.

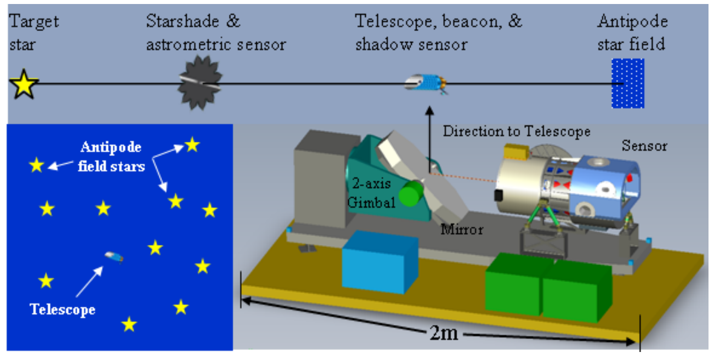

Figure 11: The astrometric sensor on the starshade observes an optical beacon on the telescope to find the telescope's location against antipodal stars for medium alignment.

The strongest visual signal from JWST is reflected sunlight off the sunshield; this reflection is ~90% specular and 10% diffuse. By estimating the diffuse component only, we estimate that there is an average signal of ~12th magnitude from the sunshield over the angular range of interest for NWO alignment (Fig. 12). The specular component will give us a much larger signal for certain angles. Using longer integration times on the astrometric camera, we can also tolerate a weaker signal: down to 15th magnitude is feasible for JMAPS, and potentially even fainter for HRI. In addition, the solar arrays and the bus on JWST will receive significant illumination, large enough to be detectible, but is not included in this calculation. These signals are further enhanced by light reflected off the sunshield and onto the spacecraft. The sunny side of the sunshield is canted back from the line of sight, so in science observation mode, the starshade will be looking at the dark spaces between the layers of the sunshield. During science observation, only a portion of the spacecraft bus will be visible over the edge of the sunshield. JWST can be commanded to periodically perform a small roll maneuver so NWP can see the bright part of the sunshield. If feasible, a white panel could be added near the bus to ensure that JWST is bright enough. A full analysis of the JWST integrated reflected light is the immediate next task of the NWP project.

Table 2: HRI and JMAPS

Capability	HRI	JMAPS
Vis magnitude limit	15	12
Field of View	7′	1.2°
Integration time	3.3 sec	10 sec
Positional uncertainty	4.4 mas	5 mas
Heritage	TRL 9 –Deep Impact	scheduled 2012 launch

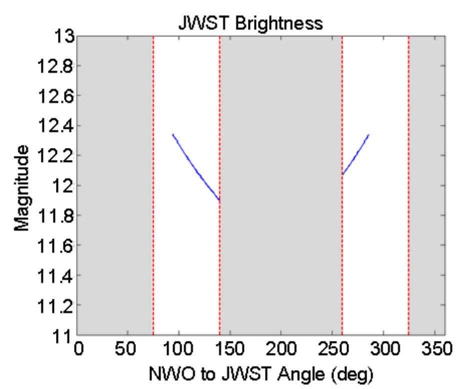

Figure 12: A conservative estimate of JWST brightness, showing that it is brighter than 12th mag. over the angles of interest for NWO. The white regions indicate allowed relative angles between JWST and the starshade during alignment acquisition.

IV. TECHNOLOGY DRIVERS

Technology development for NWP is very similar to that needed for the NWO project (Fig. 13). We refer the reader to the Starshade Technology Development white paper for further information about the technology, or the NWO ASMCS final report (see References section) for more details. There are three tall poles for NWP: 1) Starshade Optical Performance, which involves the need to validate the optical performance of the starshade via simulations and testbeds; 2) Starshade Precision Deployment and Shape Maintenance, were the technology needed for deployment and on-orbit shape maintenance of the starshade needs to be integrated; and 3) Trajectory and Alignment Control, where the technology for alignment with JWST needs to be developed. The first two are the same as for the NWO flagship mission, so they are not discussed here. Technology impacts to JWST can also be thought of as a tall pole, as any impacts to JWST carries significant risks.

The NWP can be implemented with zero impact to JWST as it is planned now. However, minor changes can be implemented at near zero cost in the very near future and make significant improvement in the scientific return should the starshade be flown.

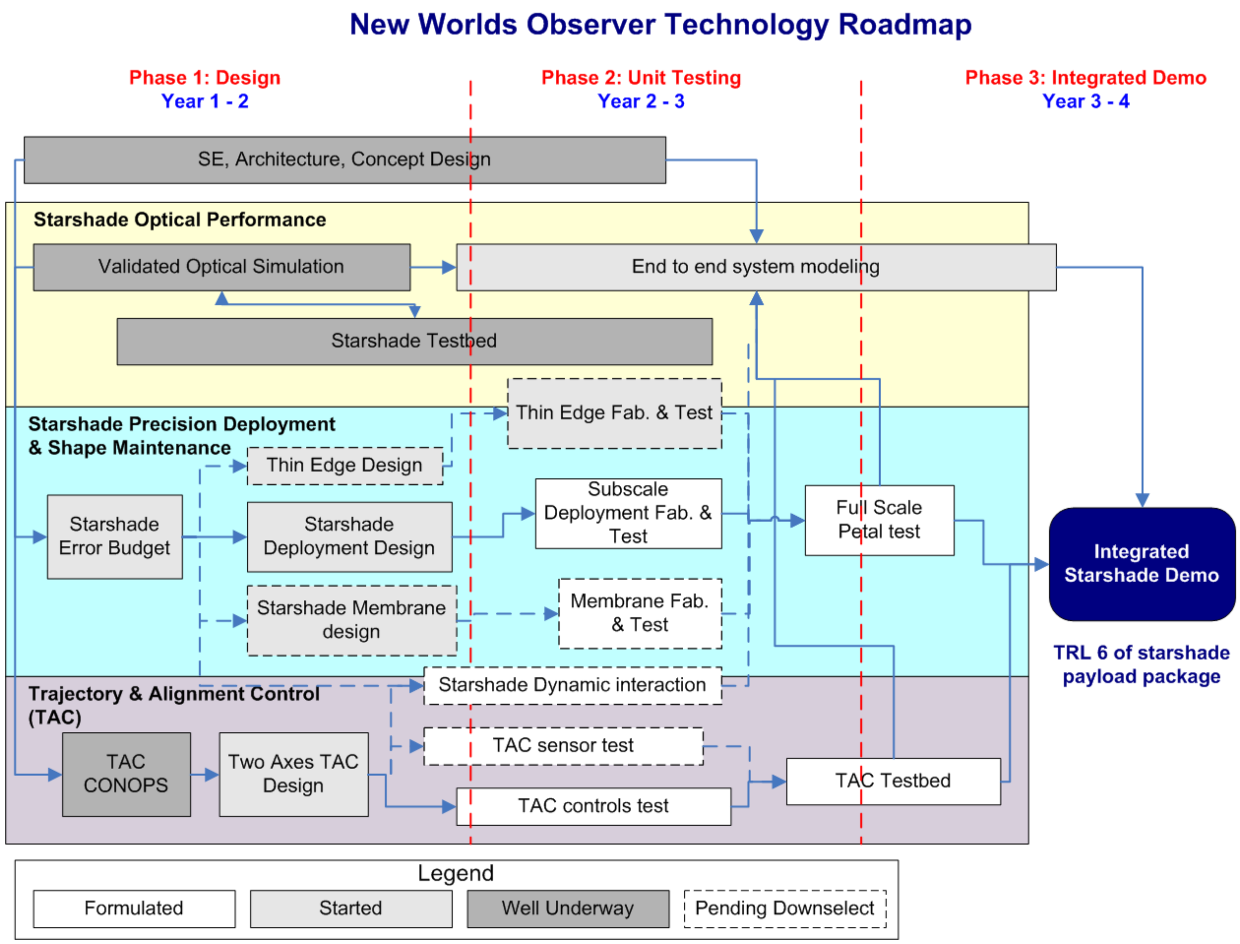

Figure 13: Using existing and heritage components, NWP can be developed quickly. The Starshade can reach TRL 6 in ~30 months.

Alternative Trajectory and Alignment Control Operations Scenario

To further increase the accuracy of the AS, a calibration maneuver is included in the checkout portion of the mission shortly after the starshade arrives at L2. Using no more than 50 hours of JWST time, NWP performs a correlation of the AS output with data from JWST's NIRCam data. The JWST Wavefront Sensing and Control mode in NIRCam includes a pupil-imaging lens (PiL), which can be used to map the pupil plane of JWST. With the starshade in place, NIRCam will measure the profile of the starshade's shadow at the pupil. Having this data and the corresponding AS data during the same epoch will allow calibration of the AS accuracy and precision. Each NIRCam pixel is sensitive to 10.4 nJy in a 10,000 sec integration. Fig. 14 shows the expected starshade shadow profile in the NIRCam F200W band. The average suppression in this band of 10^{-5} applied to a typical m=5 star results in a 0.35 mJy signal, orders of magnitude above the sensitivity threshold of NIRCam.

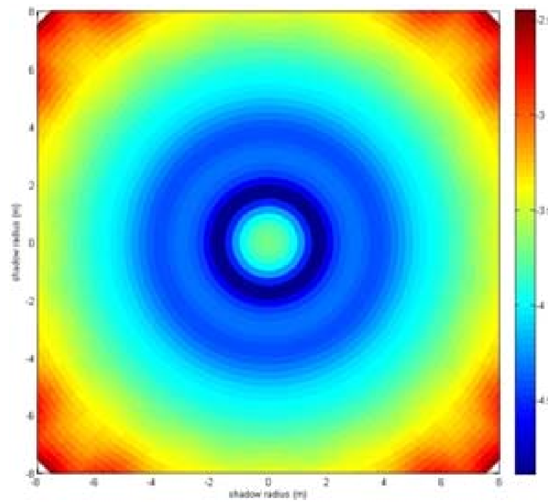

Figure 14: The starshade shadow in the JWST pupil plane. The shadow has an intensity variation of more than 2 orders of magnitude over the JWST aperture in the NIRCam F200W filter.

During the Science Observation mode, the AS may not have adequate signal from the JWST sunshield and this same method may be required to perform alignment. In this case, the alignment loop would have to be closed via the ground. The frequency of such ground contact depends on the location of the spacecraft during the observation. In the worst case scenario, the starshade drifts ~1 m every 17 min. Ground contact will be required in this case once every 60 min, in order to ensure the starshade never drifts out of the ±2 m alignment box. The median, or expected, contact rate is 160 min, and the optimal case is once every 392 min. *We plan to optimize target selection with this criterion to minimize the contact frequency*.

The DSN contact requirement and cadence is determined by the starshade during the Alignment Acquisition & Calibration mode. The starshade determines if there is enough flux from JWST for alignment and, if not, sends the necessary telemetry so that the ground can calculate the required cadence by correlating JWST NIRCam output with starshade telemetry and astrometric data. NIRSpec may still be used in parallel during this operation, but NIRCam observations will be impacted. It is expected that this mode will occupy a total of ~20 min per contact (every 60 to 392 minutes). In the worst case scenario, the total telescope time required to do a NIRCam observation will increase by ~30%.

The DSN cost for 168 hours of continuous contact is ~$304K. For the optimal case, it is approximately $216K. For 30 targets, this is an additional $9M in DSN station costs ONLY (no ground-support personnel costs).

We have assumed no changes to JWST. The next technology development page outlines several minor changes to JWST in order to make alignment much simpler and improve the science return of the mission. We want to stress that NWP is feasible with ZERO modifications to JWST; the list are simply suggestions should NASA see fit to implement them.

<u>Technology Development Mitigated by Minor JWST Upgrades</u>

With very minor upgrades to JWST, we can obtain much more useful science data and lower the risk levels for some of the technical issues. We list below the hardware (Table 3) and operations (Table 4) modifications that will assist the NWP project. These are not necessary changes to JWST, as NWP is feasible with no JWST modifications.

Table 3: Possible JWST Hardware Modifications

Upgrade	Benefit
Different filters on NIRSpec	Reduce red leak to short wavelength and reduce Exoplanet spectrum data acquisition time
Reduce width of small part of a NIRSpec slit	Reduce background light to improve exoplanet spectra S/N
Different filters on NIRCam	Reduce red leak to short wavelength and reduce Exoplanet spectrum data acquisition time
Add passive reflective element on JWST bus	Enhances reflected light signal from JWST to allow AS acquisition

Table 4: Possible JWST Operations Modifications

Upgrade	Benefit	Impact
Allow JWST backup omni to send partial telemetry data from NIRCam to starshade	Bypass Ground for alignment calibration, provide a backup method in case of AS JWST acquisition failure	Additional NIRCam processing software required, minor impact for

A top-level schedule and cost for this development is shown in Table 5. Most of the individual technology elements needed for NWP exist, but they have never been used together. For example, the three major pieces of the starshade deployment system: telescoping tubes, thin edge, and membrane are of high heritage, but have never been combined in this way. Our main task is to integrate the design and test the pieces together as a unit. We believe we have a cost-effective technology development program that can be immediately implemented and bring the system to TRL=6 within 30 months.

Table 5: 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**
Total		**$5M**	**$17M**	**$19M**	**$42M**

V. ACTIVITY ORGANIZATION, PARTNERSHIP, AND CURRENT STATUS

The New Worlds Probe team will implement a management plan fully compliant with NPR 7120.5D. NWP is intended for a Probe-class Exoplanet mission, and therefore will comply with all organization structure mandated by the AO. We assume an NWP Principal Investigator (PI), is directly responsible to the appropriate NASA agency, such as the ExoPlanet Program Office, for all aspects of the mission.

The organization of the activity as it moves forward is still being determined. PI-level leadership has been provided by Webster Cash at the University of Colorado through the New Worlds Observer Study (supported by GSFC and Northrop Grumman Corporation) and by David Spergel at Princeton University through the THEIA study (supported by JPL and Lockheed Martin Corporation). Given the similarity of the outcomes of those two studies, Cash and Spergel have agreed to remerge their teams. Both NWO and THEIA studied mission architectures that assumed a 4 m UVOIR telescope dedicated and designed to work with the starshade. The Space Telescope Science Institute has joined the NWP consortium and will provide the needed expertise in the operation and use of JWST. John Mather, JWST Project Scientist will act as liaison between the NWP and JWST projects. Thus we believe our team covers well all the needed bases both technically and scientifically.

The NWP team will continue to work on refining the mission concept, understanding mission impacts on JWST, developing technology and the verification & validation plan, and conducting research in our testbeds. Particular attention will be given to addressing schedule critical and JWST related risks. The team continues to work on partnerships with industry and international entities, and growing the science community support for NWP. We are also investigating international participation by agencies such as ESA and JAXA where contributions could reduce the total NASA cost.

VI. ACTIVITY SCHEDULE

The planned operational lifetime of the NWP mission is 2 years with a goal for an extended mission of an additional 1 year. The NWP project schedule is shown in Fig. 15. The schedule assumes a project start date of 2011, but we have given the project in terms of Year 1, Year 2, etc., since the date of the Exoplanet Probe AO is uncertain. Phase A duration is 12 months, leveraging the learning from the NWO and THEIA projects. Phase B duration is 12 months and development (Phases C and D) is 36 months. System-level integration and testing lasts 9 months. Specialized starshade testing facilities will be built for the starshade development. Launch is scheduled for June, 2016, approximately 3 years after JWST launch. This permits JWST to perform its key science and NWP the flexibility to design to changes in JWST performance. NWP will then have a planned operational lifetime of 24 months with JWST.

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. 15.

The critical path lies along the Trajectory and Alignment Control system in the schedule. This represents the (non-mechanical) interface to JWST, and is a critical part to the mission success. In particular, impacts to JWST must be studied and carefully controlled. The design, development, and manufacture of this system is given 36 months to reflect the complexity. The systems integration to the spacecraft is relatively straightforward and can be accomplished within the system I&T schedule.

The NWP schedule includes a total of 12 months of reserve for the starshade and 4 months of reserve for the TAC system, a total staggered reserve of 16 months. Mission schedule reserve is held at 4 months. The NWP budget includes funding for this schedule reserve and is $64.3M.

The starshade/payloads/spacecraft may be developed by a separate vendor from the TAC system to facilitate parallel development in order to accelerate the schedule. The starshade payload development and I&T is 17 months. Starshade spacecraft development and testing is 21 months. Starshade spacecraft launch/early orbit checkout is 21 days and the cruise to L2 orbit and checkout is launch date dependent, with a nominal of ~100 days. Transition to normal operations is ~4 months after launch with the mission operating 2 years.

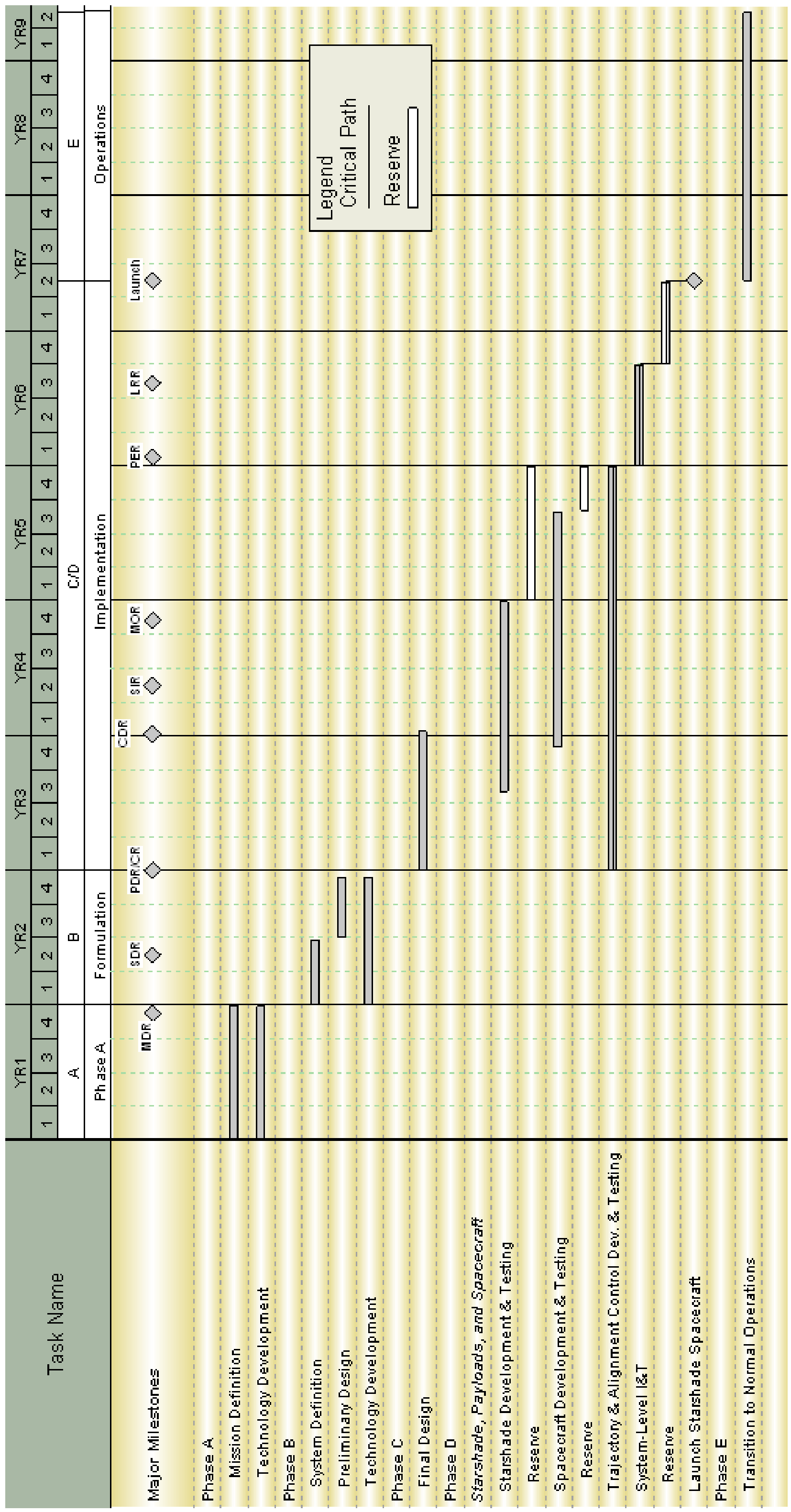

Figure 15: NWP Proposed Project Schedule

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 1 year, Phase B duration of 1 year, Phase C/D duration of 3 years, and a Phase E duration of 2 years of cooperative operation with JWST. The starshade payload and spacecraft will be built in parallel with the Trajectory and Alignment Control system. Specialized test facilities at NGC are required for the starshade. One EELV is needed with to launch the starshade in June 2016. Funded schedule reserve is included in the budget at $64.7M. Thirty percent costing reserves were applied to all cost elements except EPO and launch vehicle.

Table 6: Cost Estimating Methods by Work Breakdown Structure Element

WBS Element	Method
1.0 Project Management	Grassroots by GSFC New Business Office, from 2006
2.0 System Engineering	Grassroots by GSFC New Business Office, from 2006
3.0 Safety & Mission Assurance	Grassroots by GSFC New Business Office, from 2006
4.0 Science & Technology	Grassroots estimate from GSFC science directorate, grassroots estimate from NGC and Ball Aerospace, 2009
5.0 Starshade	Grassroots estimate from NGC, from 2009
6.0 Spacecraft	Grassroots estimate from IDC, from 2009
7.0 Mission Operations	Grassroots estimate from IDC, from 2006
8.0 Launch Vehicle	ROM from IDL, 2009
9.0 Ground Systems Development	Grassroots estimate from IDL, from 2006
10.0 Mission I&T	Grassroots from NGC and Ball Aerospace
11.0 EPO	ROM from IDL

Cost Estimating Methodology

Our costing efforts were centered on achieving realistic estimates for a probe class mission. 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. The Spacecraft, Technology Development, and Starshade Payload costs incorporate latest cost analysis and development as of the writing of the document. Cost elements such as Science, Mission Operations, Ground Systems, Project Management, and System Engineering uses escalated costs developed in 2006 for a Discovery proposal. The starshade cost estimate was generated by NGC 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 validated by IDC grassroots calculations. 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.

Table 7: NWP Project Element Estimate in 2009 Fix Year Dollars

	Base	W/Contingency
Starshade	**427.4**	**555.7**
Starshade Payload	129.6	168.5
Spacecraft	217.0	282.1
Astrometric Sensor	60.8	79.0
Astrometric System	20.1	26.1
Science and Technology	**65.4**	**85.0**
Science	21.4	27.8
Technology Development	44.0	57.2
Mission Ops, Ground, System I&T	**20.6**	**26.8**
mission operations	10.8	14.0
ground systems	3.5	4.6
Mission I&T	6.3	8.2
Mission subtotal	513.4	752.5
Mission wrappers	**48.8**	**127.4**
PM, SE, SMA	46.2	60.1
Funded Schedule Slack	0.0	64.7
EPO	2.6	2.6
Launch Vehicle	**180.0**	**180.0**
MISSION TOTAL	**742.2**	**1059.9**

Cost Results

In order to provide an easy way to see the cost breakout of specific flight/ground components, we present Table 7. 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. The total starshade system with spacecraft cost is $427M; total science and technology is $65.4M; the total mission operations/ground system development and I&T costs are $20.6M, PM/MSE/SMA costs are $46.2M, and EPO at $2.6M. The cost for one EELV (specifically, one Atlas 541) launch vehicles is $180M. One can see that the total lifetime cost including technology development for NWP is $742 Million dollars, and $1060 million with 30% contingency applied on everything except launch vehicle, and including a $64.7 million dollar funded schedule slack.

We have attempted to use the most conservative path when in doubt, and the relatively advanced state of the key technologies gives NWP lower cost risk than is often encountered. Further into the development of NWP we would expect to invite international participants, most likely ESA and JAXA. Their contributions would reduce the total cost to NASA. A detailed cost assessment of the NWP project is underway.

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