Large Precision Deployables for Exo-Planet Missions

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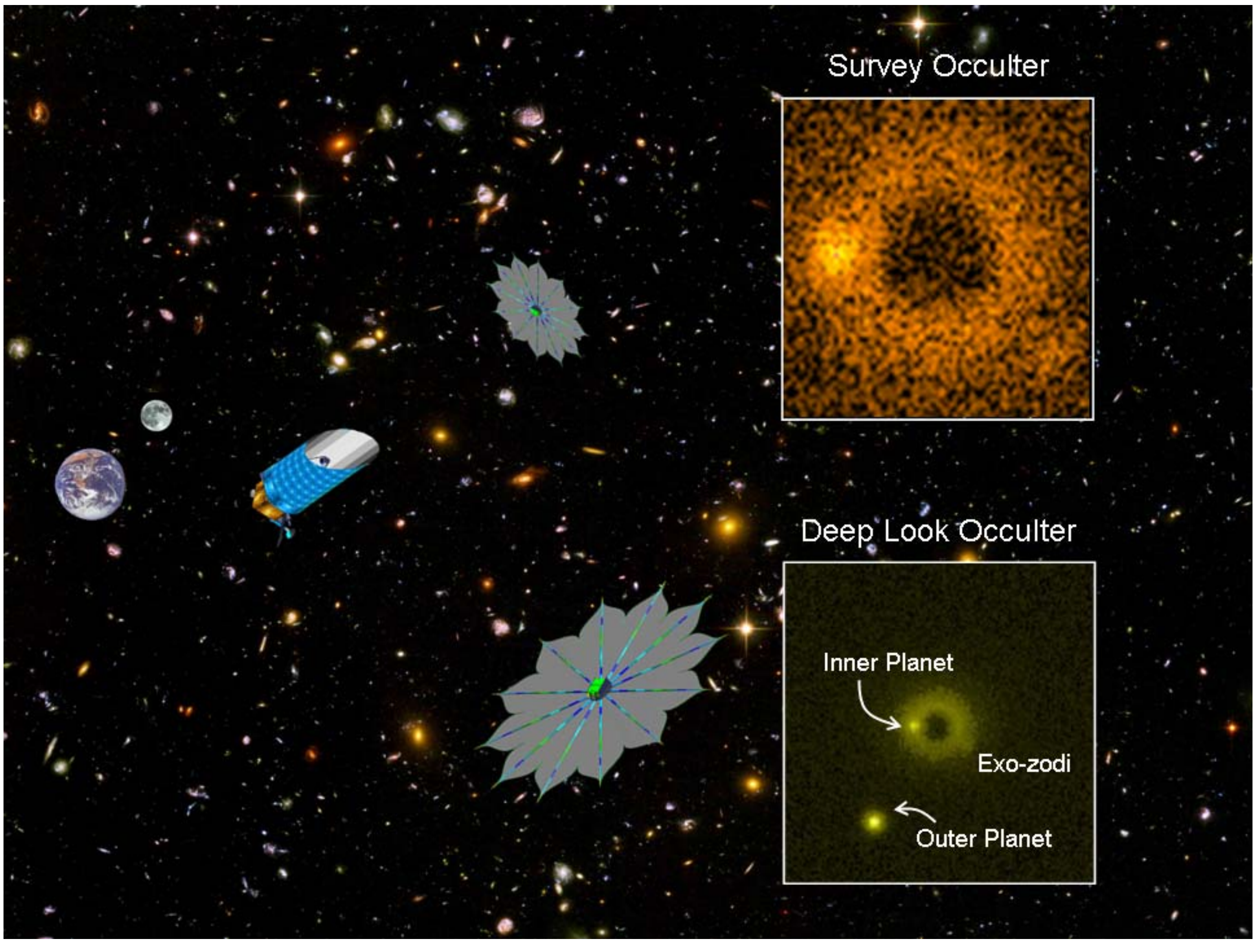

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A. Introduction

For over 40 years, astronomers have been interested in block the light from nearby stars to image an Exo-solar planet.[1,2,3,4] During the Terrestrial Planet Finder Mission Architecture study in 2000, our Northrop Grumman (then TRW Space and Defense) study team conducted an extensive study of possible terrestrial planet imaging architectures at both visible and infrared wavelengths, with designs including coronagraphs, interferometers, free flying occulters, and sparse apertures.[5] Figure 1 shows our study team's assessment of the cost of various architectures for terrestrial planet detection relative to the cost of the Space Interferometry Mission (SIM), compared to their development risk and expected science return.

Since the conclusion of the study, we have been working on developing mission concepts and engineering solutions to the problem of precision deployables, which has applications in a wide variety of terrestrial planet imaging architectures. We describe in this white paper some of our findings, and use in particular the free flying occulter and the large aperture coronagraph as examples to illustrate applications of precision deployables to Exo-planet finding.

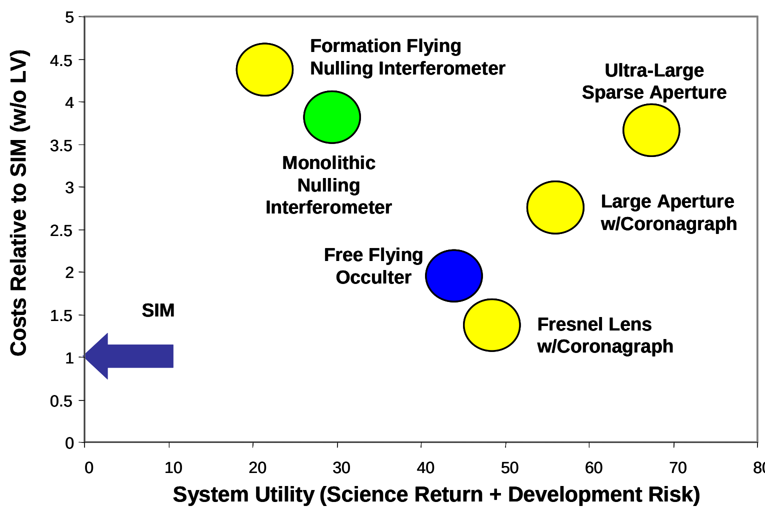

Figure 1. TPF Architecture Overall Comparison

Since 2004 we have been working with Professor Webster Cash at the University of Colorado to develop a mission concept known as New Worlds Observer (NWO).[6,7] The science of NWO is described in a white paper entitled "External Occulters for the Direct Study of Exoplanets".[8]

B. NWO Overview

NWO is a multi-spacecraft mission concept capable of detecting and characterizing Exo-solar planets. Our basic architecture for the NWO is illustrated in Figure 2: a four-meter class telescope spacecraft is located 30,000 to 80,000 km away from at least one occulter spacecraft carrying a starshade that is tens of meters in diameter. The starshade is shaped like a flower, with a solid inner disk and shaped petals that "extinguish" on-axis starlight. This allows the off-axis light from companion objects, such as a terrestrial planet, to be viewed by the telescope.

Since all the starlight suppression is being performed by the occulter, the telescope does not need to maintain exquisite wave front control; this is a general astrophysics telescope. In addition, whole Exo-solar systems can be seen in a single image, since

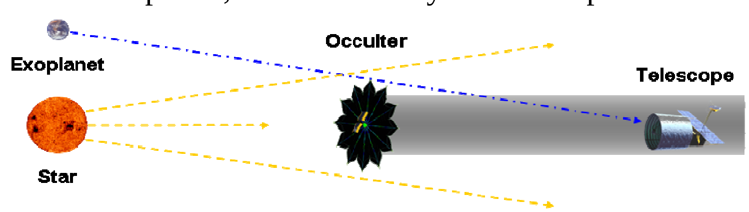

Figure 2: The Basic NWO Architecture, shown with a 4-m Telescope. The Baseline NWO Orbit is a L2 Halo

there is no outer limit to the field of view. This unique capability not only provides more complete information about a planetary system, but also enables simultaneous studies of debris disks, comets and zodiacal dust in the Exo-solar systems. See the Cash, et. al. white paper[8] for details of the occulter's performance.

We have developed an optical simulation code which allowed us to establish an engineering baseline to study the manufacturing tolerances and deployment accuracy needed for a free flying occulter system, i.e.: a 30 meter diameter (tip to tip) occulter utilizing Cash's hypergaussian apodization function can produce a shadow at least 5 meters across, with the on-axis starlight suppression reaching 10^{-9}. Two dimensional analyses show that per pixel contrast levels are lower than 10^{-10} in the image plane, because the occulter acts as a defocusing lens. Our off-axis source modeling indicates that when this occulter is operated 30,000 km from the telescope, the effective inner working angle (IWA) is ~85 milli-arcseconds (mas), and fractional planet brightness goes from 0 to 1 within ~30 mas. According to our optical simulations, this occulter needs 1:10,000 shape fidelity to enable the necessary suppression, translating to millimeters of edge control. The tips of the occulters will need to be deployed to within millimeters of each other, and held in position. These tolerances are within the current state-of-the art for aerospace manufacturing techniques.

Extensive exploration of the system design space[9] shows smooth changes to the occulter performance when input parameters are varied. For example, increasing the occulter size is directly proportional to increasing shadow width and depth. Thus, larger occulters will result in looser tolerances, but will need to be placed further away from the telescope. Occulters with IWA less than 50 mas may be constructed, and trade longer travel time for more complete observations of each target. Verification of our optical and system modeling is currently being carried out via a Northrop Grumman External Occulter testbed.

We are continuing to refine our baseline occulter design to relax the engineering tolerances and to maximize ease of manufacturing. All our work to date indicates the hypergaussian petal shape provides a robust design that tolerates millimeter level deviations from the ideal shape, and 10 to 15 degree tilts of the occulter with respect to the telescope's line of sight.

C. Precision Deployment of Occulters

Since available launch vehicles have fairing diameters restricted to less than 5 meters, external occulters must be folded during launch, and deployed after they reach orbit. Deployment of the occulter can be accomplished a number of ways. Our current deployment trade space includes the options shown in Figure 3.

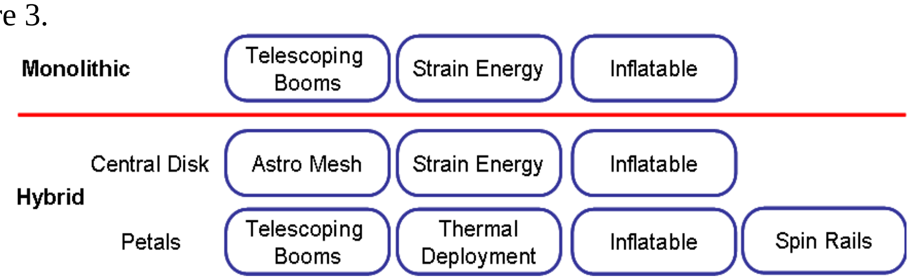

Figure 3: Precision deployment technology options

Deployment trades can be separated into monolithic or hybrid deployment options. A monolithic deployment is simple: the optical element is deployed via a single method as a whole structure. Deployment of our current baseline NWO occulter (Figure 4) may be accomplished with a system of telescoping booms shown in Figure 5. The tips of the petals are attached to the tip of the innermost of several nested telescoping booms. Each petal has its own set of stem drive + telescoping boom. The booms are nested during launch; once on orbit, a containment shield is released and the occulter fabric unfolds like an umbrella. Motor driven stem drives push out the boom segments.

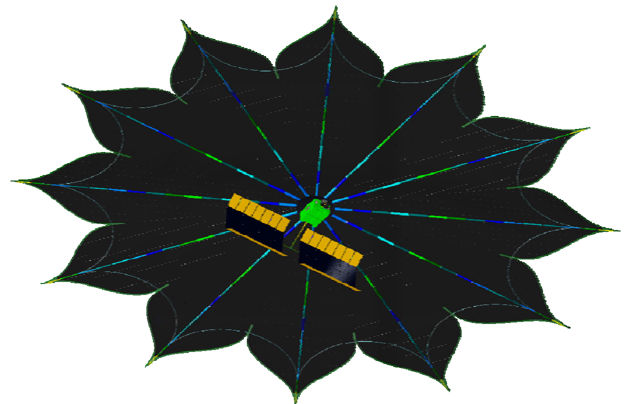

Figure 4: NWO Occulter Spacecraft

A production line example of the Astro ISIS telescoping boom is shown in Figure 6. This particular mast has a deployed length of 7.3 meters, capable of holding 137 kg of cantilevered mass on its tip. This boom is extremely stiff, with an axial strength greater than 10 kN.

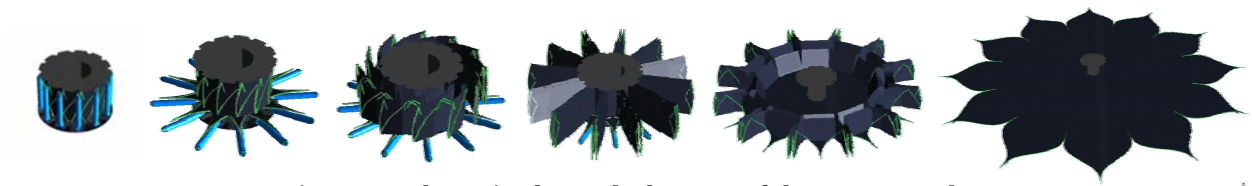

Figure 5: Telescoping boom deployment of the NWO Occulter

Although our baseline occulter design uses telescoping booms for the starshade deployment, we are continuing to study other options. Figure 7 shows our design for a strain energy deployment system. We now have constructed subscale test article of this system to evaluate its performance.

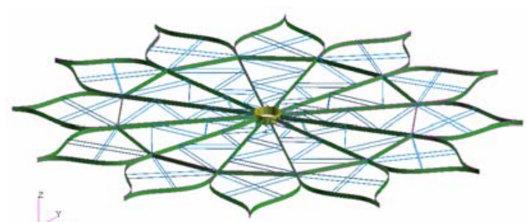

Figure 7: Strain Energy Concept

A hybrid deployment approach could trade complexity of deployment to better meet the requirements of different segments of the optical element. For example, the NWO occulter's central disk does not have precision deployment requirements; it only needs to be opaque and to provide structural support for the petals. Instead of telescoping booms, we could utilize the perimeter truss from one of our AstroMesh© antennas[10] to deploy the central disk, and greatly reduce the mass of the central disk. Our 30 meter NWO occulter has a central disk 12 to 15 meters in diameter. AstroMesh© antennas ranging from 5 to 20 meters are readily available and are flight qualified with a technology readiness level (TRL) of 9. Some properties of the Thuraya[11] spacecraft's 12 meter AstroMesh© antenna are listed in Table 1.

Figure 6: Astro ISIS Telescoping Boom

The petals can then be deployed by methods such as inflatable petals, petals that are heated to expand and then UV rigidized, or spooled petals that are spin-deployed. In this configuration, the booms would be attached to the reinforced edges of the AstoMesh© perimeter truss. Compared to the monolithic design, this method would use fewer telescoping boom segments, but would retain the structural stiffness and reliability of the telescoping booms, while reducing the overall mass of the occulter spacecraft.

Table 1: Select properties of the 12 m AstroMesh

12 m Astro Mesh Property	Value	Unit
Stowed diameter	0.91 by 1.14	m
Deployed diameter	12.25	m
Geometrical figure accuracy	(RMS) 1.10	mm
Thermal figure accuracy	(RMS) 0.05	mm
Manufacturing figure accuracy	(RMS) 0.50	mm
First mode frequency	0.80	Hz

The sunlit edges of the occulter will be seen by the telescope as local bright spots, and approximately 1 m^2 of Lambertian scattering area is enough to overwhelm an Exo-Earth signal. A "knife-edge" treatment on the perimeter will be used to minimize the edge surface area to reduce scattering toward the telescope. Here, the large occulter to telescope separation helps mitigate the light scattering problem, as the telescope intercepts a very small solid angle of the edge. An edge with a radius of curvature of 100 microns will scatter less than 30 magnitudes of sunlight towards the occulter. Manufacturing this precision edge is within the current state-of-the-art and requires no new technology development.

To obtain the precision required for this edge we could use a flattened edge member made from a shape memory material which uses the inherent tension in polycarbonate materials to retain its shape after being stowed and deployed. In addition, cross tensioning straps would hold the petals tips in position relative to each other. Negator springs or magnetically damped pistons positioned at petal joints would ensure that any motion excited by reaction wheel imbalances or thruster firings would be quickly damped and do not perturb position of the petals.

The baseline material for our NWO occulter is the 2-mil Kapton E membrane being developed for the JWST sunshield. The highly reflective Silicon and Vacuum Deposited Aluminum (VDA) coated membranes for the JWST sunshield were developed by NGST, and a similar engineering effort can be undertaken to develop the membranes for NWO. Calculations based on JWST sunshield material show that it is thermally stable, three layers of this material offer an opacity greater than 1 part in a trillion at visible wavelengths, and will provide adequate protection from micrometeorites. Studies of the JWST sunshield material show that most of the micrometeorites that penetrate the first layer sputter onto the second layer of the sunshield material. We expect only a few micrometeorites can penetration all three layers, and expect low probability that the holes would be aligned with the line of sight to a target star. For light-weighting, the three layers would be stitched together with z-stringers, creating a 5 cm gap between the layers, to eliminate the use of spreader bars.

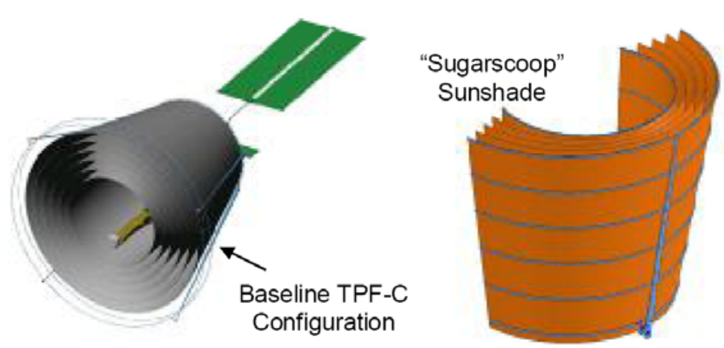

Figure 8: Precision Deployable Structures for TPF-C

Precision deployable structures are

also required for other terrestrial planet finding missions. Figure 8 shows the sunshade designs that NGST developed for JPL under our TPF-C Design Team support Contract. On the left is the baseline TPF-C configuration with a 12.5 m conical sunshade using thermal control technology developed for JWST to minimize thermal variations in the telescope optics when moving from one target to the next. A large solar sail is used to compensate for solar radiation pressure effects. An alternate sunshade design is shown on the right.

D. NWO Telescope

The telescope for the New Worlds Observer mission only needs to be diffraction limited in the visible. An on-axis telescope with $\lambda/15$ wave-front quality primary would be more than adequate. To minimize telescope cost and development schedule we plan to use a 7-segment primary that incorporates the mirror alignment and wave front sensing and control technology developed for JWST which is achieving very high Strehl ratios on the JWST telescope testbed. The mirror segment would be attached to a non-deployable support structure, since the NWO launch vehicle would have a 5 m diameter fairing. We selected a Three-Mirror Anastigmatic design for the telescope to obtain a large field of view for general astrophysics observations while the occulter is being moved to the next target. Our strawman instrument suite includes a high resolution imager and spectrometer for planetary observations plus a wide field imager and an imaging spectrometer for general astrophysics observations.

If the coatings on the first 3 mirrors of the telescope were magnesium fluoride over coated aluminum, the NWO telescope could also continue the UV-Optical observations of the Hubble Space telescope, complementing the Near-IR and Mid-IR observations of JWST. Ultraviolet observations of Exo-solar planetary systems might also detect “geocoronal” Lyman-α emissions from Earth-like planets, and (possibly) H1216 and OH3090 emissions fro Exo-solar comets.

E. NWO Precursor Missions

Our external occulter is designed to block out a bright source to enable observations of a faint companions. It is fully scaleable to much smaller missions to validate external occulter systems performance and operations. It can also be scaled up to meet the requirements of larger missions such as Life Finder and Planet Imager.

Table 2: Small Occulter Capabilities

Occulter Diameter	Distance	Effective IWA	Shadow radius
[m]	[km]	[mas]	[m]
9 m	3,700	201	1.0
12 m	6,500	152	1.3
16 m	13,300	101	1.16

The primary consideration for a precursor mission is the size of the telescope to be used. For example, we could use the occulter with a 1.8 meter telescope, and achieve a pixel to pixel contrast suppression of 10^{9}, and the IWA shown in Table 2. Some options for a NWO precursor mission, ordered by increasing cost and science return are an:

1. occulter alone, with a ground based telescope (such as SOFIA)
2. occulter alone, with an existing space telescope less than 2 m in diameter
3. occulter alone, with an existing space telescope greater than 2 m in diameter
4. occulter with a dedicated telescope less than 2 m in diameter
5. occulter with a dedicated telescope greater than 2 m in diameter

This list provides a range of missions from an Explorer class precursor mission to a full scale terrestrial planet finder mission.

F. NWO Technology Maturity

Table 3. Technical Challenges Design Options, and Technology Sources for External Occulter Missions

Technical Challenges	Design Options	Technology Sources
Deployment of large starshade	Booms, inflatable, strain	SRTM, military missions
Controlling starshade shape to ~mm	Deployed, inflatables, truss	Military missions
Controlling sunlight (edge) scatter	Knife edge, ultra-black paint	Lab demos
Alignment sensing to ~ 30 cm	Telescope, occulter cameras	Deep Impact,HST WFPC
Retargeting capacity (ΔV)	Solar-electric, slower slews	DS-1, DAWN, NEXT
Large telescope (up to 4 m)	Meniscus, segmented	JWST, Kepler, ALOT
Fitting in launcher and mass limits	Membranes, lightweighting	JWST

Table 3 lists the key technical challenges for external occulter missions, along with some of the design options for meeting these challenges and the sources of the existing technologies that can be utilized to meet the mission requirements. All the required technologies have been demonstrated in the laboratory and many are already flight-proven. No "inventions" are required for the NWO mission, just good system engineering. Over the last 40 years NGST has deployed more than 2300 deployable elements for more than 600 space systems with 100 % mission success. This includes many large structures in space including our Chandra spacecraft's solar arrays which measure 19.7 meters tip-to-tip, three of our 12.5-m diameter AstroMesh antennas for Thuraya, a 100-m dipole antenna for the Radio Astronomy Explorer spacecraft, and six of our Tracking Data Relay Satellites (Figure 9), each of which had 45 deployable elements including two 4.5 meter mesh antennas similar to the Galileo high gain antenna. JWST (with many fewer deployable elements than TDRS) will use motorized hinged mechanisms and telescoping booms to deploy an ~ 10-m by 20-m sunshield as well as a 6.6-m primary mirror and a secondary mirror support structure. The JWST sunshield is currently at TRL-6.

Figure 9. The Tracking and Data Relay Satellite

Large inflatable structures manufactured to millimeter level tolerances have also been developed, including an inflatable 15-m radio antenna that was deployed from the space shuttle and inflated in Earth orbit. Several techniques are available for rigidizing the inflated structures. The technology for shape control of both mechanically deployed and inflatable structures to sub-mm tolerances has been demonstrated in flight (TRL-9).

Techniques for controlling scattered sunlight are also available. 100-micron radius of curvature edges are well within the state of the art, and techniques for making ultra-black metallic surfaces 20 to 30 times less reflective than the best black paints have recently been demonstrated in the laboratory (TRL-3 to 4).[12,13] Placing the occulter on the line of sight from the telescope to the target star would be achieved in several steps. Coarse alignment can be achieved with DSN tracking data for the occulter and telescope, supplemented with optical navigation data from an astrometric camera on the occulter. Fine alignment could then be achieved by imaging the target star and the occulter with a camera on the telescope. Error signals during an observation could be provided either by the planetary imaging camera or a separate camera on the telescope sensing a brightening on the one side of the occulter as it started to drift off the target star. The High Resolution Instrument on Deep Impact (TRL-9) could be used for optical navigation, while an instrument like the HST WFPC (TRL-9) could provide error signals for fine alignment.

An external occulter requires a velocity change 40 to 70 m/s for each target. This requirement can best be met with a solar electric propulsion system like that flown on DS-1 (TRL-9) and being readied for launch on DAWN. The NEXT Xenon ion propulsion system[14] currently under development by Glenn Research Center (TRL~5.5) will have 30% higher specific impulse, 2.6 times the thrust, and 3 to 4 times the lifetime of the NSTAR thrusters on DS-1 and DAWN. It is the baseline SEP thruster for NWO.

Large meniscus mirror (VLT, Gemini, Subaru) and segment mirror (Keck, Hobby-Eberly, SALT) telescopes for astronomical observations are in operation on the ground the segmented mirror technology for JWST recently achieved TRL-6. The Goodrich Corporation has also developed their segmented, active optics Advanced Large Optical Telescope (A LOT) to TRL-7 (engineering model demonstrated in a simulated space environment).[15] Finally, the packaging techniques and lightweight designs required for NWO have been demonstrated by many space programs, including TDRS and the Mars Exploration Rovers (TRL-9). It will be demonstrated again by JWST.

G. Summary

Free flying, external occulters have significant advantages when compared with other architectures for planet finding, including relatively cost and development risk. The readiness levels for the key technologies are quite high and no “show stoppers” have been found in the several years that we have been studying occulters. Much work remains to be done to develop mission and operations concepts and spacecraft designs for external occulter terrestrial planet finding missions, but this is the most promising architecture we have found to date.

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