New Worlds Observer

Technology Development Plan

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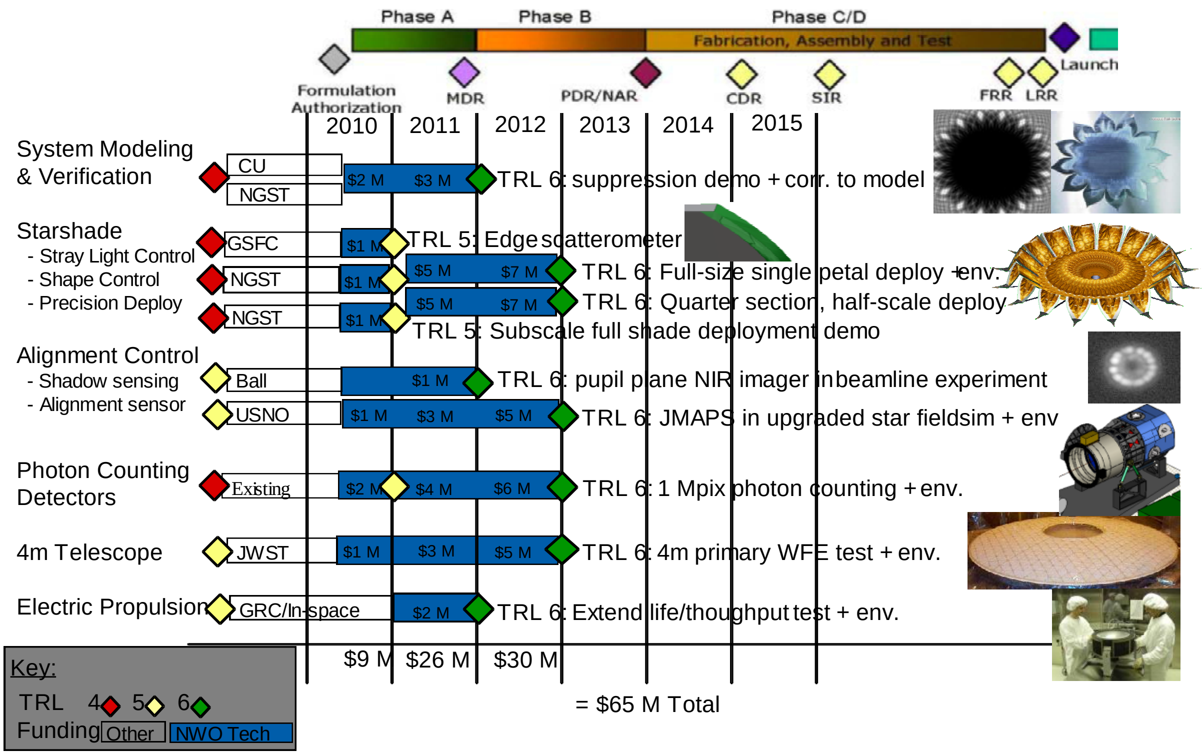
Executive Summary

New Worlds Observer (NWO) is a mission to find and characterize extra-solar planets as well as enable cutting edge general astrophysics in this decade. For exoplanet work, the parent starlight is rejected through the use of a free-flying starshade. The starshade technology development is a breakthrough for astrophysics and its maturation is valuable even if a dedicated mission is not approved. The starshade technology is scalable to match any space telescope from 1 to 16 meters aperture in a low gravity (libration or drift-away) orbit. The point design NWO mission, with launch in 2018-2019, uses a 4 meter UV/Visible space telescope with a powerful general astrophysics and exoplanet imaging and spectroscopy instruments. The matched starshade for this point design is 50 meter (62 m tip-to-tip) located about 80,000 km away. The point design mission project schedule sets a preliminary design review (PDR) at the end of 2013 and this drives technology development to reach its TRL 6 milestones before that date with margin. We have reviewed the status of the technology needed to build and fly NWO in a timely manner with well-controlled risks. The figure below shows the technology development roadmap that will take all needed technologies to TRL 6 in 30 months for a cost of $65M (not including a 30% cost margin held at the project level). This gives 1 year of schedule margin before the project would be required to show TRL 6 for every required technology by the PDR.



This technology development roadmap shows how the six “tall poles” are brought to readiness and the technology development funding required for each task. Our definition of tall poles is technologies required for the mission to meet its required performance but that currently have TRL less than 6. This means they have yet to prove that they can meet performance requirements, operate in the “relevant environment” for the required life, and survive launch in the mass allocated to them. We make a distinction between technology development shortfalls where the device or system needed does not yet exist at the performance level needed and the need for reengineering where the device or system exists in some closely related form and performance to what is needed but requires additional engineering to fit the specific need of New Worlds. The identified six tall pole technologies are system modeling and verification, starshade, alignment control, photon counting detectors, 4m telescope, and electric propulsion. In this document, we also explain some “perceived tall poles”, that is, technical issues that are well understood in some communities but not widely known in the NASA science community. These include starshade materials and coatings, micrometeoroids impacts, starshade thermal control, alignment control actuation and communication, thermal control, and pointing and vibration control.

Of these, only Starshade Deployment and Shape Control is both crucial to the success of the mission and is new, in that nothing of a similar shape and precision has been built before. In that case, our baseline starshade design consists of components (membranes, hinges, latches, actuators) that are all TRL 6, but have not been demonstrated to work together in a starshade application to the required performance levels. The starshade system therefore is assessed only as TRL 4 today and is the critical path to getting the New Worlds mission technologies to TRL 6. All the other tall poles have alternatives – technical offramps that would still allow the mission to go forward, albeit at modified performance or cost. For each tall pole, the development risks are listed, each with mitigation, offramp (an alternative design that does not performance as well or weighs or costs more), and impact of taking that offramp.

This document is a technology development plan for the NWO mission. It is ready to be executed and would bring the six technologies to TRL 6 in 30 months, thereby creating a one year margin before the TRL 6 gate at the PDR. This document includes a mission summary, a description of the tall poles (both real and perceived), a dedicated section for each of the six technologies, and technology development management cost and schedule. For each technology, given are: motivation, requirements, state of the art, development plan, detailed plans for 2 to 5 tasks per technology with cost and schedule, risks, and interactions with others.

In summary, the technology overall exists, but needs to be pulled together and tested quickly so that the flight design can benefit from the experience so generated.

Mission Overview

The public wants to know what marvels of the Universe lie hidden over our horizons. Are there warm, watery paradises awaiting a space-faring race? Do planets everywhere harbor teeming life? Or is Earth a unique and fragile outpost of life in a vast and empty Universe? NASA may be able to definitively address these questions in the coming decade.

Hundreds of planets have now been detected through ground-based radial velocity measurements. Many hundreds more (including some true Earth-like planets) will likely be detected by the Kepler Mission in the next three years. Space missions under design today must acknowledge that detecting the existence of Earth-like planets is no longer a goal worthy of the high price and long lead time inherent to a space observatory. Only direct spectroscopy, pushed down into the habitable zones of many dozens of planetary systems will provide the answers to the burning questions that will remain at the forefront ten years from now.

We have shown that the starshade technology cleanly resolves the issues of exoplanet observatory design that have arisen over the last decade. Full suppression of the starlight before it en-ters the telescope relieves the telescope of all special requirements such as ultra-high wave front quality correction and maintenance.

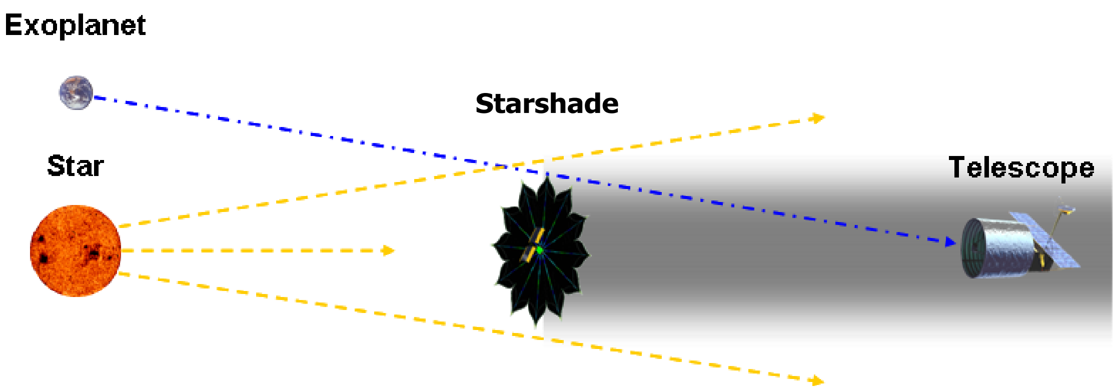


Figure 1: The New Worlds Observer Mission uses a starshade to block the parent starlight while observing the exo-planet.

Indeed, we have shown that starshades can be used in conjunction with any telescope flying in a low acceleration environment like L2. A starshade can be designed to work with JWST with no changes to the current telescope design. The telescope need only be sufficiently powerful to re-solve and study the exoplanetary system revealed once the starlight is suppressed. Having full versatility in telescope design makes the mission even more valuable, since the majority of time is spent by the starshade moving from target to target. So most of the time the telescope is in service to the rest (i.e., non-exoplanet part) of the astronomy community.

An external occulter works as is shown schematically in Figure 1. An opaque screen, larger in diameter than the aperture of telescope is flown into the line of sight from the telescope to the star. If the shade is sufficiently distant it will subtend a small angle and can blot out the star, while allowing the light from an exoplanet to slide unobscured over the edge. Geometrically, the occulter would have to be at least 5m in diameter to cast a shadow large enough to fully darken the telescope aperture. And, for a 5m object to subtend 0.2 arcsecond, it must be 5Mm (5000km) away. So the idea fundamentally requires two spacecraft flying at large separations.

In the course of this study we settled upon a set of baseline mission architecture parameters, given in Table 2. This starshade design represents a balance between size and cost on one side and Inner Working angle, and long wavelength limit on the other. The shade is 50m in diameter to the petal inflection points and 62m tip-to-tip. It is made of opaque plastic and is not an optic in the conventional sense of the word. It is only the projected outline onto the sky that determines its performance.

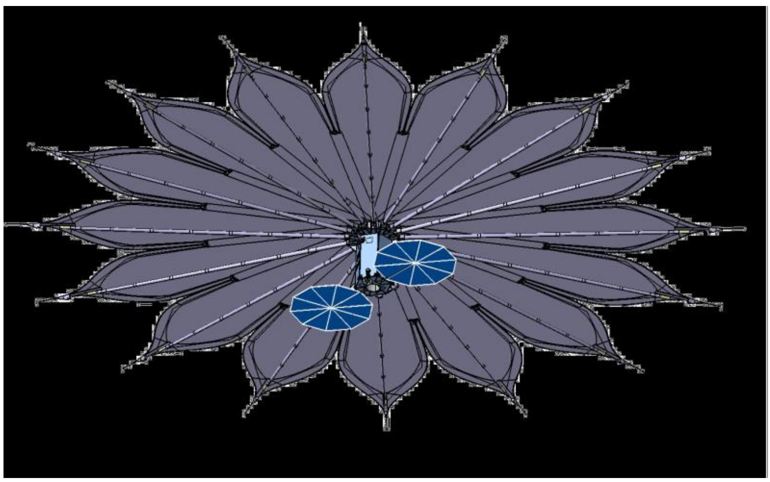


Figure 2: CAD Drawing of the 62m tip-to-tip starshade spacecraft.

We have shown in this study that the starshades can be used in conjunction with any conventional telescope in a low acceleration orbital environment like the Sun-Earth L2 point. But the size of the telescope makes a major difference in what can be observed. Figure 5 shows a series of simulations of our Solar System viewed pole-on from a distance of 10pc with a starshade blot-ting out the central star. As the diameter of the telescope increases from left to right, the exoplanets emerge from the confusion. The diffraction limit on a telescope determines its resolu-tion and hence the quality of observation on a distant system. A 10m telescope, returns truly spectacular images with Earth-like planets leaping off the page. However, with a telescope of only 1.5 meter aperture the resolution has fallen to the point where individual planets cannot be resolved from each other, and many planets would be difficult to separate from the fog of exozodiacal light. We have chosen to study a 4m telescope as that is the largest that can be readily built in the coming decade.

Technology Tall Poles – Real and Perceived

Here are listed the real and perceived technology "tall poles" for the New Worlds Observer mission concept. Our definition of tall poles are technologies required for New Worlds to it's required performance that have Technology Readiness Levels less that are less than 6. This means they have yet to prove that they can meet performance requirements, operate in the "relevant environment" for the required life, and survive launch in the mass allocated to them. In this discussion we will make a distinction between technology development shortfalls where the device or system needed does not yet exist at the performance level needed and the need for reengineering where the device or system exists in some closely related form and performance to what is needed but requires additional engineering to fit the specific need of New Worlds. The identified six tall pole technologies are system modeling and verification, starshade, alignment control, photon counting detectors, 4m telescope, and electric propulsion. We also list "perceived tall poles": technical issues that are well understood in some communities but not widely known in the NASA science community. These include starshade materials and coatings, micrometeoroids impacts, starshade thermal control, alignment control actuation and communication, and telescope wavefront sensing and control, thermal control, and pointing and vibration control.

Technology Development Needs

1. System Modeling and Verification-
Diffraction modeling of the starshade and the NWO system are key to proving the performance of the New Worlds Observer and establishing manufacturing tolerances. Two critical aspects of this modeling is the validation that those codes give accurate results using subscale tests and that the translation from subscale to full systems is well understood since it is not physically possible to validate a full size NWO on the ground. To test these diffraction models a beamline experiment is run. The limitations on the beamline will likely limit the demonstration to only 10^8 contrast and the remaining two orders of magnitude will have to verified by models validated with the beamline test. Since it will be impossible to test the New Worlds Observer system at its operating separation, the starshade and telescope elements will be tested independently and the results included in a system model (see previous tall pole). Testing of a 50 m starshade to determine accuracy is included in the PDS tall pole. Testing of a 4 m space telescope is within the state of the art bounded by HST and JWST. Current TRL: 4.

2a. Starshade Deployment and Shape Control-
The precision deployment system (PDS) for the starshade is one of the true tall poles. Subsystem elements of the system exist at high TRLs but nothing of similar shape or precision has been built before. Multiple deployment approaches have been identified that are capable, in principle, of meeting NWO needs. However, these must be quantitatively studied for feasibility, risk, cost, and system performance in order to reduce the list of options to two or three approaches that can be matured through engineering prototypes, eventually leading to the selection of the most suitable and

affordable architecture. Shape control is closely related to the PDS and is another true tall pole. Once deployed the starshade must maintain its shape to within the required tolerances needed to perform the science. Essential to understanding this is the starshade performance-tolerance relationship. Knowledge of this relationship will set the requirements for shape control. Current precision deployed systems have shape control to around 2 or 3 mm for large systems (simpler shapes); current analyses suggest that shape control tolerances of order ~1 mm will be needed to achieve the required science performance and that these tolerances are a function of the level of starlight suppression. Technology development will be required here but detailed analysis must await a requirements definition from starshade performance/tolerance analysis. Current TRL: 4.

2b. Starshade Straylight Control-
Stray light control is, most likely, a reengineering effort and not a technology development. The edge of the starshade must be analyzed to ensure that any sunlight scattered into the telescope is well below the planet's brightness. Similarly, the opacity of the starshade material must be sufficiently small that the transmitted light (through the starshade) is also well below the planet brightness. These effects must be carefully modeled and assessed before we will know if this is a "pole" of any size. Current TRL: 4.

3. Alignment Control-
This is another tall pole, although in this case it is only the formation-flying sensor that is truly a tall pole. The control actuators, algorithms, communications, and other necessary elements are not tall poles. Even the formation-flying sensors may be a candidate for reengineering. The key issue is the resolution of the fine sensor – it must deliver an error signal with sufficient resolution to allow the control law to keep the telescope in the shadow of the starshade. The baseline alignment sensor is USNO's JMAPS camera on the starshade spacecraft. The baseline shadow sensing technique is a NIR pupil camera in the main science telescope. Current TRL: 5 for Alignment Sensor, 5 for Shadow Sensing.

4. Photon Counting Detectors-
This is a tall pole because it will be very difficult for any spectrometer, regardless of starlight suppression approach (starshade, internal coronagraph, nulling interferometer) to efficiently obtain a spectrum of an exoplanet without the low noise performance of a photon counting visual/near infrared detector: without photon counting detectors exposure times will be measured in weeks, with them, only hours. Similar detectors exist for other wavebands, but all those that operate in Vis/NIR bands are all at relatively low TRL levels. There are a number of different technology approaches that are being pursued in the detector community, each with its potential advantage. This photon counting technology has very broad application (civilian and military) apart from New Worlds application funding and our mission can benefit from the best available at the time needed. Current TRL: 4 depending on the specific technology.

5. 4m Telescope-
Lightweight mirrors are an enhancement, not a requirement for NWO. Existing mirror technologies provide sufficient lightweight performance, however lighter, lower cost

mirrors are always desirable and NWO will select the most appropriate mirror technology when necessary. We also recognize that a space telescope diffraction limited in the visible of a 4m diameter has not yet been demonstrated. Therefore a demonstration of the actual mirror fabrication technique is prudent before implementing the mission. The selection of mirror materials will be influenced by whether the primary is a monolith or segmented. Current TRL: 5.

6. Electric Propulsion-
The NEXT electric propulsion system technology products developed by NASA GRC is needed for the high Isp to allow moving the starshade between many targets with a reasonable fuel load. This development has been funded by the NASA In Space Propulsion Program and all components will reach TRL 6 in 2008. Continued life testing will continue in 2009 as proving NWO mission propellant throughput will be required before this can be retired as a tall pole. Current TRL: 5.

Perceived Tall Poles

Starshade Materials and Coatings, Micrometeoroids Impacts-
The current NWO architecture uses the JWST sunshade material as baseline starshade material. This material has been extensively analyzed and tested, including environmental and micrometeoroid impact, and will be further studied as JWST moves toward launch. These are not tall poles.

Starshade Thermal Control-
Thermal control of the large starshade is not a tall pole. It is a very important engineering aspect of the concept, but the analytic and sub-scale test of JWST starshade materials and layer orientations shows that this is well within the experience base.

Alignment Control Actuation, and Communication-
Although the sensing part of alignment control is a tall pole (see above), the rest of the system is not. The fine control to maintain positioning of a vehicle using a set of small conventional chemical thrusters has been demonstrated multiple times in space with the autonomous docking of the Progress, as well as recent ATV and Orbital Express successes. The inter-spacecraft communication delay is a fraction of a second. Given a sufficiently accurate and low noise sensor, the rest is not hard.

Telescope Wavefront Sensing and Control-
This is not a tall pole for NWO since the requirements on the optical system are those for any “conventional” telescope. Our images must be high quality, but do not have the exceptional requirements of internal coronagraphic systems.

Telescope Thermal Control-
Similar to thermal control for the starshade, this is not technology tall pole but a engineering issue. The telescope is neither cryogenic nor does it require exceptional thermal stability.

Telescope Pointing and Vibration Control-
Although the pointing jitter of 5 mas and primary mirror vibration of 10 nm are challenging, current technologies such as the passive vibration isolation of reaction wheels and payload from the spacecraft as practiced on JWST will meet the need with margin. No picometer stability or nanoradian pointing heroics are required as with interferometers or internal coronagraphs. Also, the structural damping is not extremely low, like the cryogenic JWST telescope.

Technology Development Plan Details

Here, each section is devoted to one of the tall pole technologies and the plan to meet the TRL 6 milestone is described. Each technology addresses the motivation, requirements, and current state of the art for that subsystem. Then the tasks are described along with the estimates on cost, schedule, risks, and interactions with other related users and developers.

1. System Modeling and Verification

Motivation:

The modeling and verification of the NWO system and the starshade in particular is critical to ensuring that the starshade achieves the performance required to meet the science goals. We need to derive requirements that, if met, will garentee a certain level of scientific return from the mission. The starshade's optical performance is the most critical area that we need to model and validate since the starlight supression is done by this element and it is the most unique and unprecedented past of the NWO system.

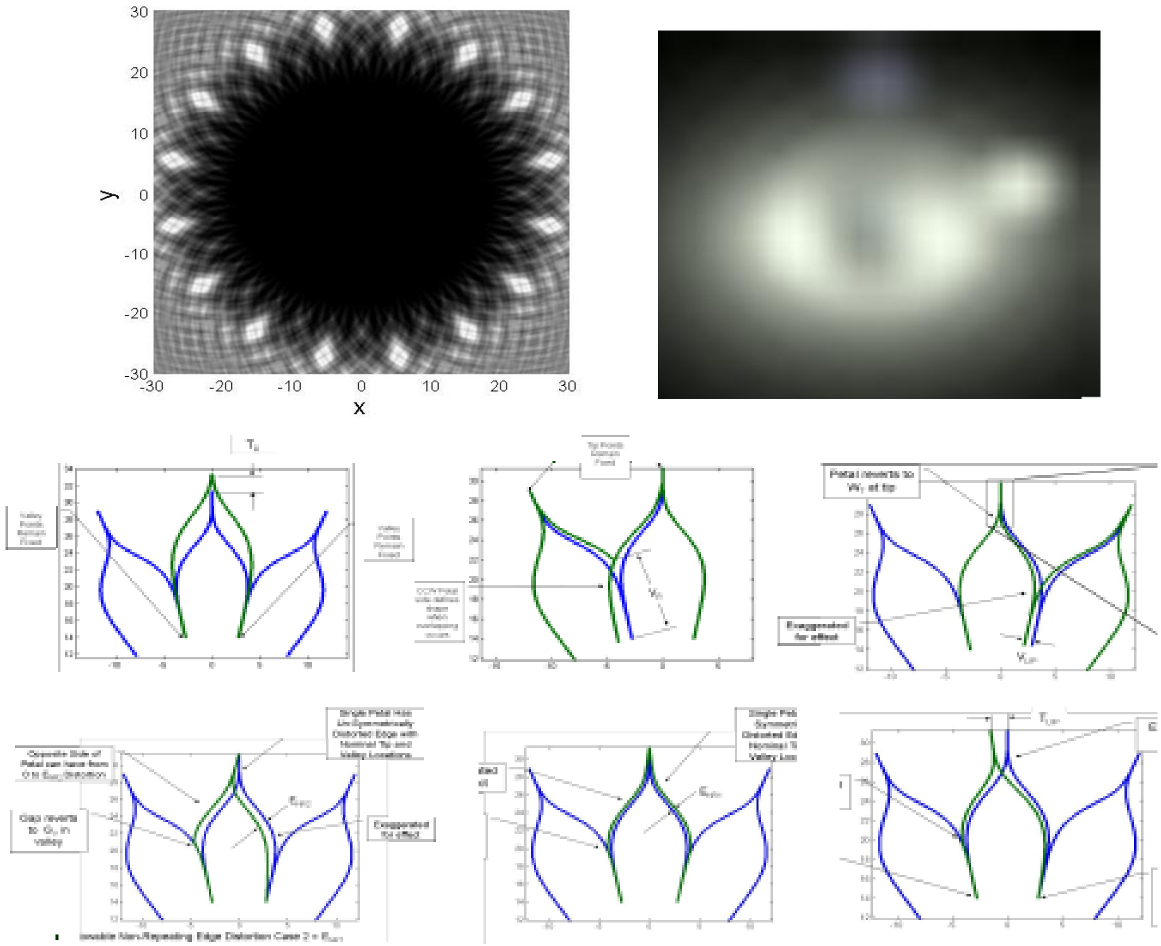


Figure 1.1: System Modeling and Validation Simulations

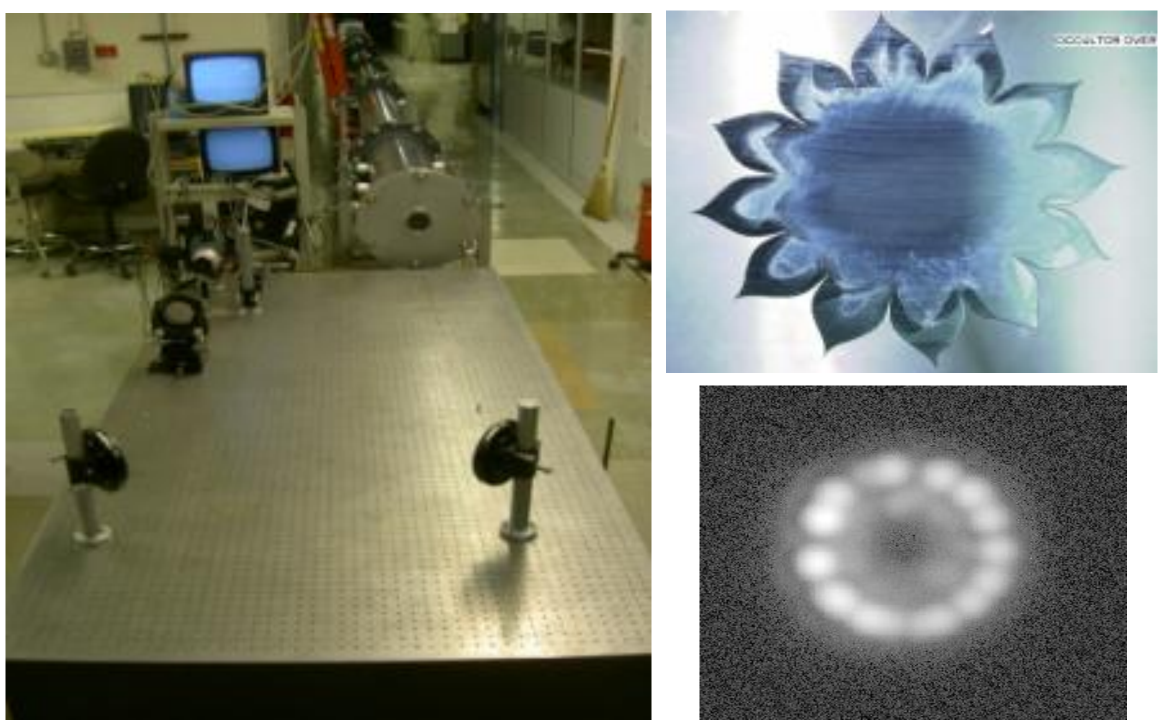


Figure 1.2: System Modeling and Validation Simulations

Requirements:

Performance 1: Set of shape requirements that can be applied to the shape control and precision deployment tasks.
Performance 2: Set of edge requirements that can be applied to the precision deployment and stray light tasks.
Performance 3: Verification that the model predictions and testbed lab demos produce the same results.
Performance 4: Full observatory error budget.
Performance 5: Plan to verify that the starshade structure meets the shape and edge requirements.
Mass: N/A
Environment: N/A

State of the art:

SOA Technology: Current (2008) modeling and sub-scale beam line tests.
Performance 1: Shape influence functions on contrast on a term by term basis have been derived.
Performance 2: Edge scatterometer testing demonstrated at GSFC in 2008.
Performance 3: Lab demos match models to the noise floor of the current beamlines.
Performance 4: Only a term by term error budget exists, not integrated.
Performance 5: The current plan is overhead photogrammetry (only rough sketch of this concept) and edge scatterometer testing.
Mass: N/A
Environment: N/A

Planned Development:

This task involves modeling the precise performance of the starshade, correlating the models with testbed results, deriving requirements that the hardware must meet, and creating a plan to verify that the requirements were met. The requirements derived here will apply to several of the other technologies being developed including shape control, precision deployment, and stray light control. Most of this work will involve running existing code and improving the code to model the optical performance of the starshade. These predictions will be compared with results from the testbeds showing the performance of sub-scale starshades. We will also integrate models of the starshade structure developed for the other tall poles into our analysis of the requirements on the starshade structure.

Another part of this task is to develop a V&V plan to confirm that the starshade will meet the stated requirements. We will describe the set of tests, models, analysis, etc. that we believe will adequately verify that the requirements were met.

Individual Task Summaries:

Task 1:Optical Simulation: Continue to improve/ run optical simulation codes to be able to derive shape requirements
Task 1 entry: At least two codes exist and requirements derivation has begun

Task 1 exit: Task is complete when a set of shape requirements exist that can be applied to designing the starshade structure

Task 2:System Modelling: End to end system modeling
Task 2 entry: Will build upon the existing optical simulation code, have a telescope model started
Task 2 exit: The completion of an end-to-end system model resulting in the development of a complete observatory error budget

Task 3:Testbeds: Testbeds to demonstrate/validate key aspects of end to end stytem model
Task 3 entry: There are currently two testbeds where the starshade performance has been measured
Task 3 exit: A starshade contrast of 1E-10 at the appropriate field location has been achieved and the performance has been matched to the predictions from the simulations

Task 4:V&V Plan: Create a plan validate the starshade performance
Task 4 entry: A very rough plan has been written down on a few charts
Task 4 exit: A full plan has been created that will get all the technologies in the NWO system to TRL 6

Budget and Schedule

	2010	2011	2012	Total
Task 1	1			1
Task 2	1			1
Task 3		2		2
Task 4		1		1
Total	2	3	0	5

Risks and Offramps:

Risk A: IF beam lines cannot be made to 10^-8 level, THEN showing modelling to the 10^-10 performance will be more of a stretch. Mitigation: Early characterization of beam line facility noise floor, alternate sub-scale test for specific terms in the error budget. Offramp: Beam line used to the best practicle level (say only 10^-7). Impact: Higher risk of reliance one other deteailed models for critical terms

Interactions with Others:

Related developers: Industry state of the art for large scale deployment accuracy with gravity offload.
Related users: Other starshade high contrast missions.

2a. Starshade- Deployment and Shape Control

Motivation:

The shape of the starshade is what creates the high level of suppression of the target star. In order to maintain this suppression, the starshade must maintain this shape very precisely.

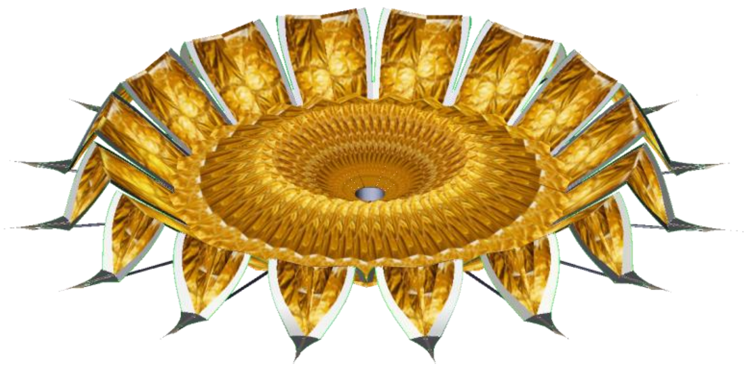


Figure 2a.1: Starshade Deployment.

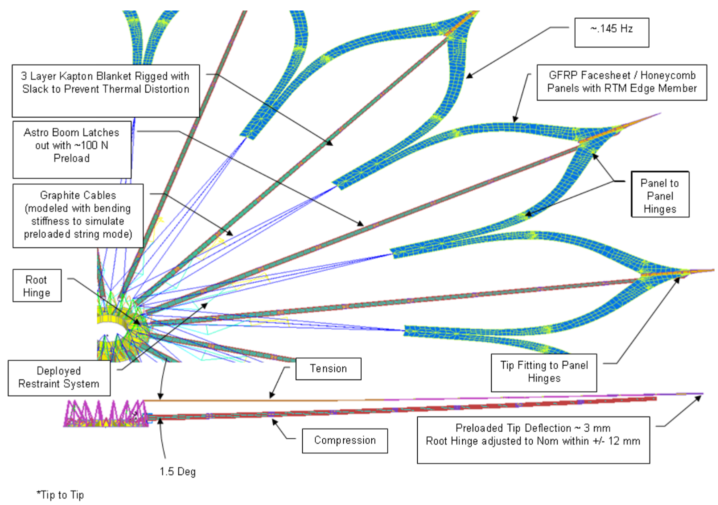


Figure 2a.2: Starshade edge shape is maintained through rigid composite panels.

Requirements:

Performance 1: Maintain specified shape within the tolerance requirements derived from the System Modeling and Verification task

Performance 2: Fit into LV fairing and deploy to the specified shape

Mass: Fit within TBD mass upper limit for LV and for maximum fuel efficiency

Environment: Factors that could effect the starshade shape:

1. Mechanical piece-part manufacturing error
2. Mechanical assembly errors
3. 1 G assembly shape verification error
4. Launch Shift
5. Deployment repeatability errors

6. Thermal distortion errors
7. On-orbit dynamics - jitter
8. CME errors (coefficient of moisture expansion)
9. Contamination errors

State of the art:

Many components in our baseline design are at TRL 6 or above. The whole system is a lower TRL.

Planned Development:

We have been working on designing a deployment method that will fit into the launch vehicle size and mass requirements, deploy to the required shape, and maintain its shape to the required tolerances despite the various possible error sources. Our design philosophy has been to use existing parts to minimize the required technology development, however putting the parts together into a starshade system will require validation.

We are currently carrying multiple designs for the starshade deployment method. We will downselect to one design once we have a better idea what the requirements are and which design best meets those requirements.

Individual Task Summaries:

Task 1:Determine shape distortion of baseline starshade deployment design due to various effects listed above.
Task 1 entry: We currently have a baseline design and the beginning of a FEM that will be used to do this modeling
Task 1 exit: Be able to compare the shape distortion due to each effect to the tolerance requirements

Task 2: Create sub-scale models of the whole deployed starshade or some sub-set of it to validate deployment design
Task 2 entry: We have the design but have not yet made any models
Task 2 exit: One or more sub-scale models have been built and their properties determined to meet the requirements.

Task 3: Full Scale Single Petal
Task 3 entry: Baseline design for starshade and it's ground test.
Task 3 exit: Risks related to the full scale manufacture, integration, and test are addressed to the TRL 6 level (deployment in 1 g through marionette offload and environment and performance tests).

Task 4: Half Scale Quarter Section Starshade
Task 4 entry: Baseline design for starshade and it's ground test.
Task 4 exit: Risks related the deployment and shape control of multiple petals interacting are addresses to the TRL 6 level (deployment in 1 g through marionette offload and environment and performance tests)..

Budget and Schedule

	2010	2011	2012	Total
Task 1	1			1
Task 2	1			1
Task 3		5	7	12
Task 4		5	7	12
Total	2	10	14	26

Risks and Offramps:

Risk A: IF deployment reliability and shape control performance cannot be verified with the baseline lightweight design, THEN further technology development will be required or a higher mass starshade design accepted. Mitigation: Several design from very lightweight to more robust ("rigid") planels are developed. Offramp: Shifting to more stable but heavier designs. Impact: Higher mass starshade will require more capable launch or few targets visited in the mission lifetime.

Interactions with Others:

Related developers: Mechanisms and unique I&T of large precision deployable structures are "dual use" with other scientific as well as military and intelligence missions.
Related users: All starshade missions.

2b. Starshade- Straylight Control

Motivation:

The telescope will be observing the exoplanets past the edge of the starshade. If the starshade is lit up by reflected sunlight, this could swamp the planet signal. Therefore we must control the amount of sunlight that can scatter off the starshade so that it is fainter than the planet's light. This risk is only a percieved risk at the moment. We need further analysis to establish it as a true risk.

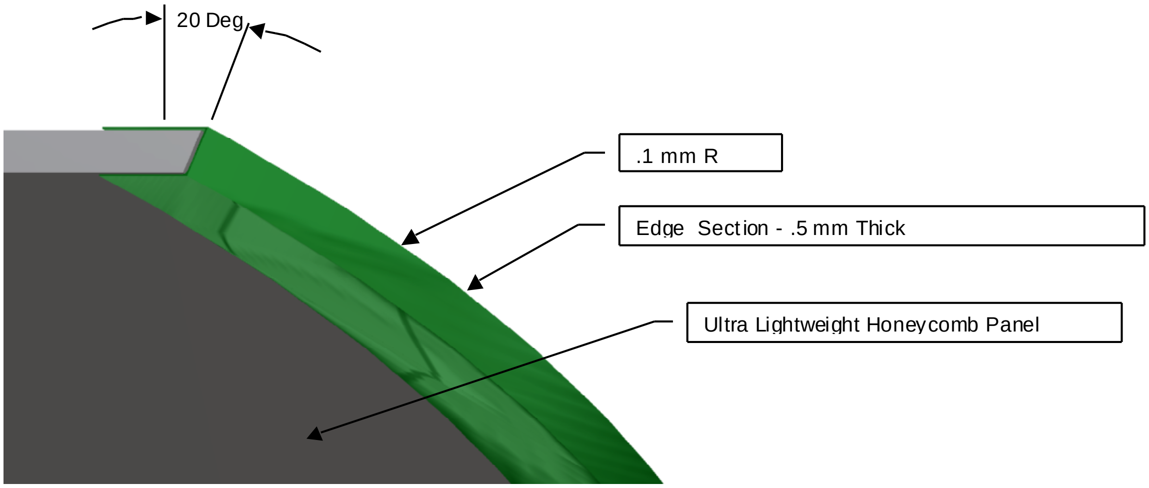


Figure 2b.1: Starshade Edge Treatment for Straylight Control

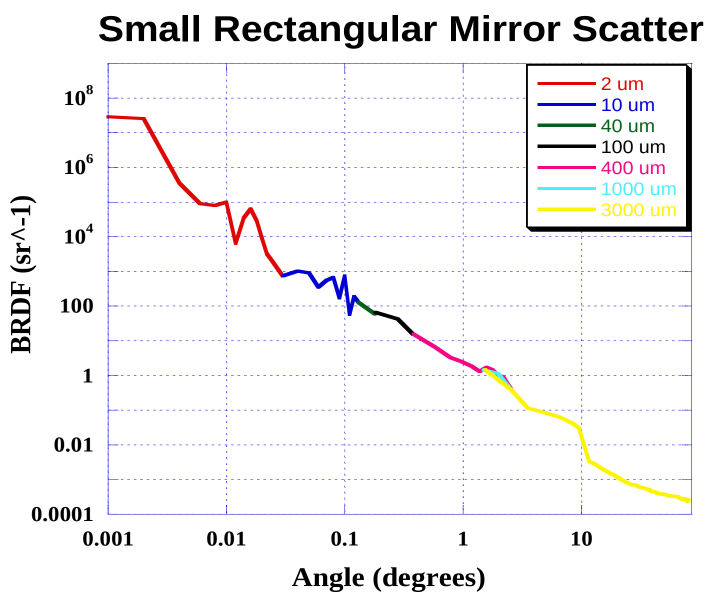


Figure 2b.2: The FAUST Scatterometer Facility at NASA GSFC has demonstrated 12 orders of magnitude of BRDF measurement sensitivity.

Requirements:

Performance 1: Sunlight reflected from the starshade's edge should be >30 mag as seen by the telescope Unknown. There are no models or measurements to determine whether an existing technology can achieve this level of performance

Performance 2: Earthshine, Moonshine, and any other stray light reflected off the face of the starshade in the direction of the telescope should be >30 mag as seen by the telescope

State of the art:

There are no models or measurements to determine whether an existing technology can achieve this level of performance. The FAUST scatterometer facility at NASA GSFC can measure over 12 orders of magnitude of BRDF over varying angles of incoming light and scattered light over 180 degrees.

Planned Development:

We will operate the starshade so that its back or edge is towards the sun. The edge will be very small (~100 microns radius) to minize the scattered area. We need to perform additional modeling and lab tests to ensure that the scattered light levels meet the requirements.

Individual Task Summaries:

Task 1:Create more sophisticated model of light scattering off the starshade and into the telescope
Task 1 entry: We currently have some very simple calculations of the scattered light levels
Task 1 exit: We have a fully validated model of the scattered light levels

Task 2:Perform laboratory tests of potential edge materials and shapes to determine if scattered light levels are as predicted
Task 2 entry: We have created a few test articles and done a few preliminary tests
Task 2 exit: The scatter off at least one of the potential edges has been fully measured and is determined to meet the requirements

Task 3:Perform laboratory tests of starshade membrane material to determine if scattered light levels are as predicted for face scattering
Task 3 entry: We expect to use a similar material to the JWST sunshield for the face of the starshade
Task 3 exit: The scatter off at least one of membrane material has been fully measured and is determined to meet the requirements

Budget and Schedule

	2010	2011	2012	Total
Task 1	.5			.5
Task 2	1			1
Task 3	1			1
Total	2.5			2.5

Risks and Offramps:

Risk A: If all starshade potential edges scatter more than 30 mag of light to telescope, then it will swamp the exoplanet signal. Mitigation: Develop more complex edge treatments and/or explore operational adjustments (e.g. tilting the starshade) to decrease the scattering or direct the scattered light to localized regions. Offramp: In the case that scattering cannot be removed, we will have to develop operational scenarios (such as lowering the S/N for detection in that area of the detector, more than 1 visit, etc.) that are compatible with the scattered light level. Impact: Potential loss of search space, increase in signal integration time.

Interactions with Others:

Related developers: Other users of the FAUST testbed include BRDF measurements optical components for other mission (the facility was built for HST instruments). Related users: Measurements of very small and very black edges would be a value to other straylight baffling applications.

3a. Alignment Control – Shadow Sensing

Motivation:

The shadow sensor provides high precision alignment measurements while the telescope is in shadow, enabling high-performance alignment control to the center of the shadow.

The major uncertainty needing verification is diffraction at the starshade producing the Poisson spot under the assumed conditions. If this works as predicted, the method of sensing is simple and routine. Need algorithms to estimate the off-axis position in shadow using instrument data.

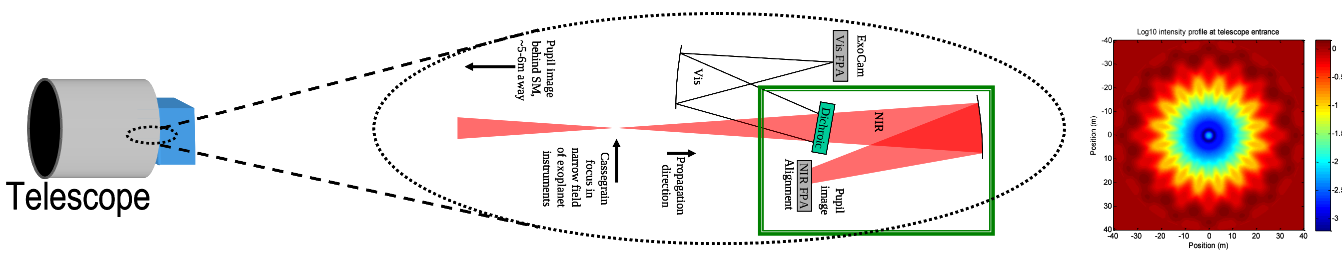


Figure 3a.1: At long wavelengths the Spot of Arago reemerges and can be used to find the line of sight to the target star to very high precision.

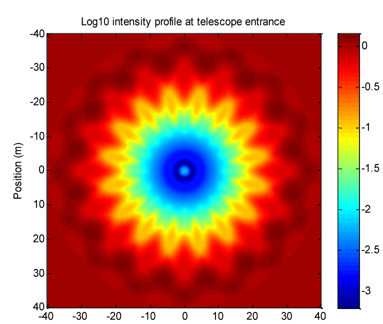


Figure 3a.2: In beamline tests, a modeled telescope image at long wavelength light will validate the position error readout algorithm for shadow sensing.

Requirements:

Stellar mag limit		7	Works comfortably for all likely exoplanet target stars
Sensitivity	0.50	m/rtHz	0.5 m in 1 sec integration, assuming 1/root t averaging
Noise floor	0.071	m	limiting value for long integration times
Measurement time		50	sec
Mass:	10	kg	Not expected to drive the mission mass

Environment: standard instrument vib, acoustic, thermal/vac
FPA is MCT, and thus needs a typical –133C operating temp

State of the art:

No SOA exists for this application; undeveloped alternative concepts exist

Planned Development:

As part of starshade diffraction testing and model validation, include measurements of diffracted light profiles at small Fresnel numbers, i.e. long wavelengths. Modeling study of instrument data reduction algorithms.

Individual Task Summaries:

Task 1: Experimentally validate models of diffracted light in shadow for low Fresnel numbers (long wavelengths).
Entry: As part of experimental validation of starshade diffraction modeling, measure diffraction at low Fresnel numbers (F<4-5), corresponding to long wavelengths.
Exit: Validated model of starshade diffraction at low Fresnel number

Task 2: Create algorithms to estimate position for any offset within the shadow
Entry: Validated model of starshade diffraction at low Fresnel number
Exit: Validate algorithms by comparing estimator to actual offset within shadow

Task 3: Model sensitivity of this signal
Entry: Validated model of starshade diffraction at low Fresnel number. Validated algorithms.
Exit: Calculated signal levels, pixel SNR, position estimate uncertainty vs. integration time

Budget and Schedule

	2010	2011	2012	Total
Task 1		0.4		0.4
Task 2	0.25	0.1		0.35
Task 3			0.1	0.1
Total	0.25	0.5	.1	0.85

Risks and Offramps:

Risk A: If experiments and diffraction models do not yield Poisson spot at Fresnel ~1.5-3. Mitigation: Use longer wavelengths (lower Fresnel). Offramp: Switch from internal shadow sensor to outrigger system. Impact: Deployment risk, complex dynamics in pointing control.

RiskB: Algorithms leave position ambiguity during navigation from shadow's edge to center. Mitigation: More complex algorithms incorporating historical data during maneuvering; such algorithms maintaining an estimate of position, as a way to reduce ambiguity. Offramp: Add more sensors such as outrigger system, or data from science instruments such as ExoCam. Impact: Increased algorithm complexity would increase verification cost and risk for those algorithms, and may increase C&DH complexity.

Interactions with Others:

Related Users: XPC or any other external occulter mission; excluding such missions that can't add an instrument to the science telescope.

3b. Alignment Control – Alignment Sensor

Motivation:

Optical sensor to guide trajectory of starshade from one star to the next one. Useful for long slew maneuvers with only faint catalog stars (mag>12) as a reference; helps reduce reliance on frequent DSN contact and mandatory zero-thrust periods. Also useful for fine guidance to the onset of shadowing, which requires finer accuracy than DSN can provide. This is a versatile sensor filling a critical "middle range" of precision and FOV. Baseline performance is sufficient when a shadow sensor is provided on the telescope. Goal performance is needed for a precursor mission that may not be able to use a shadow sensor.

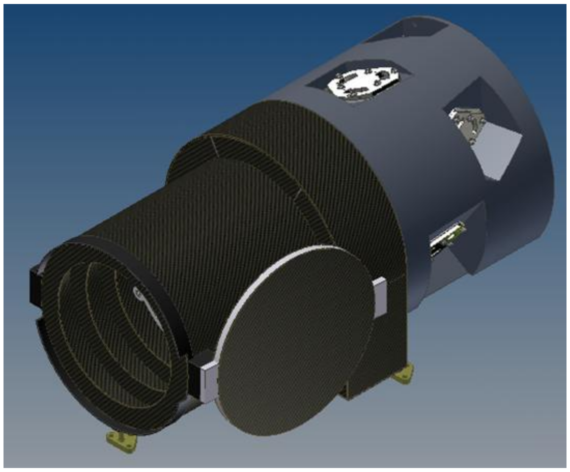


Figure 3b.1: CAD drawing of the JMAPS instrument shows surprising simplicity for such a powerful astrometric instrument.

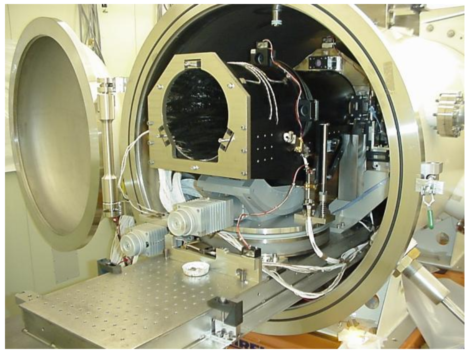


Figure 3b.2: The differential astrometry test facility at Ball Aerospace.

Requirements:

Field of regard	45-135	deg from sun-line
Field of view	1	square deg (any shape)
Sensitivity	12	stellar mag, V band
Accuracy baseline	50	mas (3s) angular difference between stars, to achieve onset of shadow
Accuracy goal	<2.5	mas (3s) angular difference between stars, to provide fallback for shadow sensor
Pointing jitter	TBD	arcsec, using readout from the sensor to guide a gimbal in tip-tilt
Mass:	120	kg
Environment:		vib, acoustic, thermal/vac,

State of the art:

SOA Technology: An existing Ball star tracker approaches and may be able to meet the looser 50 mas "accuracy" requirement; and meets all other requirements.
The USNO JMAPS design is believed capable of 5mas (1s), and is scheduled on a LEO mission in 2011.
No known sensor at TRL>= 6 can achieve all of these requirements including the goal accuracy.

Field of regard	45-180	deg from sun-line	Estimated - not known
Field of view	77	square deg	
Sensitivity	10.5	stellar mag, V band	
Accuracy	30	mas (1s) total boresight uncertainty	Not angular difference
Pointing slew	<4	deg/sec	
Mass:	21	kg	
Environment:		vib, acoustic, thermal/vac,	

Planned Development:

Testing a prototype instrument with 2 sources (or more) in Ball star tracker facility for differential-astrometry tests. Form a budget for instrument and facility errors; use experimental data to validate the performance budget.

Individual Task Summaries:

Task 1:Requirements development and error budgeting for test facility and instrument.

Task 1 entry: Funding.
Task 1 exit: Requirements and error budgets for test facility and instrument.

Task 2: Borrow or design/build a prototype instrument; upgrade Ball facility.
Task 2 entry: Requirements development
Task 2 exit: Working stable prototype instrument

Task 3: Conduct 2-source tests in Ball facility
Task 3 entry: Dual source head in Ball facility.
Task 3 exit: Experimental results on stability of differential measurements.

Task 4: Compare performance to error budgets for the test, plan follow-on work.
Task 4 entry: Complete a draft of error budget for instrument and facility.
Task 4 exit: Validation of error budgets.

Budget and Schedule

	2010	2011	2012	Total
Task 1	0.5			0.5
Task 2	0.5	3.0	2.5	6.0
Task 3			1.5	1.5
Task 4			1.0	1.0
Total	1	3	5	9

Risks and Offramps:

Risk A: If performance doesn't meet requirements on the first try. Mitigation: Identify error budget elements that are out of range; redesign & rebuild to mitigate them.
Offramp: Beacon on starshade, observed from telescope. Impact: Telescope time diverted from science to shadow acquisition. May need new spacecraft and instrument mode(s).

Interactions with Others:

Related developers: USNO JMAPS instrument performance predictions meet baseline performance requirements; approaches goal performance.
Related users: US DoD, esp. Navy.

4. Photon Counting Detectors

Motivation:

The sensitivity of space astronomical telescopes with near diffraction-limited spatial resolution observing faint objects is limited by the background. Depending on design details, for low spectral resolving power R<~20 in the visible and NIR, the background is dominated by the zodiacal light, but for higher resolving powers the background is normally dominated by detector background, read noise and dark noise.

If the read noise can be removed by using a photon-counting detector, without losing much quantum efficiency, the observing time required to detect a very faint object, such as the spectrum of an exoplanet, or a galaxy in the recombination era, can be reduced by more than an order of magnitude, from many weeks to a few days, rendering a previously virtually impossible observation feasible.

For example, Figure 4.1 shows the observing time required to measure the spectrum of a faint object with a 4-m telescope at a signal-to-noise of 10 at R=70 (resolving the oxygen A-band in an exoplanet), using an excellent analog CCD and a photon-counting CCD.

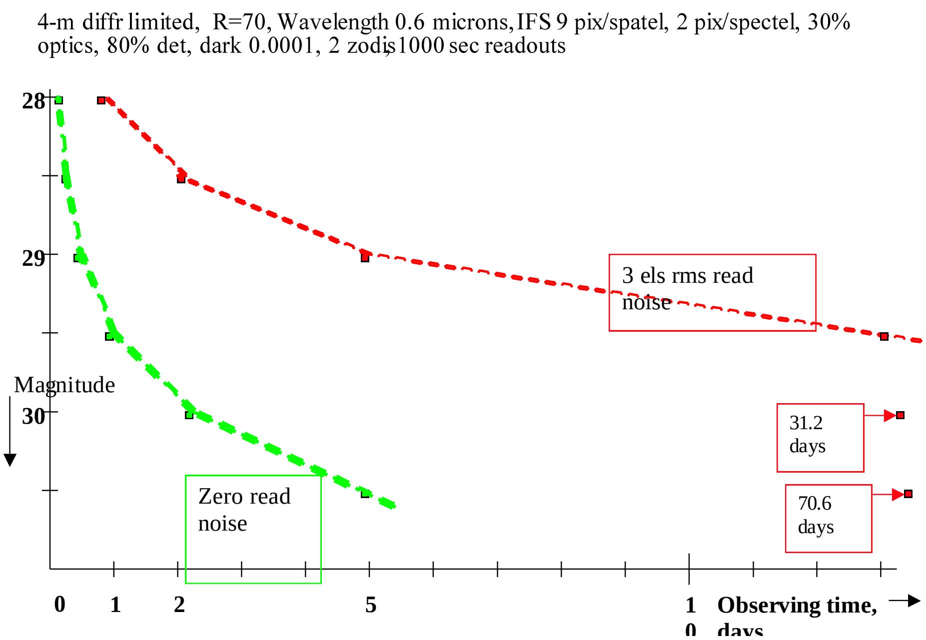


Figure 4.1: Photon counting detectors greatly improves New Worlds Observer sensitivity.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

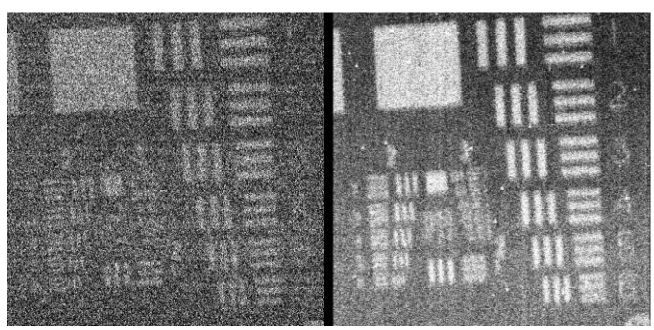


Figure 4.2: State of the Art Low Light Level (L3CCD) by e2v (left) and images taken with e2v CCD201 (1k x 1k) in regular readout mode (10 of 50s exposures) (center), and electron multiplied photon counting mode (1000 of 0.5sec exposures)(right). The data were taken at the same count rate level, 0.06 els/pix/sec, for the same total observing time, 500sec. Fine structures and characters are clearly distinguished in photon-counting mode that are hidden beneath read noise in regular mode.

Requirements:

Performance 1: very low read noise	< 1 electrons rms
Performance 2: high quantum efficiency	> 70% over 300 - 900 nm
Performance 3: low dark current	< 10 pA/cm2 @ 300K
Performance 4: well capacity	40,000 to 80,000 electrons
Performance 5: clock induced charge	< 4e-3 event/pixel/frame
Power: on-chip power	< 500 mW
Radiation: radiation tolerance	20 kRad(Si)

State of the art:

State of the Art Technology: The state of the art technology is that offered by e2v and Texas Instruments (TI) with the electron multiplying (EM) CCD: the L3CCD by e2v or the Impactron by TI.

Performance 1: very low read noise	≤ 1 electrons rms
Performance 2: high quantum efficiency	70 % to 95% over 300 - 1000 nm
Performance 3: low dark current	< 10 pA/cm2 @ 300K
Performance 4: well capacity	80,000 electrons
Power: on-chip power	< 1 W
Radiation: radiation tolerance	20 kRad(Si)

Planned Development:

In the short term, it is anticipated that low risks development of the electron multiplying CCD can be under taken to best meet mission requirements. There are several preliminary tasks to be worked before building the New Worlds FPA. These include conducting a trade study among 2K, 4K and 8K devices; a program to reduce the voltage swing required by the avalanching gate; developing a viable second source; optimizing the AR coatings and maturing the modified device to TRL 6.

Individual Task Summaries:

Task 1: Conduct a trade study to determine the optimum choice of array size for a photon counting detector (and mosaic).
entry: Funding.
exit: An engineering report detailing this trade study and presenting a final recommendation.

Task 2a: Reduce the voltage swing, and therefore the power, required to obtain gain for the L3CCD.
entry: Producing sufficient gain in the electron multiplying register requires a voltage swing of 40 V on one of the serial phases.
exit: A demonstrated L3CCD with a lower voltage swing on the serial avalanche gate and lower power requirements.

Task 2b: Optimize high QE AR coatings.
entry: QE at 300 nm needs to be augmented by an improved AR coating.
exit: Demonstrate QE > 70% from 300 nm - 1000 nm on a device with improved coating.

Task 2c: Reduce clock induced charge.
entry: Clock induced charge on existing device needs improving.
exit: Demonstrate less than 4e-3 event/pixel/frame clock induced charge on a device with improved layers.

Task 3: Develop a second source of L3CCD-like devices. (risk mitigation to eliminate single-point process capability - i.e., single point supplier)
entry: TI has been unwilling to consider design modifications to their EM CCDs. No viable second source to e2v exists.
exit: Working to a defined list of performance parameters, a second vendor will successfully fabricate an L3CCD-like device.

Task 4: TRL 6 FPA Qualification Program.
Task 4 entry: Device design modifications ready.
Task 4 exit: Demonstrate FPA performance after exposure to vibration, thermal vac, and radiation.

Budget and Schedule

	2010	2011	2012	Total
Task 1	0.5			0.5
Task 2	0.5	2.5		3
Task 3	1			1
Task 4		1.5	6	7.5
Total	2	4	6	12

Risks and Offramps:

Risk A: IF it is not possible to reduce the avalanching gate swing THEN more development will be required. Mitigation: Make the multiplication register longer and use a lower gain per stage. Off ramp: Revert to smaller format where technology is already at TRL 6. Impact: Costs of redesign. Increases in device size complicate the mosaic and possibly increase the size of gaps in the array.

Risk B: IF the financial and physical health of the current foundries is not stable THEN other sources must be developed. Mitigation: There are very few places in the world where one can acquire CCDs. Off ramp: The alternative will be to use CMOS or p-channel (LBNL) technology. Impact: Possible cost and schedule delay to switch technologies.

Interactions with Others:

Related developers: Funding of large format detectors has and will always be complementary with other government agencies doing space imaging (the DoD and Intelligence Community).

Related users: Lower noise, higher QE and radiation tolerance are universally desired traits in sensors. Development of these detectors supports future astronomical telescopes in space, including small or large format mosaic arrays for use in the visible to NIR spectral range for both imaging and NIR spectral ranges. Applicable missions are ATLAS-T, THEIA, and Exo-Planet missions.

5. 4m Telescope

Motivation:

NWO exoplanet science requires a large telescope which is diffraction limited at about 400-500 nm. The nominal size is 4m diameter, driven mainly by collecting area (for measurement speed) and angular resolution on the exoplanet system. Similarly, the ambitious program of general astrophysics requires a diffraction limited telescope, high angular resolution, and wide field of view.

Figure 5.1: ITT's 2 meter class Mirror Demonstrator

Figure 5.2: SOFIA's 2.7 m Zerodure mirror.

Figure 5.3 Herschel's 3.5m mirror being coated

Requirements:

Angular resolution: 27 mas FWHM at 500 nm wavelength, drives 3.93 m diam.
Collecting area: 12.57 m^2
Wavelength range: 0.12 – 2.3 micron, UV through Shadow Sensor
Primary Mirror mass: 750 kg or 59.7 kg/m^2 about 85% lightweighting
Environment: L2 vib, acoustic, thermal/vac.

State of the art:

SOA Technology: Ground based telescopes much larger than this; JWST in cryo; HST (2.4 m) and commercial remote sensing (1.1 m) in visible.

Planned Development:

Telescope architecture development, especially trading monolithic vs segmented: wavefront budget allocations (residual design error, manufacturing error, alignment error, stability, scatter, etc.), performance comparison to merit factors (e.g., PSF, encircled energy), cost and risk comparison. Extrapolate and assess required wavefront sensing and control and the verification approach.

Demonstrate WFS&C at 4 times better performance than JWST. Analyze verification approach and design telescope and test GSE for a feasible verification process at 4 times better performance requirements than JWST. Demonstrate key elements of that verification process. Demonstrate coating process and coating verification that is scalable to 4m diameter optics.

Individual Task Summaries:

Task 1: Requirements refinement, design and analyses trades for the telescope and primary mirror segmentation (if any), control approach (if any), lightweighting architecture
Task 1 entry: Starting with initial mass allocations, wavefront performance
Task 1 exit: Detailed models and performance analyses for specific architecture chosen; substrate material define, number of segments defined, actuator figure correction approach and phasing defined.

Task 2: Mirror coating tasks
Task 2 entry: Trade optical coatings (passband, thickness & uniformity, scatter, durability) consistent with the overall telescope error budgets. (This may be a relatively minor factor in segmented versus monolithic trades, where lot-to-lot coating deposition runs would be traded with uniformity over the entire or subsets of the 4-m aperture.) Trade segmentation and size vs. coating facilities. Several coating chambers exist in the continental US for 2 to 3m complex optical coatings, but only one (e.g., MSFC 5.5-m) could be modified for a 4-m optic. Assess facility augmentation or upgrades."

Task 2 exit: Demonstrate implementation of chosen coating on witness samples across appropriate aperture and appropriate number of coating runs Develop cost estimates

Task 3: Wavefront control testbed
Task 3 entry: Chosen architecture and control approach. (Note that even a monolithic PM could require low order spatial frequency correction for testing in a 1-g environment and to compensate for on-orbit thermal distortions). Include SM hexapod.
Task 3 exit: Sub-scale telescope testbed demo of final wavefront performance meeting requirements. Demonstration of verification process and roll-up of uncertainties. Validation of control algorithms.

Task 4: Fabrication of either single PM segment full-scale or 1/6 segment of monolithic PM; include blank procurement, lightweighting, polishing, coating, mounting, and figure control on full-scale
Task 4 entry: Detailed lightweighted PM engineering drawings including method of mounting, fiducials, verification features, etc.
Task 4 exit: Completed engineering unit fabrication and optical test

Budget and Schedule

	2010	2011	2012	Total
Task 1	1.0			1
Task 2	0.1	0.4		0.5
Task 3		0.5	1.5	2
Task 4	0.5	2.0	3.0	5.5
Total	1.6	2.9	4.5	9

Risks and Offramps:

Risk A: IF scaling of 2.4m lightweight mirrors to 4.0 meters at 60 kg/m2 yeilds unforseen wavefront error effects, THEN additional development would be required. Mitigation: Segmented and monolithic telescope are acceptable to New Worlds Observer. Offramp: Segmented telescope as a backup to passive monolith primary. Impact: Additional cost of development for the 4m segmented design.

Risk B: IF scaling of 2.4m lightweight mirrors to 4.0 meters at 60 kg/m2 yeilds unforseen wavefront error effects, THEN additional development would be required. Mitigation:

Increase areal density and/or thrmal control system fidelity. Offramp: Add mass to mirror to achieve rigid or increased semi-rigid design to reduce wavefront deformation. Can reduce thermal impacts by tightening thermal control system on PM and telescope. Impact: Reduced mass margin. Increased number of thermal sensors and heater locations.

Interactions with Others:

Related developers: Commercial imaging space telescope are already at 1.1m and growing larger quickly. Alternative materials such as Silicon Carbide are also quickly advancing.
Related users: Military, intelligence, and commercial space imaging.

6. Electric Propulsion

Motivation:

A key functional element of the starshade spacecraft is to move, within the Lagrange space, from observation state vector to observation state vector. On the order of 70-80% of the starshade spacecraft life cycle is spent in these translation maneuvers. This mission characteristically has a very large mission delta-V. With the current baseline New Worlds Observer concept, the translation maneuver delta-V for the primary mission is on the order of 7-8 km/s. Electric propulsion systems can execute this delta-V with significantly less propellant than a chemical propulsion system. The NEXT ion thruster (Figure 6.1) has a high input power capability of 7 kW, as well as high xenon throughput per thruster, both of which allow starshade spacecraft maneuvers with a minimum number of operating thrusters. NEXT also has a high specific impulse, which minimizes the xenon propellant required for the primary mission. These provide more capability, in number of target stars, and flexibility in adapting to variations in the maneuver planning, than other potential electric propulsion systems. In addition, the efficient use of xenon propellant provides more xenon reserves that can be used in extended mission operations.

Figure 6.1: The NEXT Thruster and Multi-thruster testing.

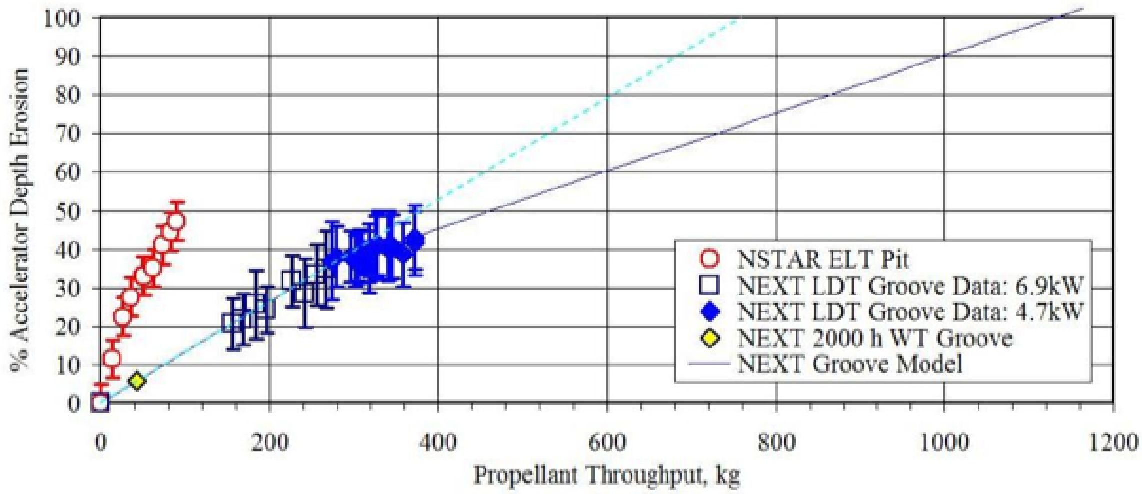


Figure 6.2: NEXT accelerator grid erosion test and analysis results indicate first failure at approximately 750 kg xenon throughput.

Requirements:

NEXT:

Max. Thruster Input Power	6.9 kW
Thruster Specific Impulse	4190 seconds (at full power point)
Thruster Thrust	236 mN (at full power point)
Total Xe Thruput	1.5 x 450 kg = 675 kg
PPU Efficiency	94.5 percent (at full power point)
PPU Specific Power	0.21 kW/kg

State of the art:

SOA Technology: NSTAR Ion Thruster

Max. Thruster Input Power	2.3 kW
Thruster Specific Impulse	3070 seconds (at full power point)
Thruster Thrust	91 mN (at full power point)
PPU Efficiency	90.6 percent (at full power point)
PPU Specific Power	0.18 kW/kg

SOA Technology: BPT-4000 Hall Thruster

Max. Thruster Input Power	4.5 kW
Thruster Specific Impulse	2150 seconds (at full power point)
Thruster Thrust	254 mN (at full power point)
PPU Efficiency	92.5 percent (at full power point)
PPU Specific Power	0.37 kW/kg

Planned Development:

NEXT technology development is continuing under the In Space Propulsion Technology (ISPT) project, with the objective of bringing key system components to TRL 6 in FY2009. A Technology Maturity Assessment will be completed in FY09, an output of which will be identification of tasks to reduce risk in transitioning NEXT to the first flight. Selected NEXT risk reduction activities and thruster long duration testing will continue under ISPT through FY2010. Additional risk reduction activities may be identified in the course of further NWO implementation definition. NWO technology budget will be allocated to a) continue thruster long duration testing to determine thruster lifetime capability, and b) execute the NWO-unique risk reduction tasks.

The NEXT long duration test (LDT, See Figure 6.2) and supporting analyses indicate that the first failure mode for the NEXT thruster is accelerator grid erosion caused by charge exchange ions impacting the outer surface of the grid. The full power throttle point, where NEXT is likely to operate over the duration of the NWO mission, is the worst cast for this erosion mechanism. Projected accelerator grid wear-through is estimated to occur at approximately 750 kg of xenon throughput at full power, as shown with the dashed line in the figure. Actual thruster failure, through structural failure of the grid, will occur some time later. Using a qualification factor of 1.5, this results in a possible qualified lifetime of up to 500 kg xenon throughput per thruster. The NEXT LDT was operated at full power (6.9 kW) for the first 13,000 hours of the test prior to changing to other throttle points.

Upon initiation of the NWO project, and establishment of Level 1 requirements, the definition of the electric propulsion system will be readdressed. Technical performance, system cost and risk will all contribute to the final selection.

The development team for the ion propulsion system is planned to be composed of NASA Glenn Research Center and Starshade Spacecraft prime contractor team members. GRC's participation will ensure that the technology is correctly transferred to flight implementation with minimum risk due to design/hardware changes. The responsibility for each element would be determined through a make/buy process during the early phases of development. As a reference, the current model is for NASA GRC to develop the thrusters and PPUs for the flight system, and provide to the spacecraft prime for integration. The spacecraft prime would develop the xenon tank and feed system elements and the gimbal. Thrusters, PPUs, xenon tanks and xenon feed system elements will likely be procured. Feed system integration and gimbal fabrication could be conducted by the spacecraft prime.

With the initial transfer of NEXT TRL6 technology to a flagship-class flight project, a full hardware qualification program is warranted. The development model assumes a qualification build and test element for the thruster, PPU, xenon tank, feed system HPA and LPA, and gimbal. Qualification testing of the thruster will be performed jointly by the thruster vendor and NASA GRC, as large vacuum facilities are necessary for some tests. Qualification testing of the other system elements will be performed by the element vendor.

Individual Task Summaries:

Task 1: Extend duration of NEXT thruster long duration testing
Task 1 entry: Test will be in progress, as initiated by ISPT project. Xenon throughput at initiation is projected to be approximately 550 kg

Task 1 exit: Xenon throughput in excess of 675 kg

Task 2: Risk reduction tasks for NEXT ion propulsion system, as identified in Technology Maturity Assessment to be completed under ISPT
Task 2 entry: Thruster, PPU, Feed system at TRL 6, gimbal at TRL 5
Task 2 exit: Completion of specific tasks

Budget and Schedule

	2010	2011	2012	Total
Task 1		1		1
Task 2		1		1
Total	0	2	0	2

Risks and Offramps:

Risk A: If the NEXT project under ISPT fails to achieve adequate technology readiness, then the NWO project could incur additional costs and risks to implement NEXT. Mitigation: The NWO project staff should participate in the NEXT technology maturity assessment to best determine what risk reduction efforts can support NWO.
Offramp: The mission could baseline alternate EP systems (BPT-4000, NSTAR, or XIPS-25). Impact: Selection of a lower performing EP system would impact mission performance, system complexity and mass. This would likely reduce the number of targets that could be achieved in the primary mission, as well as eliminate capability for an extended mission.

Risk B: If the NEXT thruster lifetime is not validated to levels baselined in the NWO concept, then the mission performance could be impacted. Mitigation: Continue long duration testing and supporting thruster lifetime analyses. Offramp: No off-ramp, all other EP system options have lower throughput than NEXT. Impact: Failure to meet the required xenon throughput per thruster would result in addition of a thruster and the associated gimbal and xenon flow controller to increase the total lifetime capability. This incurs additional mass and cost.

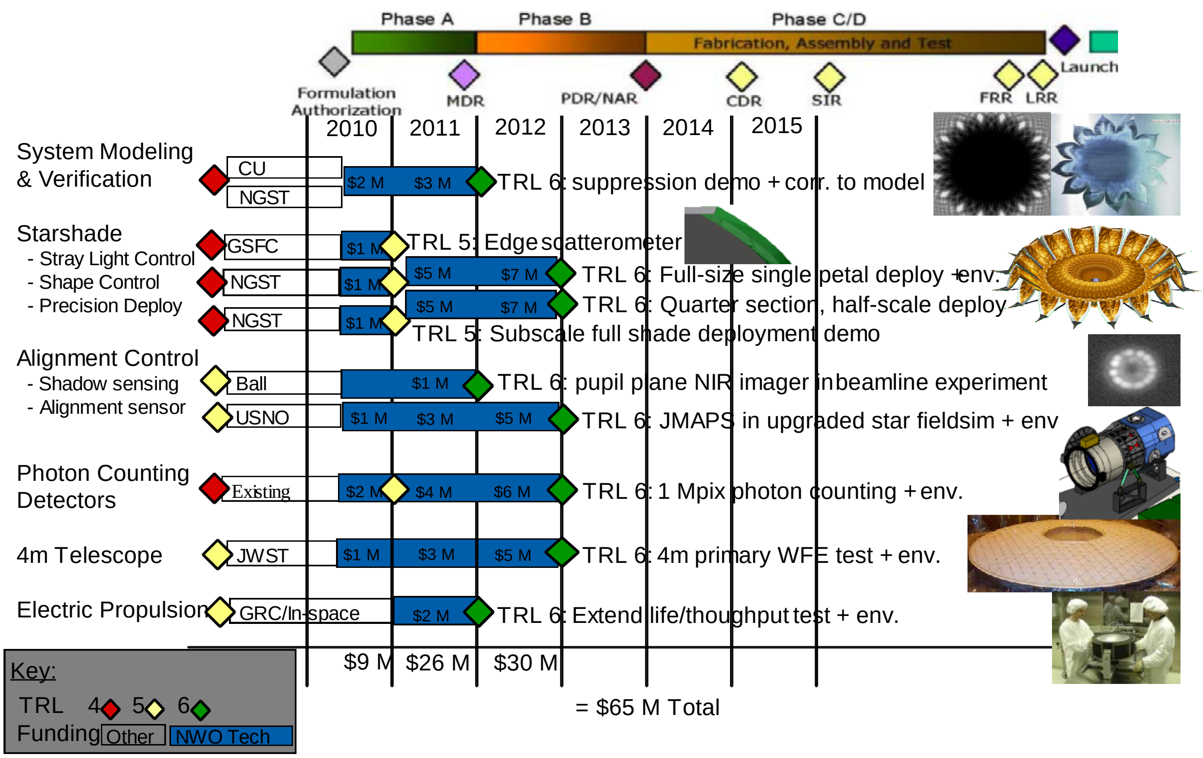
Interactions with Others:

Related developers: BPT-4000 and XIPS-25 are both being investigated for qualification for NASA missions.
Related users: NASA Planetary Science missions, including potentially: Outer planets flagship missions, New Frontiers and Discovery-class PI-led missions.

Technology Development Management

Technology Development Roadmap

The following single chart outlines the New Worlds Observer Technology Development Plan in a roadmap form. Current efforts (on IRAD funding or funding from other sources) are underway at the participating institutions as indicated by the white bars on the graphic. Assuming a Formulation Authorization in FY10, the New Worlds project would begin funding most of the high priority technology developments at a low level at first. Concentration would be on the system modeling and verification task as well as small-scale work on the other elements. Early push for TRL 5 milestones are needed for the starshade and photon counting detectors. System modeling and verification, shadow sensing, and electric propulsion would complete their TRL 6 milestones after 18 months (at the end of 2011). The rest of the technologies complete their TRL 6 milestones a year later allowing almost a year margin before the PDR.



The roadmap graphic also states the TRL 6 demonstration that each technology will mature to. In every case, these are demonstrations of the required performance (suppression, deployment, shape control, edge scatter, shadow sensing, astrometric accuracy, photon counting, primary mirror wavefront error, propellant throughput) on a flight-like article that has undergone the relevant environmental qualifications of vibration, thermal vacuum, and, for some, radiation. Each TRL milestone "gate" will be first set and then later reviewed by a board of non-advocate experts.

Technology Development Cost and Schedule

The roadmap graphic given in the previous section outlines both the cost and schedule for the technology development program. TRL 5 and TRL 6 milestones are used to measure progress. The technology development funds are allocated as shown in this Budget table:

	2010	2011	2012	Total
1. System Modeling and Verification	2	3		5
2. Starshade	3	10	14	27
3. Alignment Control	1	4	5	10
4. Photon Counting Detectors	2	4	6	12
5. 4m Telescope	1	3	5	9
6. Electric Propulsion		2		2
Total	9	26	30	65

Budget Table: The estimated costs by technology and year. An additional 30 percent of budget contingency for technology development is held by the project. A schedule reserve of 1 year (over 30 percent) is reflected in the fact that TRL 6 is not required to be shown until PDR at then of 2013.

The majority of the funding is allocated to the highest risk and most enabling item, the starshade. Early funding is applied to system modeling and verification since it is well understood that significant development in other areas is not warranted until the error budget associated with shape accuracy modeling is well understood and correlated with tests. An additional 30 percent of budget contingency is held at the project level and would be released by the project to the technology developer to address risks and better insure a TRL 6 demonstration on schedule. There is also the built in schedule margin of one year in that all TRL 6 demonstrations are scheduled before the end of 2012, but the PDR not scheduled until the end of 2013.

The major milestones of the technology development effort are the TRL 5 and TRL 6 gates. A technology evaluation board with non-advocate experts in each of the areas would be formed for the duration of the effort. The first job of this board would be to outline the exact demonstration that would satisfy the TRL 5 and 6 gates. Then, as the development efforts mature and reach these demonstrations, the test data and modeling would be presented back to the board for TRL gate review. The final review of this board is a multi-day Technology Non-Advocate Review (TNAR) several months before the PDR. The TNAR would validate all required mission technologies at TRL 6 or higher, thereby supporting a successful PDR and the mission to proceed to implementation.

Technology Development Management Plan

The technology development effort for a major mission such as New Worlds Observer needs a special, individual attention from NASA HQ and the project, but also to be well-connected to the formulation work of the project. To that end, it is recommended that the project technologist report to the project manager so that a balanced allocation of engineering workforce and funding resources can be made between the technology development effort and the project formulation design efforts. Each of the six technology efforts would then have lead engineer responsible for cost and schedule milestones through the project technologist to the project. They would formally report on a quarterly basis at the project quarterly meetings, but would have continuous rapport with the subsystem leads. Since technology development in these six areas will be happening in parallel with the phase A and phase B design engineering, it is of critical importance that the technology developers are “married” to the subsystem lead engineers. In some cases, such as the starshade, it may be appropriate that the technology development task manager also be the starshade subsystem manager in the formulation of the flight project. This unity allows systems level trades in error budgets and mass budgets for the good of the project.

The Mission System Engineer (MSE) is critical to the successful technology demonstrations that meet the needs of the mission being formulated. The MSE and the project technologist will work closely to manage risks. Since the MSE holds both the performance error budgets and the resources (mass, power, volume) budgets, he or she is the technical architect of the mission and can make critical trades in and across subsystems. This will be important when one or more technologies has not met all of it’s requirements at the scheduled milestone and a decision made as to invest more time and money or take a technology “offramp” that may shift the burden in overall mission performance to another subsystem. A project led trade study will show the mission impacts of such a decision and the decision would be taken and documented through the project’s established configuration management (CM) protocols. The resulting relaxed or tightened requirements on the technology would then be used in the final TRL 6 evaluation.

In the event that the starshade concept is selected for technology development funding but not phase A mission formulation funding, this will require a different management approach. In this case, only the enabling technologies for the starshade concept (the first three items: system modeling and verification, starshade, and alignment control) should be tackled. This plan results in a more focused scope (and reduced cost of $42M) but would require some form of mission design engineering to drive requirements and performance, cost, mass, volume trades. That is, the technology development project manager would need not only the technology develop the technology but also have “strawman” mission concepts with which to trade science performance and cost/mass/volume resources. This would require on the order of 10 engineers (and scientists) for an additional $8M. This “standalone” technology development project then would be a total of $50M over 2.5 years or $65M over 3.25 years with a 30 percent contingency added.

Conclusion

This document lays out a complete and integrated plan to develop the required New Worlds Observer technologies to a level of TRL 6, where they can be confidently infused in the implementation of the mission. The six technologies of system modeling and verification, starshade, alignment control, photon counting detectors, 4m telescope, and electric propulsion are roadmapped to complete their TRL 6 milestones with one year to spare before required at PDR.

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Photon Counters for Space Astronomy

Bruce Woodgate and Ronald Polidan

Introduction

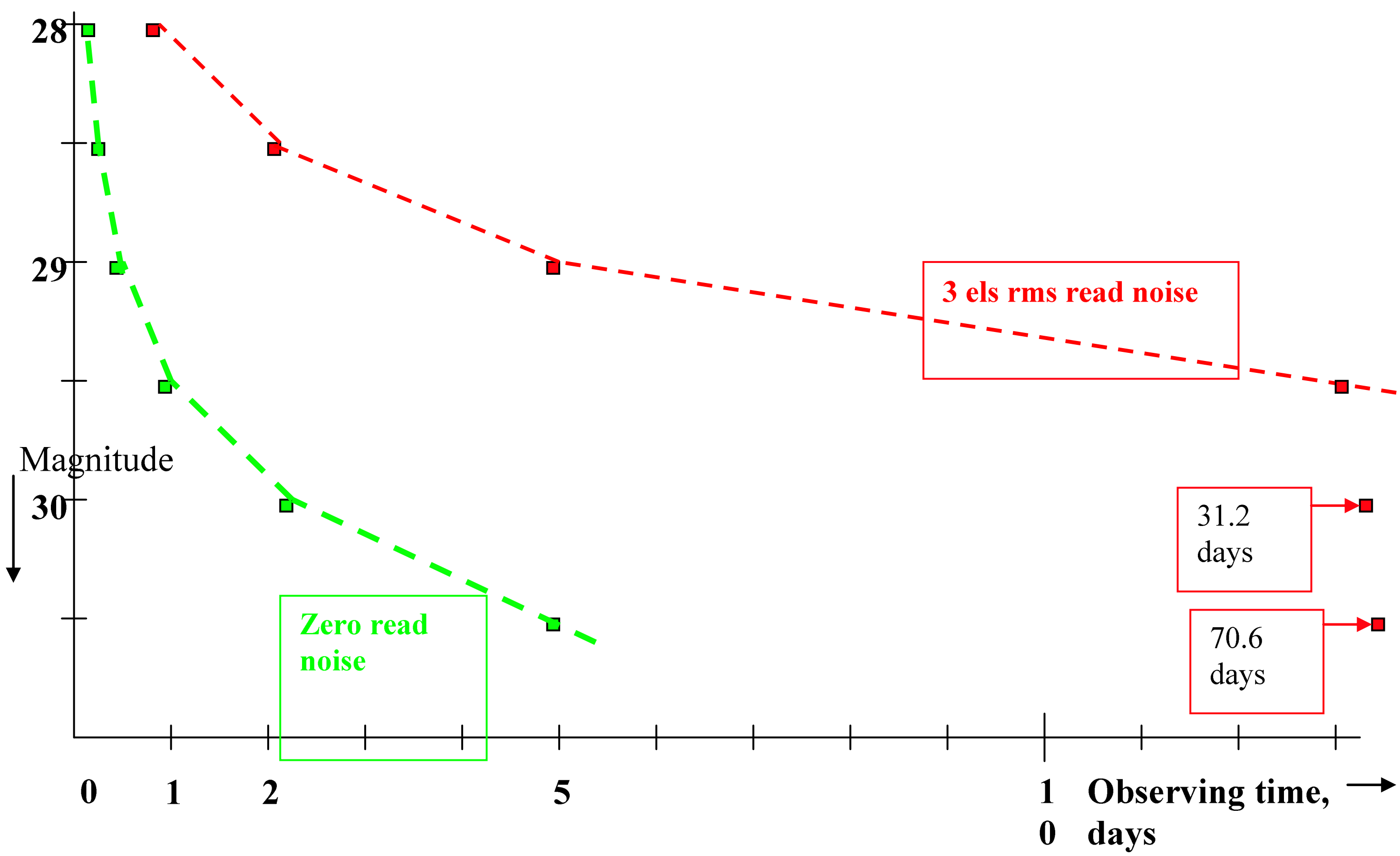
The sensitivity of space astronomical telescopes with near diffraction-limited spatial resolution observing faint objects is limited by the background. Depending on design details, for low spectral resolving power R<~20 in the visible and NIR, the background is dominated by the zodiacal light, but for higher resolving powers the background is normally dominated by detector background, read noise and dark noise.

If the read noise can be removed by using a photon-counting detector, without losing much quantum efficiency, the observing time required to detect a very faint object, such as the spectrum of an exoplanet, or a galaxy in the recombination era, can be reduced by more than an order of magnitude, from many weeks to a few days, rendering a previously virtually impossible observation feasible.

For example, Figure 1 shows the observing time required to measure the spectrum of a faint object with a 4-m telescope at a signal-to-noise of 10 at R=70 (resolving the oxygen A-band in an exoplanet), using an excellent analog CCD and a photon-counting CCD.

Figure 1. NWO Sensitivity

4-m diffraction limited telescope, R=70, λ = 0.6 microns, IFS 9 pix/spatial, 2 pix/spectral, 30% optics, 80% det, dark 0.0001, 2x zodi, 1000 sec readouts



Technical Status and Possibilities

Visible wavelengths (0.3 – 1.0 microns)

CCDs are the dominant detectors currently used in the visible, with their high QEs and low read noise, for both broad band imaging and spectroscopy. However, for spectroscopy with long exposures many reads are required. For a spectroscopic element covering 9 pixels, with a read every 1000 sec (suitable for an L2 orbit, outside the geomagnetic shield), and a read noise of 3 electrons rms, the total read noise for a 100,000 sec exposure (100 frames) is $\sqrt{(100 \times 9 \times 3 \times 3)} = 90$ els rms. For a signal of 100 counts, the detection signal-to-noise is 1.1 (a non-detection), compared to 10 for a zero read noise detector of the same QE. If we reduce the photon-counter's QE by 10%, we have S/N = 9.5, compared to S/N = 1.1.

In the last 5 years, electron-multiplying CCDs have been available commercially, and are now up to 1024 x 1024 pixels format. They are made by Texas Instruments in the USA and by e2v in the UK. The latter are combined with back-side thinning, producing high QE. An additional serial register with ~35 – 40V obtains a small gain per stage using impact ionization over many stages, producing overall gains of several hundred to several thousand. Using a discriminator, a one or zero is counted for each pixel, and the read noise is effectively zero. There is a source of noise called Clock Induced Charge, stated by the manufacturer to be at the level ~0.02 events/pixel/frame, normally hidden below the read noise in an analog CCD. Efforts to reduce this by fast shaped clocking, have reduced this further by factors 4 – 20 (Andor in Northern Ireland, Photon etc in Canada), and commercial controllers are beginning to become available. Space compatible versions of advanced controllers will be needed. The photon-counting capability needs to be extended to larger formats.

An application of these devices called "Lucky Imaging" is being used on ground based telescopes, with fast framing in intensified analog mode to select a small fraction of the data with the best seeing and add them together, to get very sharp images. In addition to losing most of the data, the QE is reduced by $\sqrt{2}$ because of additional statistical noise in this mode (which does not apply to the true photon-counting mode).

Radiation damage to CCDs is also a problem, for both imagers and spectrographs. The p-channel CCDs being built by LBNL (USA) and DALSA (Canada), are more radiation-hard than the normal n-channel CCDs by at least an order of magnitude. They are also being made with very deep depletion, up to 300 microns thick, to obtain higher QE in the 0.9 – 1.1 micron range. Initial experiments by LBNL and GSFC to make photon-counting versions of the p-channel CCDs do show some gain, and require further investment to enable photon-counting.

Near InfraRed (1.0- 1.7 microns)

In the NIR photon-counters are less developed than in the visible and UV.
In the short term, progress continues to be made in reducing the noise of photoconducting arrays, such as in HgCdTe, both in read noise and dark noise, while maintaining the high QE recently achieved. Their spectral range has also been broadened into the visible by removing their substrates to remove cosmic ray fluorescence.

Avalanche photodiode (APD) arrays of HgCdTe and InGaAs have been proposed as photon-counting imagers, but are not yet available. In principle, if even small arrays, including one-dimensional arrays such as the 1 x 512 UV arrays on the first generation HST spectrographs, can achieve high QE and low noise, they could be superior to the current NIR imaging technologies for short spectra, for low resolving power (R~100) for exoplanet or high redshift supernova spectra, or for limited range at higher resolving powers. Readout multiplexing would simplify their readouts, and are necessary for larger arrays, but for limited pixel number even separate readouts per pixel is not unreasonable. Extension into 2-D arrays is necessary for larger range and resolution spectra.

Progress is also being made using NIR photocathodes such as the InGaAs electron-transfer photocathodes by Intevac, incorporated into proximity-focused electron-bombarded CCDs or CMOS, adapted from their commercial cameras for surveillance and forensic spectroscopy. Efforts to maintain their 35-40% QE into the colder regimes needed for low dark noise for space astronomy are underway. Sufficient gain has been demonstrated for photon-counting.

<u>Ultraviolet (0.1 – 0.3 microns)</u>

In the UV, the sky backgrounds are so low that photon-counting detectors have been standard for decades, even for broad band imaging.

The dominant detectors for space UV astronomy have been based on photocathodes with microchannel plate intensifiers (MCPs) and various photon-counting readout schemes. The dominant photocathode materials are currently CsI for the far UV (0.10 – 0.17 microns) and CsTe or bi-alkali for the near UV (0.17 – 0.32 microns). These detectors can provide very large formats (up to 16,000 x 1,000 pixels, FUSE and HST/COS), without much volume or mass requirements beyond that needed for their pixel formats. They need high voltages of order 5kv. However, their QEs are generally less than 26% at wavelengths longer than 0.135 microns. QEs are reduced below the raw photocathode material QEs, due to the MCP structures for opaque photocathodes (where the photo-electrons are ejected from the surface where the photons entered) such as CsI, or due the photo-electron's mean free path being smaller than the photon's mean free path for semi-transparent photocathodes such as CsTe. CsTe has been used in semi-transparent mode on a separate window support because attempts to deposit it on MCPs have shown it to be chemically incompatible with the glass MCPs. Detectors with glass MCPs also require bright object protection because they can burn out with too high fluxes, because their resistivity decreases as their temperature increases.

Higher QEs in the 0.10 to 0.13 micron range have been achieved with CsI and KBr photocathodes in electron-bombarded CCDs (EBCCDs) in the far UV, as flown on rockets and IMAPS, without losses due to MCPs, in opaque mode with the photocathode on a separate substrate re-imaging the photoelectrons onto the CCD. This re-imaging requires high voltage for electron acceleration into the CCD, and a strong magnetic field for focusing. Current implementations of EBCCDs have small pixel formats (256 x 256) and slow input beams, but work is ongoing to reduce the high voltages (from ~20kv to ~10kv), improve their magnets, extend their formats and accept faster beams.

New increasingly pure materials are emerging for solid state lighting, LEDs and laser diodes, which can be adapted to act as photocathodes by p-doping to give their surfaces negative electron affinity, so that the photo-electrons are ejected, usually with the help of cesiation. Most work in the UV has been done with GaN, with 50-60% QE being achieved at ~0.18 microns in opaque mode, probably increasing to shorter wavelengths. This is an improvement of a factor 2-5 over CsI and CsTe being obtained on HST. GaN is part of a ternary system AlGaInN where the band gaps can in principle be tuned for cut-offs from ~0.18 – 0.8 microns by varying the proportions of Al and In. A similar ternary system is MgZnCdO.

Plane surfaces have been used so far, but experiments with nanowires of both GaN and ZnO are intended to take advantage of their higher structural and chemical purity, as well as electron ejection by electric field concentration at their tips. Currently, higher QEs are obtained in opaque mode than in semi-transparent mode. To take advantage of that, work is beginning to incorporate them into EBCCDs. Even with improved formats and f/#s, they will still need focusing magnets and relatively high voltages, but that is very cost-effective compared to improving observatory sensitivities with even larger mirrors.

While QE improvements with GaN so far rely on their crystalline structural purity, as well as chemical purity, the large format advantages and lack of magnets with MCPs drives interest in coating MCPs with materials such as GaN and ZnO. GaN is processed at temperatures that would melt glass MCPs. Work is ongoing to make Si MCPs, which would also be chemically purer than the glass MCPs, and then coat them with GaN. ZnO is processed at temperatures compatible with glass MCPs, so if high QE is obtained with p-doped ZnO, it may be possible to combine them.

Heterostructures using AlGaN and similar materials can also be formed into APD arrays, which could take advantage of the higher intrinsic QEs obtainable if the photo-electrons need not be ejected. They could provide compact arrays without the need for high voltages and magnets, but development would be needed to obtain useful formats, low noise and multiplexed readouts.

Perhaps the most near term way to obtain high QEs in the near UV would be to extend the use of CCDs to shorter wavelengths, from that used in HST (WFPC1, WFPC2, STIS, ACS/HRC, WFC3/UVIS), with improved UV AR coatings and delta-doping, and improved rejection of red-leak with new high precision coatings, and care to avoid contamination and polymerization worsened by cooling. For both imaging and spectroscopy, photon-counting versions would be needed, with adequate formats and radiation hardening, for example via p-channels, as described above.

Future Needs and Recommendations

As outlined above the fundamental role that photon counting UV/Vis/NIR (0.1-1.7 microns) detectors can provide in breakthrough science through spectroscopy of faint sources such as exo-planets, high z supernovae, recombination era galaxies requires a broad based, strategic, and sustained investment in this technology by NASA. The spectroscopic observations envisioned for these very faint objects can not be practically implemented without photon counting detectors: exposure times of many millions of seconds (a few months), rather than 10's of kilo-seconds (days) are required to obtain a useful spectrum. Photon counting detector development is rich field with a number of low TRL approaches and technologies currently being explored through varying degrees of funding through small NASA programs. Each shows promise, but each one also presents technical challenges that need to be resolved before they are ready for a flight mission.

The science need is across the UV/Vis/NIR spectral range and it is unrealistic to assume that a single detector architecture will function across that broad waveband. In addition, the science need spans the full range of science disciplines – from nearby exo-Earths to the formation of the first galaxies. So a broad based investment is needed, rather than a narrow discipline oriented investment. This investment must be also be strategic, targeted at high value science areas or missions where this technology will enable the best science. Finally, it must be a sustained investment: the problems and issues of UV/Vis/NIR photon counting detectors are starting to be understood but more issues will likely appear as these technologies mature.

Because of the science that these detectors can enable, we need a steady and focused development path with external oversight, down-selects, technology off-ramps and possibly on-ramps, to ensure the best detector approaches successfully mature and that they are ready to incorporate into NASA's future science missions when those missions are ready to implement.