Appendix: B

Mission Requirements Summary

4/23/2009

The purpose of this appendix is to document the NWO science requirements and the associated science measurements that are needed to fulfill the science requirements. The appendix contains the NWO Mission Requirements Document (MRD), a mission requirements presentation, a requirements listing and this document that summarizes the requirements approach. A science traceability matrix will be described. This appendix will describe the mission requirements and document the flowdown of the mission requirements to the lower level NWO system components. This flowdown will be captured in the mission traceability matrix (MTM). Finally, this appendix will summarize the requirements derivation rationale for key components of the NWO architecture.

[1]The New Worlds Observer mission architecture (Figure 1) aims to discover and analyze terrestrial extrasolar planets in the following way. Using the space telescope and starshade, NWO will survey nearby stars to search for exoplanets; both terrestrial and giant planets can be found by this system. Following detection of an exoplanet, NWO will map the discovered system by taking a series of images that will allow it to measure the planet's orbit, brightness, and colors. A detailed study of the individual planets will take place by taking spectra and more detailed photometry of each planet. Spectroscopy allows NWO to analyze the chemical composition of planets' atmospheres and surfaces. Detailed photometry will show variation in color and intensity as surface features rotate in and out of the field of view, allowing for the detection of oceans, continents, polar caps, and clouds. In addition to finding and analyzing terrestrial planets, NWO can discover and analyze gas giants, exo-zodiacal dust, debris disks, etc. in the same systems as the terrestrial planets. NWO will be capable of providing high quality, general astrophysics observations.

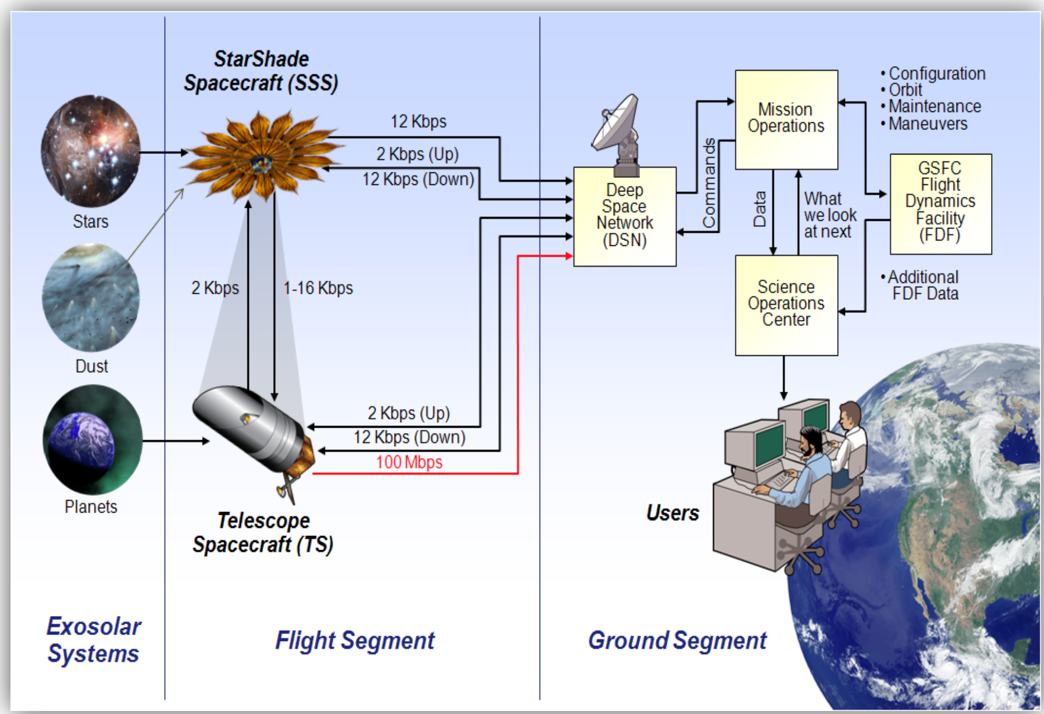


Figure 1: NWO Architecture Diagram

[1] Concept of Operation Document , Northrop Grumman

[2]The NWO system comprises a launch segment, space segment and a ground segment. The segments interact with each other to accomplish the NWO mission goals and objectives. One of the two NWO Spacecraft is composed of the Spacecraft Bus and the 50 meter Starshade Payload. The second NWO Spacecraft is composed of the Spacecraft Bus and the Telescope Payload. The Telescope is a diffraction limited telescope that is an upgrade to the HST capabilities and functions.

[i]The Ground Segment is composed of the Science and Operations Center (S&OC), the mission operations center (MOC), the Flight Dynamics Facility (FDF) and the Deep Space Network (DSN). During launch, NWO will use the services of the ground network (GN) and space network (SN). The Launch Segment is composed of the Launch Vehicle(s), Payload Adapter(s), and Launch Site Services. Figure 2 represents the product breakdown structure (PBS) of the main components of the baseline configuration. The NWO PBS is tied directly to the organization of the work that is captured in the work breakdown structure and the requirements that have been allocated. The process used for designing NWO baseline configuration has been a recursive and iterative process that started very early in the NWO concept development.

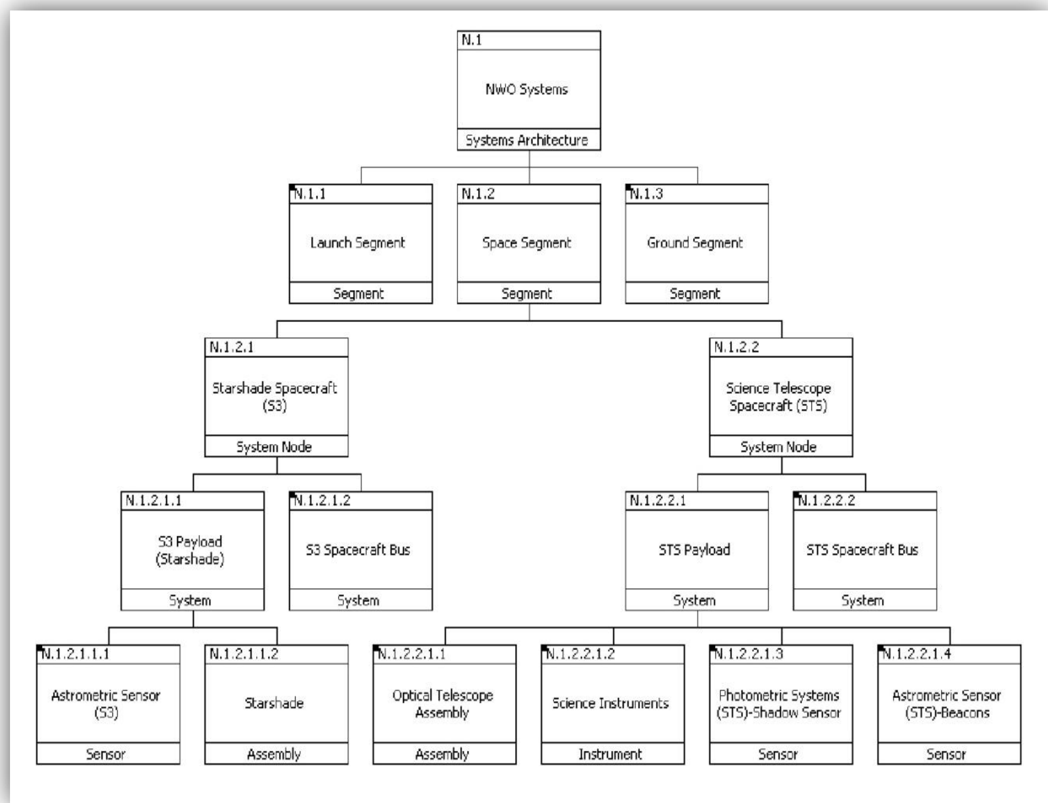


Figure 2: **Product Breakdown Structure**

[2] Mission Requirements Document (MRD), Northrop Grumman

Requirements Approach

Due to NWO's size and complexity it is critical to understand, define, and document top level requirements that will drive the execution and management of the technical solutions. Understanding and defining these top level requirements will characterize the architecture required for our budgets, resource planning and monitoring, risk mitigation, etc. The NWO science has established the mission objectives based on Science Mission Directorate (SMD) program direction and strategic plans. From the strategic plans, the science team has derived science requirements, science measurements and instrument requirements that establish the science package or level 1 requirements. The mission requirements are derived from the Level 1 requirements.

Figure 3 is a diagram that shows how the NWO design team has been working the requirements. The diagram shows how the mission requirements, the mission operations concept, technical resource allocations, and environmental requirements are established as the Level 2 requirements. Those requirements have flowed down to the different segment boundaries to establish a set of segment level requirements (i.e., Level 3). The Level 3 requirements are flowed down to Level 4 spacecraft, instrument and ground system requirements documents and ICDs. DOORS is being used to document requirements flow, define the verification methods, and later to track and report compliance. All of these requirements have been established in a Mission Requirements Document (MRD). The documents, requirements listing and system models have been established to make sure everyone understands the requirements. The traces within the database allow the team to look for goldplated requirements, gaps or verification issues.

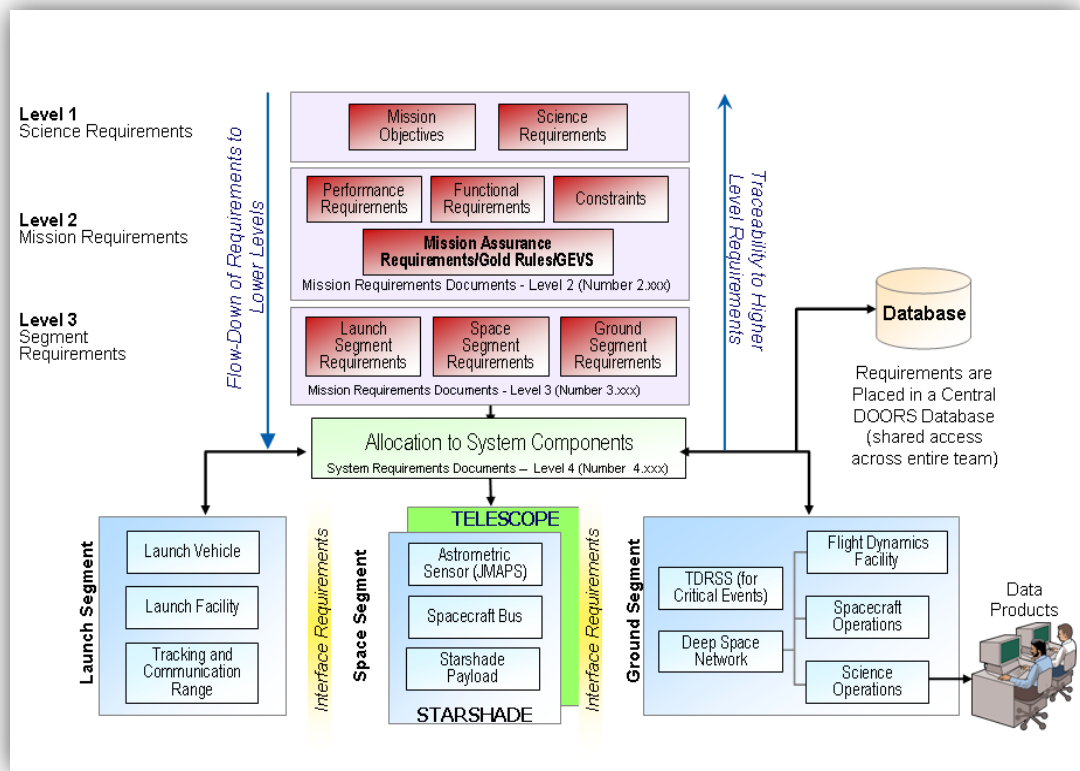


Figure 3: NWO Requirements Approach

1.1 Science Objectives

The NWO mission is to discover and study Earth-sized planets. The secondary science objectives are to study giant planets and planetary system architecture. Another science objective is to conduct general astrophysical science. These science programs form the basis for three scientific activities; terrestrial science, giant planet and planetary system's architecture science and general astrophysics. These objectives lead to the Level 1 requirements key performance parameters (kpp) for both the baseline and minimum missions (Table 1.) The NWO key performance parameters are used by the design team to gauge how "well" the solutions meet the goals of the NWO mission.

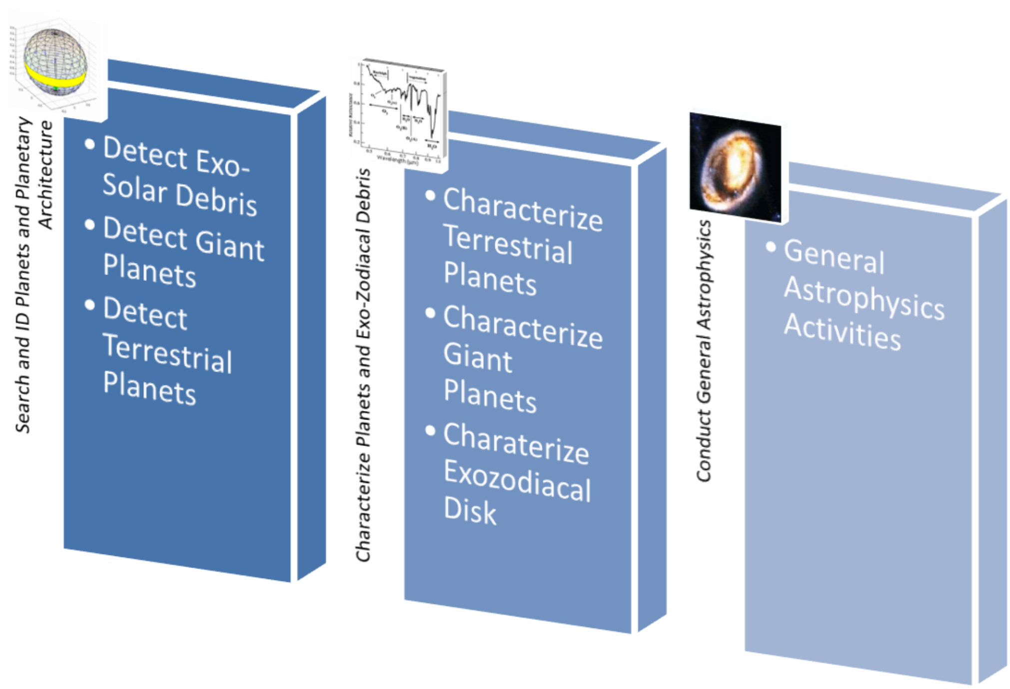


Figure 4: Science Objectives

Table 1: NWO Level 1 Requirements

Name	Baseline Mission	Minimum Mission	Performance Floor
Mission Duration (years)	10 & 5	5	3
Completeness	30	20	10
NWO Inner Working Angle (mas)	50	60	70
NWO Observation Contrast- 10^-10	10^-10	10^-10	10^-9
Observations	140	100	60

The *driving scientific parameters* for NWO are the *angular separation* of the planet from the star and its *observed contrast*, i.e. the ratio of the planet brightness to the reduced starlight in the planet pixels. These two parameters <u>set requirements</u> on NWO's *inner* *working angle* (the closest to the star that NWO can effectively probe for planets) and its achievable contrast (the faintest planet NWO can detect relative to the stellar brightness).

Baseline Mission Driving Requirements

The number of Earth-like planets is unknown, but some astronomers have estimated that as many as 10% planetary systems may contain one. The possibility that Earth-like planets are infrequent makes it desirable to survey as many nearby stars as feasible. Considering the minimum number of stars we should observe to yield a few Earth-like planets, together with technical, schedule, and cost constraints, we have concluded that a 150 target stars is a suitable NWO goal.

To detect a terrestrial planet requires that the achievable contrast, i.e., the contrast achieved after calibration and removal of the background is of the same order. Similarly, the requirement on the inner working angle simply says that a planet located outside the projected starshade should be detectable in the processed data. Most measurements will consist of the telescope holding steady on a target for several hours to several days. For detection of the terrestrial planets, the system should search the most likely range as well as the complete range of temperatures within which life may be possible on a terrestrial type planet.

Once a planet is detected, the system is to characterize the planet's color, orbit, brightness and look for biomarkers (if looking at a terrestrial planet). If we learn that the number of Earth twins are low, we will shift the science campaign towards characterizing the exo-solar planetary systems architecture and establish criteria for subsequent techniques to peer deeper into future planetary system.

1.1.1 Science Traceability Matrix

Table 2 shows the traceability from science objectives to the selected instrument. This Science Traceability Matrix (STM) matrix helps to ensure that the program's scope, requirements, and deliverables remain "as is" when compared to the baseline. It "traces" the deliverables by establishing a thread for each requirement from the program's initiation to the final implementation. This STM can be used during all phases of a project to: 1) Track all requirements and whether or not they are being met by the current process and design. 2) Where requirement gaps are identified, this matrix can assist with any additional project assignments and/or make-buy decisions. The matrix is bi-directional and tracks the requirement "forward" by examining the output of the deliverables and "backward" by looking at the program requirement that was specified for a particular feature of the deliverable. The STM provides a necessary input to the program verification planning to help determine the types and number of integrated ground and/or flight tests and test facilities required by the program. Finally, the STM is used to verify that all requirements are met and to identify changes to the scope when they occur.

	Requirement#	NW 1.1	NW 1.1	NW 2.1.1	NW 2.1.2	NW 2.1.3	NW 2.1.4	NW 3.1.1	NW 3.1.2	NW 4.1.1	
		Search HZ	Detect Planets	Measure Color	Determine Orbit	Measure Brightness	Measure Spectra	Characterize GP	Characterize Debris Disk	Conduct GA	
WBS		Terrestrial Science						Giant Planet and Planetary Arch. Science		General Astrophysics	
5.2	Optical Telescope Assembly	X	X	X	X	X	X	X	X	X	
5.2	WFCAM	X								X	
5.2	UV Imaging Spectrometer						X			X	
5.2	EXOSPEC			X	X	X	X	X	X		
5.2	EXO-CAM	X	X	X	X						

Table 2: Science Traceability Matrix

Figure 5 is a snapshot of the requirements database to establish another STM perspective. The measure planet's color requirement is one of the measurements performed by NWO to meet the terrestrial planet science objectives/requirements. In the diagram, the measure planet color requirement has been allocated to the measure planet color function. The function is decomposition of the conduct terestrial planet science (function) for the NWO mission functions (functional flow diagram). There are other requirements that refine the higher level requirement (Measure Planet's Color). These refinements include establishing the spectral range, completeness, and reference color and magnitude requirements. The measure color function is being performed by Exospec. [Planet's Color Data] from Exospec is identified as the product (or output) from the function. For NWO there are over (250) components that have been identifed in the database. The components in the database are those components that were provided by the Integrated Design Center (IDC). The Price H cost data has been applied to the components along with the key attributes such as mass and power. The components are specified by (performance) requirements. There are several accomodation requirements that are established for Exospec and are flowed down to the spacecraft bus (ex. Mass, power, and data). A summary of the accomodation requirements can be seen in Table 3.

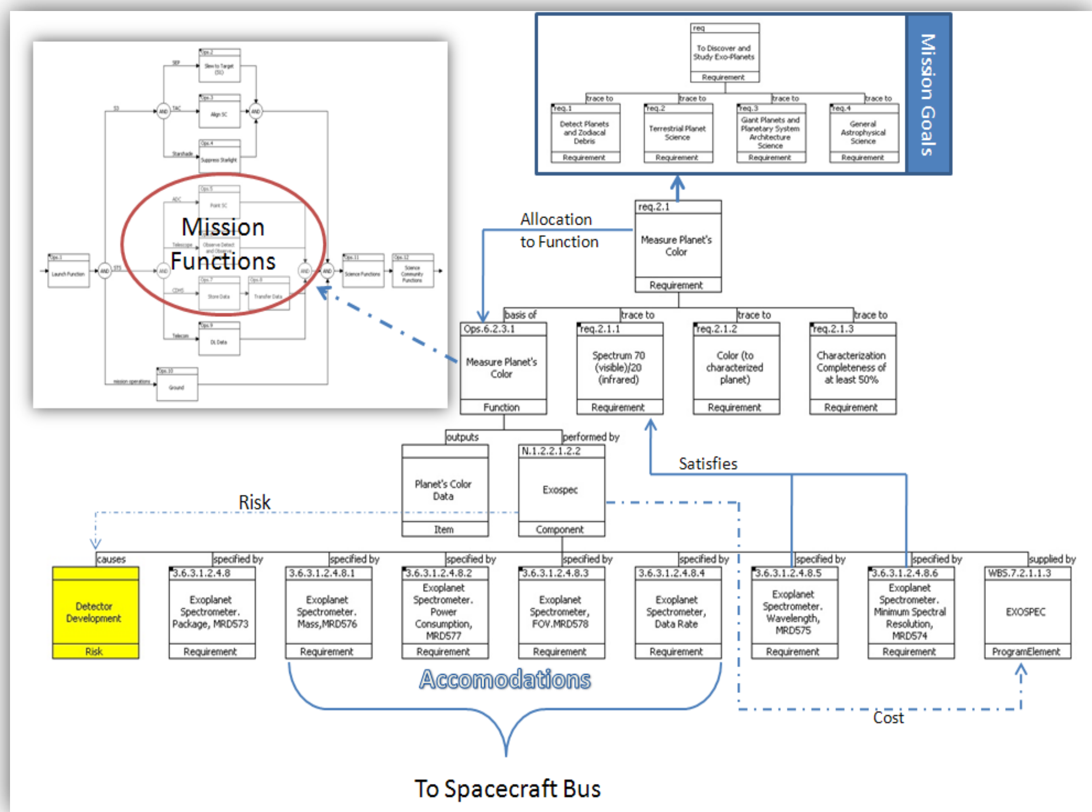


Figure 5: EXO-Spec Traceablity- Database Example

Some of the (performance) requirements that define Exospec are listed and shows the (satisfy) higher level requirements relationship. You can also see that cost and risk relationships have been established in the the NWO requirements database.

		Accommodations				
WBS		Data (Gb/day)	Storage (Gbytes)/day	Mass (kg)	Power (w)	FOV
5.2	OTA	0	0	3114	220	
5.2	WFCAM	2,453,800,715,551	3.06725E+11	476	300	20.2' x 10.1'
5.2	IFS (Spec)	4,831,838,208	603979776	124	100	<1"
5.2	EXOSPEC	30,136,320,000	3767040000	137	200	10.3" x 3.1"
5.2	EXO-CAM	1,932,735,283	241591910.4	209	200	26.4" x 26.4"
		2,490,701,609,042	3.11338E+11	4060	1020	

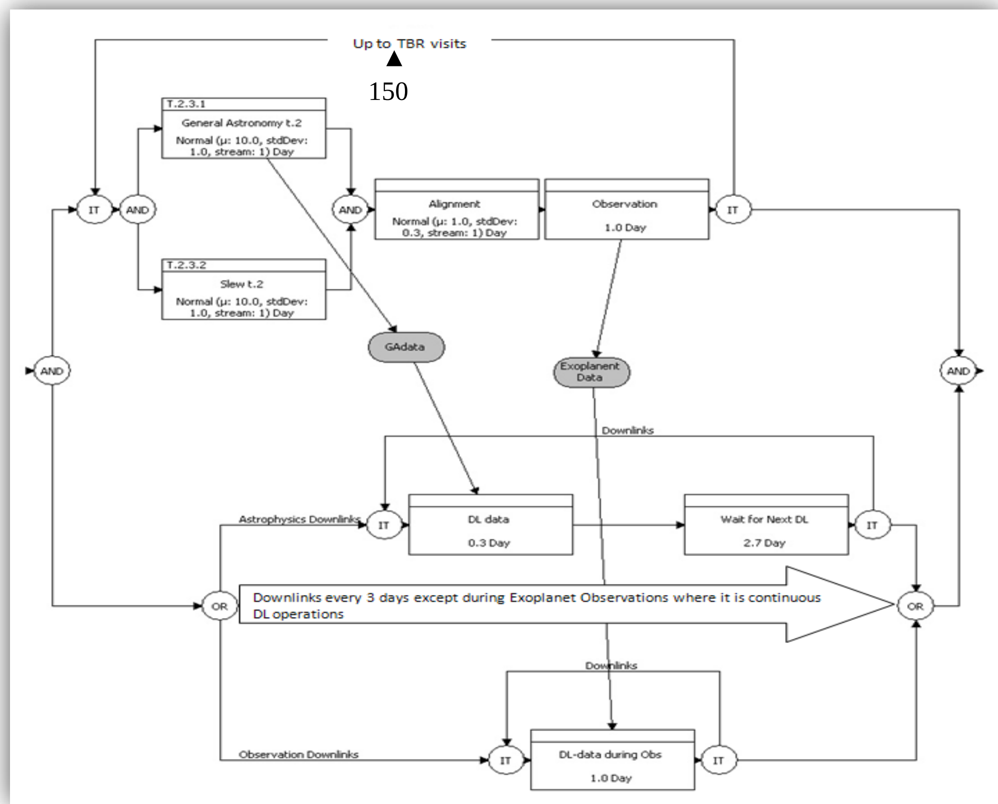
Table 2: NWO Instrument Accomodation Summary

Minimum Mission Driving Requirements: Our minimum mission is defined by the lowest science performance we are willing to accept. We have graceful descope options all the way down to the performance floor, with a minimum mission well worth doing. The minimum configuration is simply providing a starlight suppression capability that can be used with other space telescopes.

1.1.2 Mission Functions

[3]The starshade and telescope will be launched into the same L2 halo orbit where they will be separated by approximately 80,000 km. We have developed several scenarios within the concept of operations (CONOPS) that allows the baseline system to perform ~ (150) observations in 5 years. Figure 6 is a functional flow diagram that outlines the high level activities (i.e., functions) associated downlinking science data to analyze whether the activities will meet the observation (or visit) requirements (ex., ~150 observations).

Figure 6: Science Data Downlink Thread



Each observation consists of a retargeting maneuver, where the starshade moves into the telescope's line of sight, and a stationkeeping period, where the starshade is maintaining alignment with the telescope and the telescope is taking exo-planet science data. Each retargeting maneuver will take between 5 – 15 days. The Starshade and Telescope are

[3] Concept of Operations, Northrop Grumman

aligned during the observation in which we may obtain both an image and spectrum of the exo-planet, as well as a wide-field image of the exo-solar system for comparative planetology and astrometry. Starshade stationkeeping maneuvers will have to done every -approximately 20 minutes to stay aligned with the telescope. The starshade has knowledge of its position from on-board startrackers, Deep Space Network (DSN) information and RF-ranging instruments. All of the NWO mission (functional) requirements have been allocated to specific mission functions as seen in Figure 8. Each function is performed by NWO components. Using the results from the Integrated Design Center (IDC) and the Mission Requirements Document (MRD), each of the components and their related requirements has been applied.

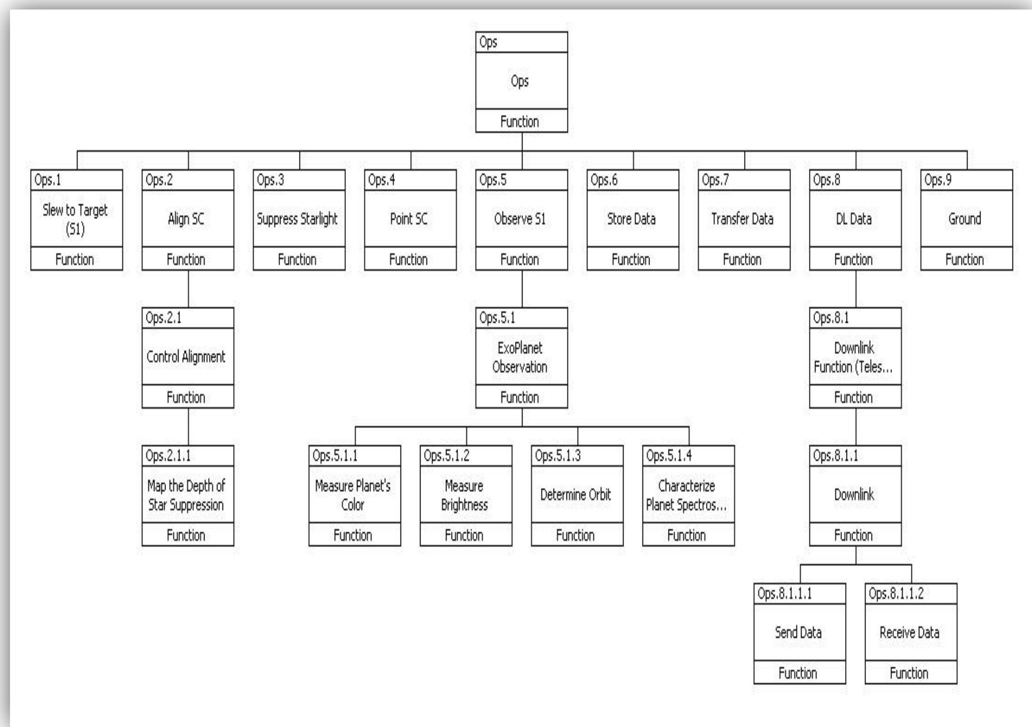


Figure 7: Mission Functions Hierarchical View

1.2 Operations

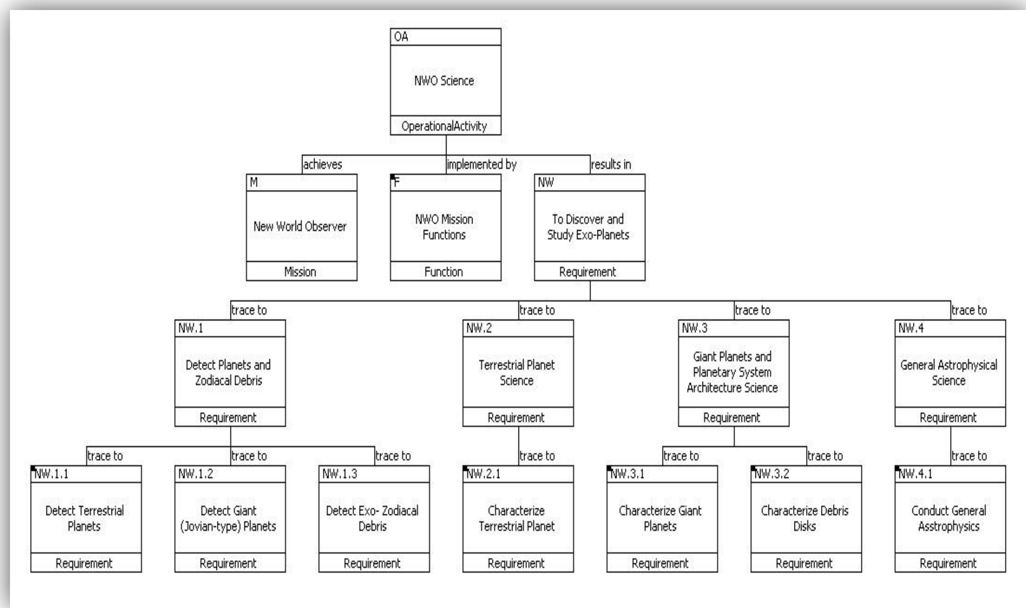


Figure 8: Science Operational Activity Heirarchical View

NWO has several features that drive the operations concept and the mission architecture. Figure 8 is a hierarchical view of the science operational activities. The coordinated operation of the two separate spacecraft to perform the exoplanet observations is the most significant driver; a detailed scenario describing how the exoplanet observation is accomplished is provided in the CONOPS. The coordinated operation requires a single operations unit that consists of the science team and the mission operations team as seen in Figure 9 to operate the two spacecraft as a single instrument for exoplanet observations. Each spacecraft will have its own operations team at launch; these teams will be consolidated into a single team during the exoplanet observation commissioning phase.

The telescope has the potential to downlink large volumes of data - up to 2.5 Tbits per day. This drove the architecture to include the DSN Ka-band capability, which can receive data at rates up to 150 Mbps. The exoplanet observations have a number of points in the alignment and observation process that require ground system involvement, particularly early in the mission.

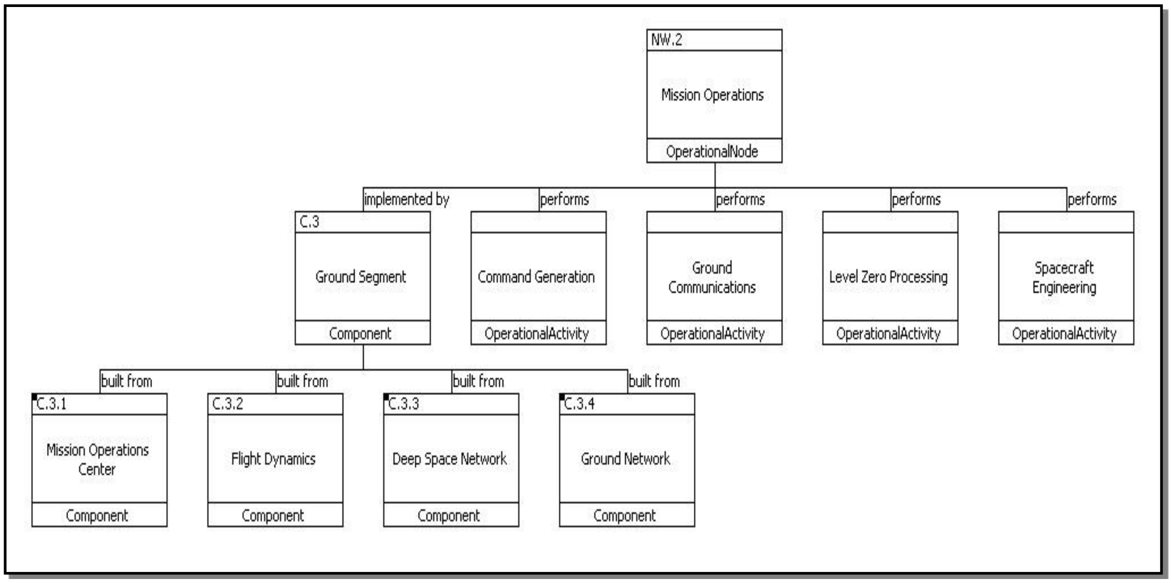


Figure 9: Mission Operations Hierarchical View

The DSN is not a flexible network; therefore, an additional network of ground station is included which can be scheduled with less leadtime. The need for timely evaluation of alignment and exoplanet observations also drives the operations to be staffed around the clock for the telescope operations. For the starshade operational staff, the staff shall be available 8 hours a day/ 7 days a week. The general astrophysics phase of the mission is expected to be similar to HST.

1.2.1 Science Operations

[4]The NWO science operations will be located at the STScI, which is eminently capable of supporting a world class space observatory. Because of the tight connection between science and mission operations, the mission operations will also be located at the STScI.

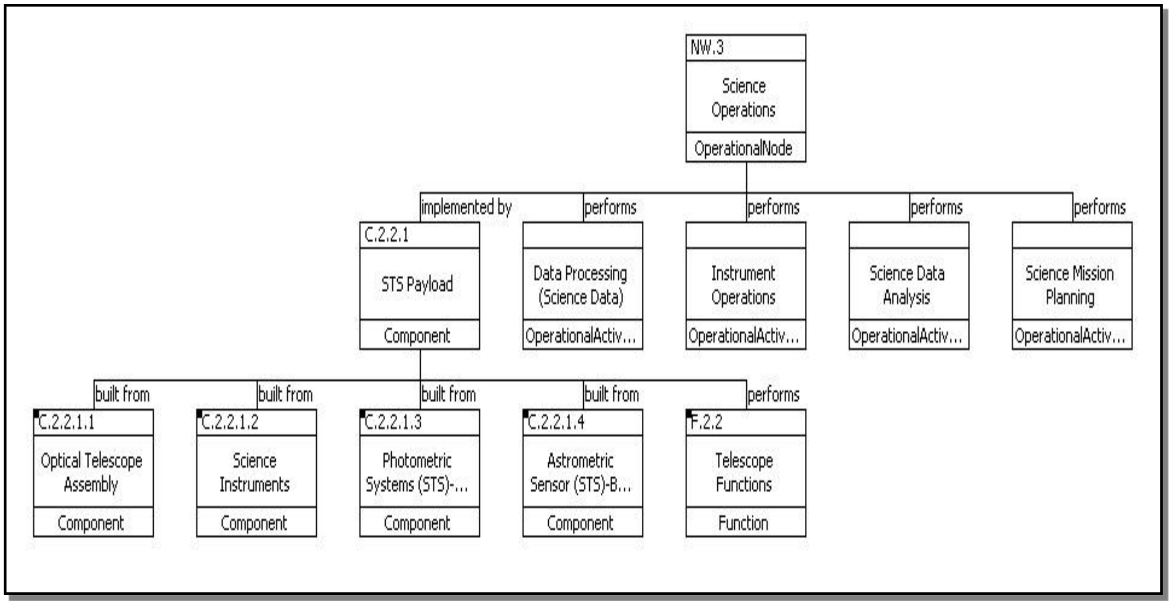


Figure 10: Science Operations Heirarchical View

Figure 10 is a view that describes the activities that are associated with science operation and the systems (or components) that are used to implement the activities. Our goal is to produce reliable images of exoplanetary systems with a full pixel-by-pixel accounting for the propagated error of the pixel value. The images should be suitable both for scientific interpretation and for public display and enjoyment. Downlinked STS data will go to the Science Operations Center (SOC) at the *Space Telescope Science Institute* where the raw Instrument data (Level-0 data) will be reformatted into FITS format (Level-1 data). Each of the exposures will be individually calibrated via an “on-the-fly”calibration system (Level 2). Exposures, e.g., multiple exposures at a single telescope pointing, will be combined and calibrated as a group (Level 3). The Level-1, -2, and -3 data will be stored in the Science Data Archive and made available to the SOC, where they will be distributed to the NWO team for further analysis.

NWO data processing starts with the Level-2 and Level-3 data sent by STScI, which comprise a set of calibrated images that have had detector dark current, bias, flat-field nonuniformities, and cosmic-ray events removed (Level-2 data) and grouped by telescope pointing (Level-3 data). To create NWO Level-4 processed images it will be necessary to remove all sources of background light. Exozodiacal light is a signal to those studying exozodiacal disks, but a source of background to those searching for and studying

[4] NWD Discovery Proposal

exoplanets. Unlike a coronagraph using deformable mirrors for wavefront control, ExoCam has no outer working angle, so we can estimate the local zodiacal light and isotropic, large-angle scattered starlight from the regions of the observed image well away from a star. Subtraction of residual in-band diffracted, reflected sunlight scattered off the edges of the starshade and the “red light leak” from the star will be more difficult. The level and structure of these sources will vary with the angle of the starshade to the Sun and STS and the centering of the starshade on the target star to STS. In-flight calibration data will be used to construct models for these sources of background light.

Initially, these models will be crude, but they will improve throughout the life of NWO as additional targets are observed. We will use positioning telemetry from the NWO spacecraft during an observation sequence to subtract the models from individual exposures (typically 10 to 15 min.) and compute optimal weights when combining these exposures. We may find it necessary to be more aggressive than the standard STS pipeline processing in identifying cosmic-ray pixels and masking hot detector pixels when combining data from multiple dither positions to decrease “false” detection of planets that will be near 30th magnitude. We may find it necessary to go all the way back to the uncalibrated data (Level- 1) data to remove cosmic-ray hits. To locate planets, we will subtract the exozodiacal gas and dust disk using disk models and low frequency filtering. Planet dectection will be accomplished using Co-I Kasdin’s matched filtering and Bayesian planet detection algorithms. Level-3 and -4 NWO data will be made available to STScI/MAST within 6 months after the observations are obtained.

Design

[5]There are two key performance requirements in designing the starshade spacecraft: Inner Working Angle (IWA) and suppression. The basic performance requirement is to suppress light from the target star by a factor of 1E10 while allowing planet light ≥ 50 mas from the star to pass. There are other several design parameters in the trade space that play a significant role in the starshade design: the starshade's size, number of petals, shape and various starshade design tolerances. The starshade's design tolerance parameters are described in detail in Appendix E 4. There are interactions across all these parameters across both Starshade and Telescope spacecraft. The key mission requirements are noted below.

Requirement	Baseline Value
Inner Working Angle (IWA)	50 mas
Starlight Suppression	10^{10}
Spectral Range,	300 to 1000 nm
Shadow Size	6 meters
Number of Observations	~150

There are other secondary requirements that play a role in the design of the starshade. An example of some of the key secondary requirements is the following: the starshade has to be capable of absorbing design thermal and vibration flexure without exceeding the design tolerances. The starshade has to be capable of enduring solar pressure or meteoroid impingement without exceeding the tolerances, as well as distributing tension without exceeding the design tolerances described in Appendix E.4. At the system level and across both spacecraft, NWO has other key parameters in order to meet the NWO objectives: the diameter, sensitivity, and wavelength range of the Telescope spacecraft. The primary mirror diameter on the telescope determines the resolution and sensitivity of the observations while the instruments on the telescope determine the wavelength range and spectral resolution of the observations. The primary parameters describing apodization function of the starshade are shown in the table below. The apodization parameters affect the starlight suppression requirement. There is correlation between the Starshade parameters and the requirements. Changing Starshade Parameters has an effect on the requirements which can either be a positive or negative effect. The performance versus parameters trade is described in detail in Appendix E.3.

[5] Starshade Summary, Northrop Grumman

[6]The starshade spacecraft uses solar electric propulsion (SEP) to propel itself for the retargeting maneuvers. Our baseline choice for the SEP system is the NASA Evolutionary Xenon Thruster (NEXT) system with I_{sp}=4100 s and 235 mN thrust. Our full ephemeris simulation shows that ~11 km/s of ΔV is needed to do the retargeting for 200 observations over a 5 year mission. This requires 900 kg of Xenon, which includes a 10% reserve for additional retargeting. The effectiveness of the Starshade Spacecraft propulsion system directly translates to science return. Key mission-level requirements that drive the Starshade Spacecraft propulsion system concept include:

1. The system shall be capable of detecting an Earth twin at Quadrature in a Solar System twin that is up to 10 (TBR) parsecs away.
2. The system shall be capable of finding at least 30 Earth twins if all target stars have such a planet.

These requirements drive the key elements of the telescope/starshade architecture, including distance between spacecraft, relative angles between spacecraft with respect to heliocentric space, starshade size and thus mass, and the number of observations that are required in the baseline mission. The current mission concept has determined a conceptual baseline for these parameters as documented in the Mission Design Laboratory study products. The key mission parameters that drive the Starshade Spacecraft propulsion system design are:

- Spacecraft dry mass: assumed to be 3523 kg based on MDL results, including contingency mass growth
- Telescope-to-Starshade Spacecraft separation distance: 80,000 km
- Minimum number of observations in the 5-year primary mission: 100
- Number of observation extensions in the 5-year primary mission: 30
- Slew angle, or the distance the Starshade Spacecraft must travel between observations: A function of the specific mission plan. Prior design reference missions indicate that the mission-average slew angle for coverage of high value targets is 20 – 25° (telescope slew angle), which translates to 28,000 to 35,000 km translation distances for the Starshade Spacecraft.
- Total ΔV capability of Starshade Spacecraft (assuming electric propulsion): 12 km/s

After the starshade arrives near the telescope line of sight, command control is handed off to the alignment system. The NWO navigation system must sense the relative locations of the starshade and ST and give commands to the propulsion system. It enables efficient acquisition of alignment on the first and all subsequent stars, closed-loop alignment control during science observations, navigation between observations, "lost-in-space" post-anomaly reacquisition, and later rendezvous of a new starshade with the ST (Science Telescope).

[6] Solar Electric Propulsion (SEP) Summary, LaRC