Instrument Design Laboratory (IDL) Summary

(Includes Cost Estimate)

FOR

New Worlds Observer (NWO)

Prepared For:

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The purpose of this appendix is to summarize the results from the NWO instrument design activity that was conducted at the Instrument Design Laboratory (IDL) located at the Goddard Spaceflight Center (GSFC) Integrated Design Center. The main purpose of the activity was to baseline a design for a photometric and astrometric sensor suite. A more detailed description of the sensor components can be obtained through the Principle Investigator and the Virtual System Design Environment (VSDE).

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Summary

The IDL held a design activity for the NWO (customer) team. The following requirements were received from the customer team:

- NASA Strategic Goals and The Vision for Space Exploration specify the need for "advanced telescope searches for Earth-like planets around other stars, and the study of the origins, structure, evolution, and destiny of the universe". To that end, the New Worlds Observer (NWO) program, an advanced study concept, seeks to observe "Earth-like" or potentially life sustaining planets around distant stars.

- NWO will utilize two spacecraft flying in formation to block out the obscuring light from the distant stars and directly observe distant planets, or exo-planets.

- One spacecraft will comprise the Starshade, used to occult and remove the central star light, while the other spacecraft will contain a telescope that will use sensors to directly observe orbiting exoplanets and characterize them via spectroscopy.

Mission Parameters:

The NWO mission parameters are as follows:

- NWO will launch both vehicles on a single rocket to the Lagrange Point (L2) where it will be stationary with respect to the Sun and Earth via balanced gravitational forces.
- 5 year baseline mission design life
- Launch date potentially in the 2018-2020 timeframe
- Class B Mission with selective redundancy; we will be costing with both Class S and Class B parts
- The Starshade will be maneuvered into a location that will occult the target star (by being in the telescopes line of sight of the star). The positioning of the Starshade into the correct position could take about two weeks depending on the target. During this time the telescope will conduct some secondary science.
- Once the Starshade is in place, the telescope (4m) will begin imaging around the star to search for the presence of exoplanets. Observations could require 1-2 days (more for discovery).
- The two spacecraft will be separated by 50-100 Mm with control to ~4 Mm.
- The Starshade will have a diameter of ~50m, which at the separation distance will subtend an angle of 100-200 mas.

1 IDL Summary

Study Objectives:

The study objectives are:

- Create a conceptual instrument point design for the AS and SS with mass, power, volume, and data rate that is consistently represented in all engineering subsystems
  - Realize all subsystem components (optical, mechanical, electrical, electro-mechanical and electro-optic/detectors) for both sensor systems with redundancy that meets a 5 year lifetime
  - Scope out the Beacon for the Astrometric System
  - Design the Shadow Sensor System
    - Optics and Detector plane
    - Help spell out the detector requirements (eg gain stability, etc…)

- Characterize the conceptual point design
  - in terms of accommodation needs: mass, power, volume, data rate, redundancy
  - in terms of performance: reliability, radiometric performance, fine guidance performance; contamination
  - in terms of operation: mission ops, instrument modes

- Cost the conceptual point design using a parametric analysis tool.

1 IDL Summary

Driving Requirements:

Figure 1 displays therequirements that drove IDL design decisions.

Requirement	Design
Lead lengths for the Astrometric Sensor detectors (JMAPS) to processing electronics to be as short as possible.	JMAPS EE Boxes are located adjacent (within 5") to the JMAPS OTA on the AS mounting plate, but NOT on the AS Optical Bench (which is thermally isolated from the mounting plate).
Laser Beacon on JMAPS to be co-aligned with the JMAPS OTA, accounting for the scanning mirror and mechanism.	Laser Beacon attached to JMAPS OTA exterior shroud and utilizes pentaprisms (2) to "handoff" beacon signal to the scanning mirror, centered in the optical path. 1st prism is mounted to the OTA exterior shroud, turning the beacon 90 degrees, then passes through a small aperture in the OTA shroud. 2nd prism is mounted to the backside of the secondary mirror structure in the obscuration area caused by the mirror mount, which then directs the beacon to the scanning mirror.
Class B Mission and 5 year mission drives redundancy.	Full redundancy used as a general philosophy using primary/redundant electrical boxes, or primary/spare boards in same enclosure. Triple redundancy on laser beacons, and redundancy for all critical components. No redundant optics at instrument level.
AS Gimbal needs to be aligned to JMAPS.	Gimbal mechanism mounted on AS Optical Bench, but electronics are NOT to minimize thermal gradients. Gimbal electronics (AS-EE) is located close by on the AS mounting plate in notional design, but thermally isolated from the AS Optical Bench.
SS optics/detectors desire cold temps for optimum performance.	SS designed as a separate optical bench enclosed in a shroud to ease thermal control burden.

Figure 1: Driving Requirements

Pointing Modes:

Figure 2 shows pointing modes that were developed for the TAC concept of operations.

Mode	Sensors active				Accuracy		Knowledge	
	GT	R	B	S	Range	Bearing	Range	Bearing
Independent safe	X				Any		50 km sphere?	
Formation safe	X	X	/		Any		1 km	arcmin
Formation coarse	X	X	X		Any		1 km	arcsec
Cooperative transition		X	X	X	1 Mm	100-1000mas	1 km	10-100mas
Cooperative fine		X		X	1 Mm	<1 mas	1 Mm	<1 mas

Figure 2: Pointing Modes

1 IDL Summary

System Components

The NWO telescope is a conventional, diffraction-limited telescope, optimized to work in visible wavelengths. The “starshade” craft sits in the telescope’s line-of-sight to a nearby star, occulting only the star to allow detection of the exo-planet signal. The telescope spacecraft incorporates a diffraction-limited astronomy telescope for visible to near-ultraviolet wavelengths and requires no new technology. The team members dedicated to study of the telescope, GSFC and Ball, have world-class, relevant experience from HST, JWST, and Kepler. Monolithic mirrors up to 4m are a straightforward extension of current high-TRL glass mirrors with decreasing areal density. To take advantage of the high angular resolution, the telescope will have a fine-guidance sensor (FGS) and a fast-steering mirror to improve pointing stability. The following focal plane instruments are baselined. Figure 3 displays the functional block diagram of the Science Telescope Spacecraft (STS) payloads. The IDL focused on the allignment system.

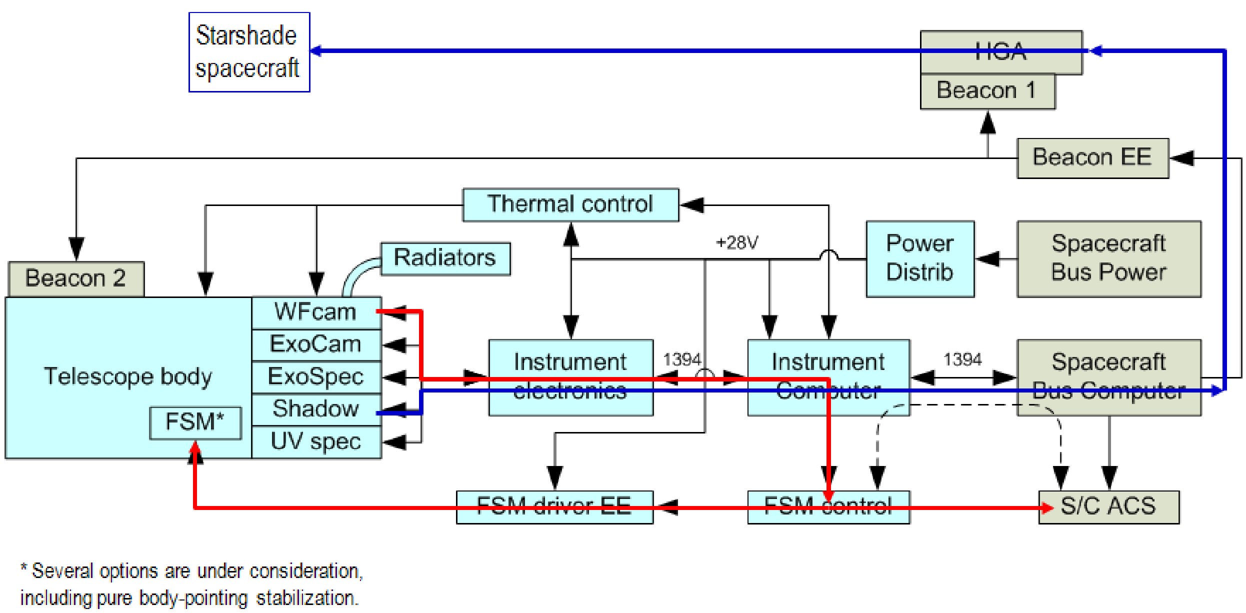

Figure 3: Payload Functional Block Diagram

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Figures 4, 5, and 6 list the data volumes, mass summary and power modes for the instruments.

	WFcam	ExoCam	ExoSpec	UV spec	SS
Instrument FOV	20.2' x 10.1'	26.4" x 26.4"	10.3" x 3.1"	<1"	60" diam
Array size (pixels)	92k x 46k	2k x 2k x 4	500x150x728	16k x 256	256 x 256
Pixels	4.44E+09	1.68E+07	5.46E+07	4.19E+06	6.55E+04
Bit rate/sec	3.55E+07	1.34E+05	4.37E+05	3.36E+05	5.24E+04
Bit rate/day	2.45 Tbit	1.93 Gbit	31.38 Gbit	4.83 Gbit	4.53 Gbit
Downlink w margin	3.67 Tbit	2.89 Gbit	46.91 Gbit	7.22 Gbit	6.77 Gbit
Downlink time	6.8 hr	19 sec	5.2 min	48 sec	45 sec

Figure 4: Instrument Data Volume

	CBE Estimate (Kg)	% Total Dry Mass	Contin-gency	Allocation (Kg)
Optical Telescope Assembly (4-m)	2395	59%	30%	3114
Exo Cam	161	4%	30%	209
Exo Spec	105	3%	30%	137
UV Instrument	95	2%	30%	124
GA WFC/ Guider	366	9%	30%	476
Shadow Sensor Assembly	49	1%	30%	64
Misc.	137	3%	30%	178
Payload Total	**3308**	**81%**	**30%**	**4300**

Figure 5: Instrument Mass Summary

	Modes							
	Launch	Commiss	Cruise	Peak	Exo Sci	GA Sci	Commun	Safe
PM heat	100 W	200 W	100 W	200 W	200 W	200 W	200 W	100 W
SM heat	10 W	20 W	10 W	20 W	20 W	20 W	20 W	10 W
Instr heat	20 W	50 W	20 W	50 W	50 W	50 W	50 W	20 W
ExoCam	80 W	80 W	80 W	200 W	200 W	80 W	200 W	80 W
ExoSpec	80 W	80 W	80 W	200 W	80 W	80 W	80 W	80 W
WFcam	120 W	300 W	120 W	300 W	300 W	300 W	300 W	120 W
UVspec	40 W	40 W	40 W	100 W	40 W	100 W	40 W	40 W
Shadow	15 W	15 W	15 W	30 W	30 W	15 W	30 W	15 W
Avionics	100 W	170 W	100 W	170 W	170 W	170 W	170 W	100 W
	565 W	955 W	565 W	1270 W	1090 W	1015 W	1090 W	565 W

Figure 6: Instrument Power Modes

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Trajectory and Alignment Control

A starshade subtending 100-200 milliarcsec (1 mas=5 nanorad) in diameter must be placed and kept centered on the star for a few hours of observing, to within a few mas. The starshade's angular diameter is chosen to match that of habitable zone orbits of the selected science stars. The starshade casts a shadow toward the telescope, whose aperture must be centered in that shadow within about 1 m. This tolerance is an engineering compromise between starshade size looser tolerance and larger IWA and alignment sensing capability. This 1 m alignment offset might be measured by an angular sensor on one spacecraft which finds the celestial coordinates of the partner spacecraft. For a typical 20-100 megameter (Mm) separation, this means the sensor needs precision, stability, and ultimate accuracy as small as 2 mas.

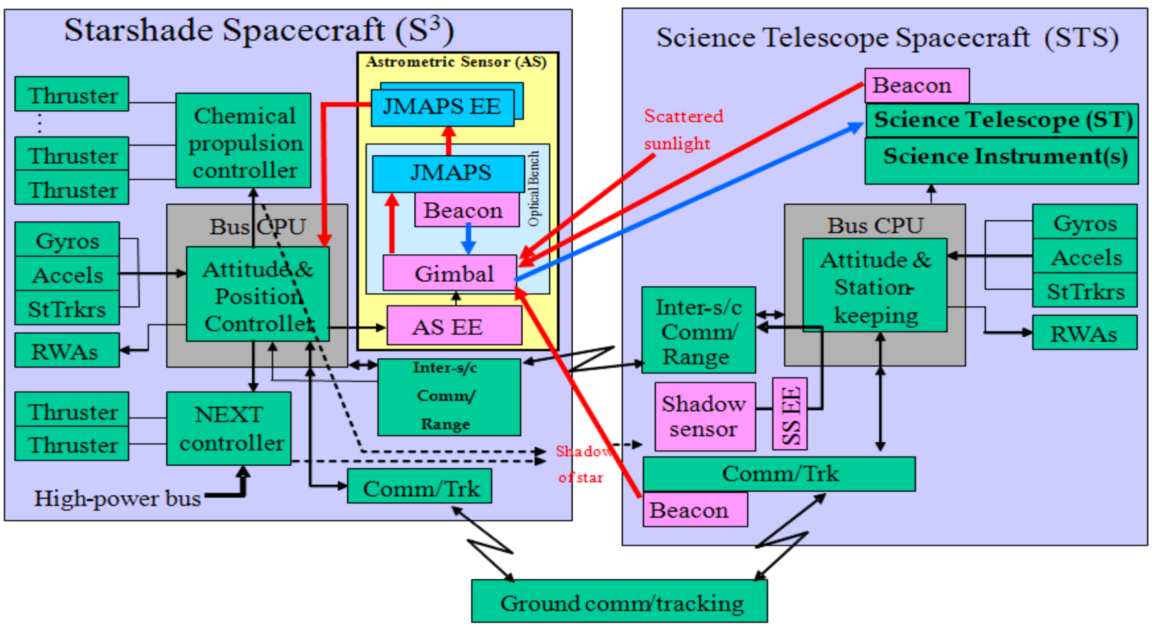

Figure 7: TAC Functional Block Diagram

1 IDL Summary

The starshade has an Astrometric Sensor (AS) that measures the bearing or the direction the telescope is from the Starshade, and guides the alignment of the shade between the telescope and target star. The baseline AS for NWO is the JMAPS. Telescope contains a Shadow Sensor (SS) and a Laser Beacon. The SS is used to perform the fine control of aligning the telescope and Starshade once the coarse control is performed by the AS on the Starshade. The SS measures the centering of the telescope within the shadow created by the Starshade. The Beacon on the telescope is aligned with the telescope boresight and is used by the Starshade for locating the telescope. Both vehicles contain an RF ranging system to acquire ground based ranging data as well as to collect inter-vehicle ranging data.

Astrometric Sensor (S3)

The starshade has an Astrometric Sensor (AS) that measures the bearing or the direction the telescope is from the Starshade, and guides the alignment of the shade between the telescope and target star. The baseline AS for NWO is the JMAPS show in Figure 8..

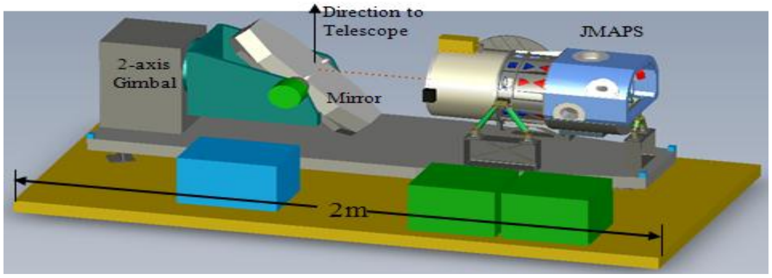

Figure 8: Astrometric Sensor

Retro-Reflector

Retros inject 1-2 copies of the target star into the antipode field. It is fatter because of small aperture through the retros. Those fat images of the target star are “synthetic astrometric references” at a fixed offset from the location of the target star’s shadow. In the illustration, the shadow would lie on the “Telescope”. Misalignment of retros is tuned to give chosen non-zero offsets. The relative position of science telescope with respect to those copies is a direct measure of telescope-starshade-star collinearity. Integration times of order 10 sec each for Telescope, synthetic and real reference stars. Ground calibration knowledge is good enough to initiate first occultation. After on-orbit calibration, knowledge improves to ~5 mas, and gives an accurate portable reference that is available on every target star. (Figure 9)

1 IDL Summary

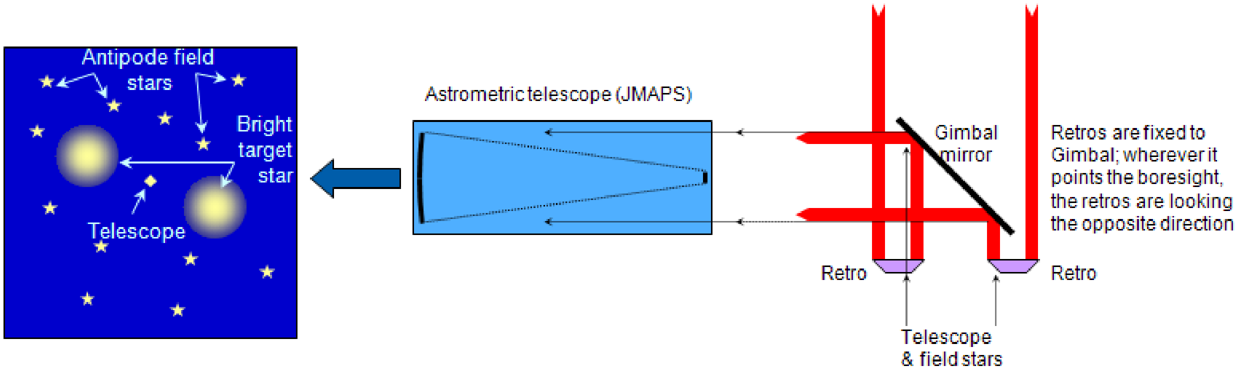

Figure 9: Retro-Reflector

Beacon

A similar beacon is mounted on AS, pointing out along JMAPS boresight Gimbal allows this beacon to be steered also In case of AS failure, this beacon enables a fallback alignment procedure Beacon is observed by Telescope (optionally through a laser line filter). Measurement of its position in the sky, compared to the target star, enables Starshade guidance to the onset of shadow Periodic measurement of its position during slew (with respect to background stars) enables the slew position and velocity estimates to be updated. This is a fallback mode because it places much heavier operational burdens on the Telescope. (Figure 10)

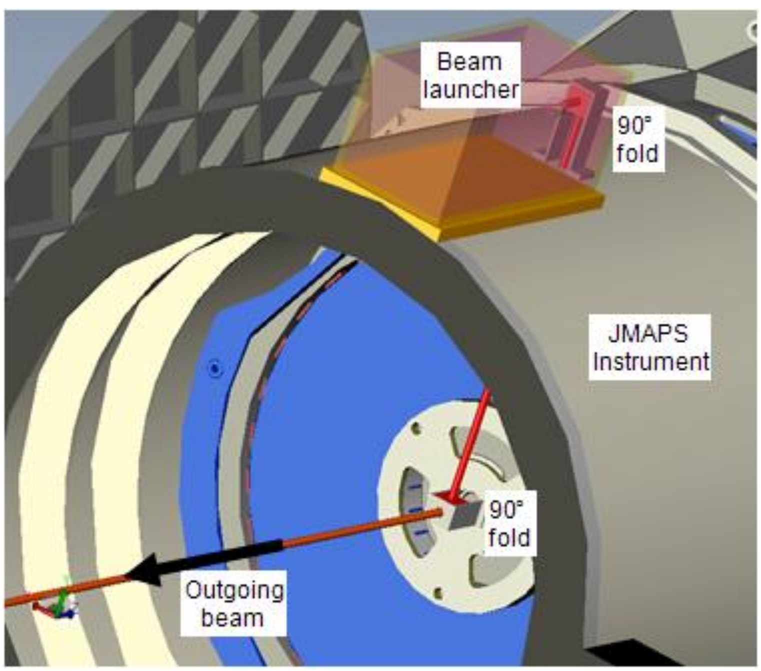

Figure 10: Beacon on Telescope

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Photometric Systems (STS)-Shadow Sensor

Telescope contains a Shadow Sensor (SS) and a Laser Beacon. The SS is used to perform the fine control of aligning the telescope and Starshade once the coarse control is performed by the AS on the Starshade. The SS measures the centering of the telescope within the shadow created by the Starshade. The Beacon on the telescope is aligned with the telescope boresight and is used by the Starshade for locating the telescope. Starshade is designed to produce adequate stellar suppression out to ~1µm which is well beyond that (>1.5µm), stellar suppression degrades sharply. At some point the Spot of Arago returns also, forming a strong peak exactly in the shadow's center. Measuring that spot profile is the basis for the Shadow Sensor concept.

Cost

The cost numbers have been removed for posting to the web site. NASA HQ SMD was delivered the cost numbers with the final report.

1 IDL Summary

IDL Results

- IDL provided mass, power and overall configuration concept for SS and Beacons. Figures 12 and 13 show the mass of the hardware associated with the astrometric and photometric sensors on both the starshade and science telescope spacecraft.

Starshade Spacecraft	Mass CBE (Kg)
Astrometric Sensor (AS)	113.3
JMAPS Telescope Assembly	38.0
JMAPS Electronics Box (2)	38.0
2-Axis Gimbal Assembly	11.1
AS Assembly Electronic Box	7.1
Laser Beacon (780 nm)	0.3
Thermal Subsystem	10.8
AS Misc items	8.0
Total with 5% Misc Hardware	113.3

Figure 12: Starshade Spacecraft (TAC) Mass

Science Telescope Spacecraft (STS)	Mass CBE (Kg)
Shadow Sensor Assembly	1.0
Shadow Sensor Electronic Box	6.3
Laser Beacon (780nm) (2)	0.6
Harness	3.0
Thermal Subsystem	5.5
TOTAL with 5% Misc Hardware	16.4

Figure 13: STS (TAC) Mass

1 IDL Summary

- IDL developed the scanning gimbal overall design concept and performance assessment for the starshade spacecraft and JMAPS. A notional instrument mechanical model completed and the model can be seen through the Principle Investigator. The initial thermal assessment and notional design was performed with radiators, blankets, control, etc. was provided to the customer team.

- The starshade spacecraft electrical concept for the payloads was provided with mass/power/data handling/FSW. The resulting notional design was provided to the customer team. Instrument redundancy for all electrical performed to present a robust design concept. AS and SS sensors fully redundant without need for failure prone mechanisms. Two, two-way Beacon sources implemented.

- A laser assessment was performed and overall concept achieved.

Recommendations

Based on the results of the design activity, the IDL provided the following recommendations:

- Additional thermal analyses are needed to assess alternate attitudes needed for instrument safety.
- Electrical accommodation for Shadow Sensor can be combined with other SI electronics for packaging efficiency and cost savings, or could utilize S/C power or processor capability.
- Mechanical models need to mature in conjunction with S/C bus integration. The mechanical model did not include a thermal shield (heat shield) sized in accordance with radiometric analyses. Further analyses to size the heat shield appropriately will need to be performed and that shield factored into the layout of the Shadow Sensor optical bench and enclosure.
- Secondary Science Objectives need to be integrated fully into science plan and engineering design so that ALL science is primary.
  - Consider the possibility of adding science instruments to the S^3 so prime science could be conducted during S^3 translation, or in the event of STS failure.
  - Seek out opportunities to increase primary science objectives to a utilization above 80%
  - Incorporate engineering design that allows S^3 attitude flexibility.