Imaging Planets About Other Stars with UMBRAS II

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ABSTRACT

Large space-based telescopes have specific design requirements which offer challenges to the instrument designer. The optical design and detector fabrication are frozen years before the launch date. The Umbral Mission Blocking Radiating Astronomical Sources (UMBRAS) space mission design consists of a Solar-Powered Ion-Driven Eclipsing Rover (SPIDER) and possibly one or two metrology platforms. The ultimate goal of UMBRAS is to provide pseudo-coronagraphic capability for direct imaging of extrasolar Jovians and other brighter, distant substellar companions.

In this paper we discuss operational considerations for the free-flying occulter. Operations consist of maneuvering the SPIDER between targets, alignment with the space-based telescope line of sight to the target, and stationkeeping. Target-to-target maneuvers need to be optimized to conserve propellant. A reasonable balance needs to be determined between target observation rate and the number of targets that are observable during mission lifetime. Velocity matching of the SPIDER with the telescope is essential to mission performance. An appropriate combination of solar electric and cold-gas thrusters provides the ability to match velocities using positional information derived from communication and ranging between telescope, occulter and any metrology stations.

Desirable features of using an external coronagraphic vehicle include the ability to obtain coronagraphic data with any instrument on the telescope – imaging, spectroscopic, or interferometric.

Keywords: UMBRAS, free-flying occulter, coronagraph, extrasolar planets

1. INTRODUCTION

The Umbral Mission Blocking Radiating Astronomical Sources (UMBRAS) space mission is a free-flying occulter design consisting of a *Solar-Powered Ion-Driven Eclipsing Rover* (SPIDER), and possibly one or more metrology platforms, flying in formation with a large space telescope as depicted in Figure 1 (metrology platform not shown).[1] The occulting screen will fly in front of the telescope at large distances to block the light of bright sources from

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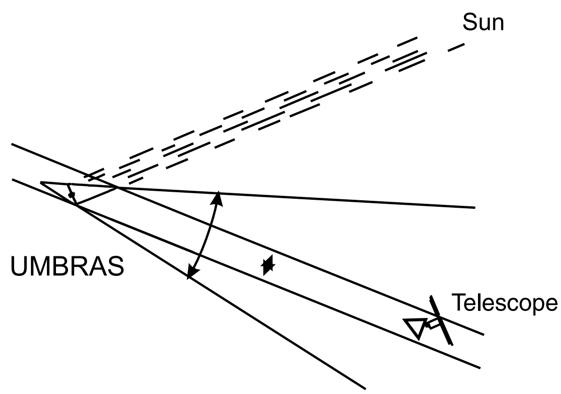

Figure 1. UMBRAS spacecraft flying in formation with a space telescope.

entering the telescope aperture, enabling the imaging of nearby faint sources. Candidate targets include some of the Doppler-detected giant extrasolar planets about solar-like stars.

The UMBRAS space mission requires mission operations and spacecraft management. Depending upon the size of the mission and its goals, the mission operations can be divided into six main phases: launch, deployment, transfer to station, target-to-target transit, target acquisition, and stationkeeping. The launch, deployment, initial transfer from Earth to station, and the initial rendezvous of the UMBRAS spacecraft with the telescope are separate, one-time operational phases. The UMBRAS design for an occulter spacecraft is scalable from large to small missions. We define an "N-Class" (NGST-Class) occulting vehicle as a craft of sufficient acceleration, propellant capacity, and screen size to operate with a 5-10 meter space telescope for up to 6 years. A smaller "D-Class" (Discovery Mission) vehicle can be built to operate with a smaller space telescope (1-2 m aperture) or with a shorter mission lifetime ($\sim$2 years). An "E-Class" (Explorer Mission) is a scaled-down vehicle, without redundant systems or with a reduced target observation rate, that would operate with a 1 m telescope for about 1 year. Table 1 presents operational parameters for the three classes of occulter missions. The occulter's low acceleration necessitates operation at Earth-Sun L2 or solar orbit.

Table 1. Basic mission parameters for occulter missions spanning the range of possible missions for which UMBRAS design concepts are considered.

	E-Class	D-Class	N-Class
Telescope Aperture	1 metre	1-2 metre	5-10 metre
Mission Duration	$\sim$1 year	$\sim$2 years	$\sim$6 years

Coronagraphic observations using a free-flying occulter can be a subset of a space telescope mission. Guidance during stationkeeping can be performed with the aid of imaging by the space telescope and onboard image processing. We define stationkeeping as the process of maintaining the SPIDER on the target-telescope line of sight (TTLOS) vector. After rendezvous, the space telescope and the occulter vehicle operate together through a communications link. Knowledge of occulter attitude, translational capability, range information, and occulter drift rate will determine the guidance requirements for stationkeeping. In this paper we address the operation of an N-Class mission with the occulter at a distance of $\sim$15,000 km from the telescope.

2. LAUNCH, TRANSIT, AND RENDEZVOUS

The SPIDER spacecraft could be delivered to orbit, and possibly to station depending on the size of the SPIDER, from a single launch vehicle, either from an expendable rocket or the Space Shuttle. After the high acceleration phases of launch and deployment, the solar arrays will unfold from their anchor points on the spacecraft bus. When

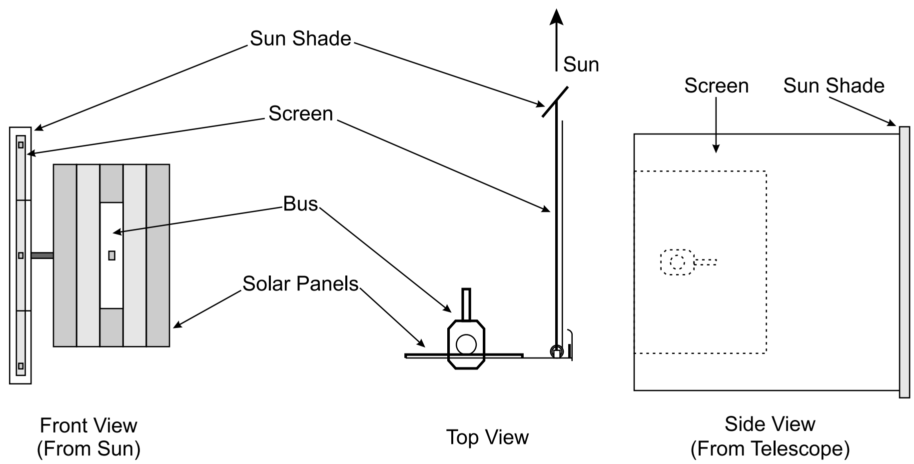

Figure 2. SPIDER overview. The four main structures are the occulting Screen, the Sun Shade, the spacecraft Bus, and the Solar Panels. Propulsion unit not shown. Top view is referenced from the pole of the plane containing Sun, telescope, and occulter.

deployed, the occulter will act as an opaque apodizing screen[2] blocking and redistributing the stellar energy over the telescope aperture. Figure 2 depicts an older design for the SPIDER spacecraft.[1]

2.1. Launch Options

The E-Class occulter can possibly be packaged for launch with a small space telescope on an Atlas IIAS. The N-Class SPIDER design can be folded to fit into a Titan IV fairing or the Space Shuttle payload bay for launch. When configured for launch, the SPIDER's solar panels are folded against the bus along with the propulsion booms, screen platform, and furled occulting screen. Figure 3 shows a cross-sectional view of an N-Class SPIDER sitting within the Titan IV fairing and shuttle payload bay restrictions. A Titan IV launch could deliver an N-Class occulter directly to an L2 orbit.

An N-Class SPIDER would be too heavy to place into a transfer orbit directly to L2 or an Earth-Moon escape trajectory using the shuttle and a single, small, perigee-kick-motor-class (PKM) solid booster. A novel approach for a 10-tonne SPIDER Space Shuttle launch would be to configure it with four PAM D-II class PKM boosters. Stacked pairs are mounted on each end of the SPIDER long axis. After initial deployment, each PKM booster would be fired and staged sequentially. The SPIDER would slew 180^o before a PKM booster on the opposite side ignites. The remaining kilometre per second of velocity needed for escape from the resulting highly elliptical orbit could be gained through prolonged acceleration with the electrostatic thrusters.

2.2. Xenon-ion Electrostatic Thrusters

Xenon-ion electrostatic thrusters provide acceptable thrust for propulsion and attitude control. The N-Class SPIDER design incorporates four to six spherical, 1.2-m diameter, high pressure ($\sim$1500 psi) xenon propellant tanks. NASA-Hughes' NSTAR electrostatic thrusters, chosen as a baseline engine, consume 2.3 kW of power and deliver up to 92 mN of thrust. Two important measures of thruster performance and mission constraints are total impulse delivered before failure and thruster lifetime. An N-Class mission will use 4-6 of these thrusters at a time.

During target-to-target transit, practical limits must be set on thrust levels to minimize propellant consumption. Increased propellant consumption rate decreases mission lifetime, while lower thrust levels result in an operational penalty of longer target-to-target cycling time. Increasing the amount of onboard propellant at launch does not necessarily result in longer lifetime as the additional mass lowers acceleration which lowers the operating range and target visitation rate.

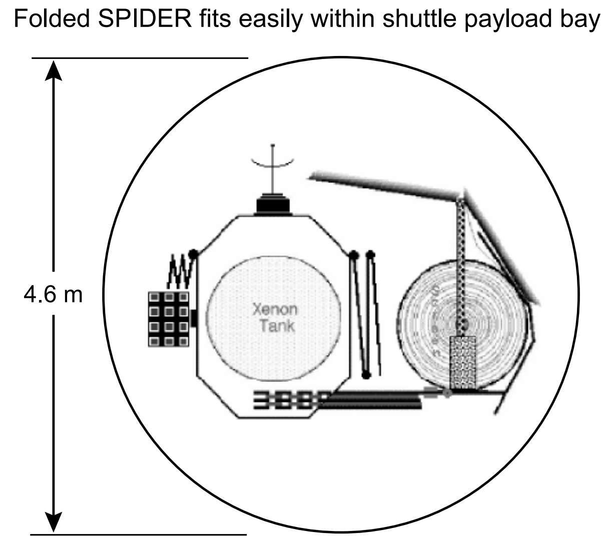

Figure 3. UMBRAS fits within existing payload size limits. An N-Class SPIDER in cross-section fits comfortably within the shuttle or the Titan IV payload restrictions.

2.3. Rendezvous & Deployment

In order to properly position the SPIDER with respect to the telescope, relative position and velocity measurements between the telescope and occulter are necessary. Once the SPIDER has arrived on station, maneuvers are performed using a variety of relative position and ranging techniques between spacecraft to locate the SPIDER relative to the telescope. Quite possibly, sunlight scattered from the occulter will allow locating the SPIDER by imaging with the telescope or optical navigation camera. The occulting screen will be unfurled from its cannister after the last high-thrust maneuver which may or may not be when the SPIDER arrives on station. Depending on how quickly the SPIDER is required to arrive on station, the last high-thrust maneuver may be timed well in advance of the L2 regime.

3. TARGET ACQUISITION & STATIONKEEPING

The primary requirements of the UMBRAS mission are to achieve formation flying of the SPIDER with the space telescope and to maintain the occulter on the target-telescope line of sight (TTLOS) vector. Target acquisition requires the telescope to have onboard image processing capabilities in order to independently identify and locate the target and the SPIDER within the field of view (FOV) and to store the images and locations for later use. In addition, a command link must be established between the telescope and the SPIDER. Once the SPIDER is within the imaging instrument FOV, stationkeeping thrust sequences are initiated as a result of the science imaging requirements which are specified for each observation. The automated tasks are controlled by the SPIDER's attitude and translational control system (ATCS). This target acquisition and stationkeeping scenario is based in part on experience of the authors with target acquisition and slew commanding capabilities of the Hubble Space Telescope (HST) science instrumentation, current and past.[3]

The target acquisition and stationkeeping process starts with arrival of the SPIDER within the FOV of an imaging instrument onboard the telescope and ends only after the final exposure is completed. This process will involve several steps and possible iteration until the desired positional accuracy is attained. The steps, or phases, include locating the target within the instrument FOV, locating the SPIDER within the instrument FOV, sending commands to the SPIDER to move to a position on the TTLOS vector (coarse alignment), velocity matching (fine alignment), target acquisition (small maneuvers to position SPIDER accurately on the TTLOS vector), and stationkeeping (maintenance of alignment). We assume here that Fixed Head Star Trackers (FHSTs) or possibly something similar to the Fine Guidance Sensors (FGS) onboard HST are used to maintain telescope guiding.

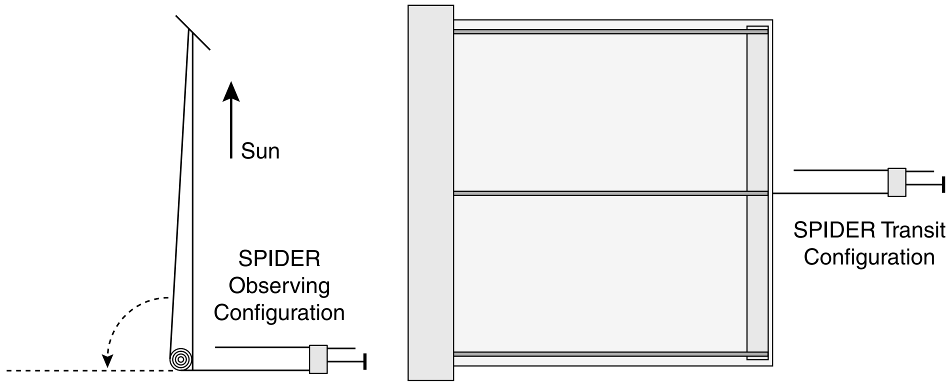

Figure 4. SPIDER configurations. The SPIDER is aligned with the Sun and the telescope in the observing configuration (left). In the transiting configuration (right), the screen is articulated to provide a more symmetric configuration to simplify control during movement between targets.

3.1. Coarse Alignment

The acquisition strategy requires that a pair of exposures be obtained to identify the target (star) and the field stars in advance of the SPIDER arrival. A pair of exposures is needed to remove cosmic ray hits. The resulting processed image (reference image) is stored for later use. Centroiding software determines the positions of the target and surrounding field stars in the image. This information will be used during "Fine Alignment and Stationkeeping."

At a large distance from the telescope, the occulting screen will be a spot (diameter $\sim 0.3''$ or smaller depending upon occulter size and operational range). The screen should be bright in its transit configuration due to reflected light since it does not yet have a special orientation or configuration to make it dark. Imaging of the field should be sufficient to locate the SPIDER. When the occulter is close enough to the TTLOS, it articulates from the transit configuration to the observing configuration (see Figure 4).

3.2. When The Screen Becomes Dark

When the SPIDER is in the observing configuration, properly aligned with the Sun and the telescope, the occulting screen is dark because no sunlight falls upon the side of the occulting screen facing the telescope. Navigation beacon lights will be switched on during the target acquisition phases and switched off during exposures. If the telescope observations are in the near-IR, then the beacon lights may need to be on booms that can be retracted behind the screen.

When the SPIDER arrives in the FOV of the imaging instrument, the beacon is turned on, and a pair of exposures (coarse acquisition image) of the field is obtained to locate the occulting screen. The beacon can be located by subtracting the reference image from the coarse acquisition image thus removing features common to both. The difference image is then scanned to locate the beacon with respect to the target star. An offset distance and angle on the sky are determined, and this information is sent to the SPIDER along with the command to translate to the desired position. The software onboard the SPIDER calculates the required thruster firing sequence and timing to move to the desired location. Once the maneuver is completed, the SPIDER sends a confirming command back to the telescope, at which point the beacon is turned on and a repeat of the relative position determination is performed. If the beacon is found within a specified acquisition box, the fine alignment sequence is initiated. If not, then a repeat of the maneuver is performed based on the new location of the beacon.

3.3. Fine Alignment & Stationkeeping

Once the SPIDER is positioned adequately along the TTLOS vector, and within the acquisition box, a pair of confirming exposures (fine alignment image) is taken. The star field surrounding the SPIDER and the position of the SPIDER are mapped. The position of the SPIDER relative to the map is compared to the saved position of the target. A series of translations are performed to adjust the occulter position relative to the target position. The

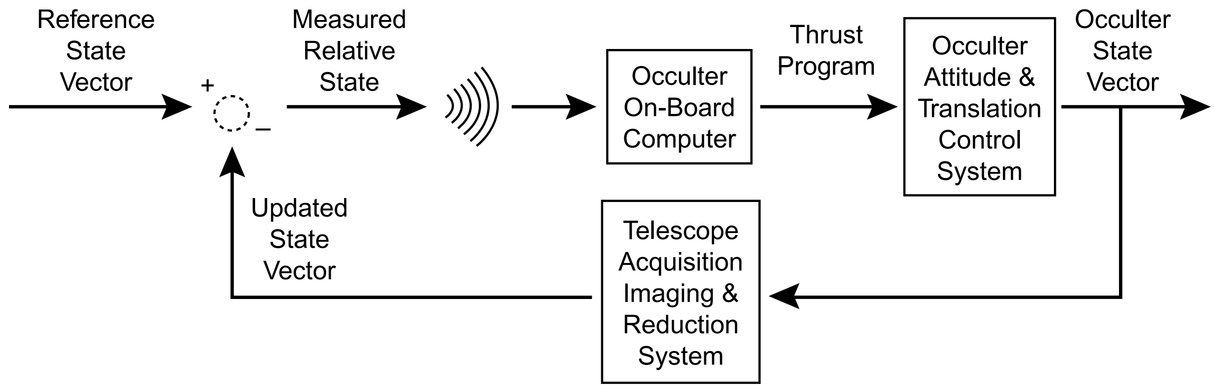

Figure 5. An elementary control flow diagram depicting the elements of the telescope-occulter-target acquisition logic.[3]

position of the SPIDER relative to the field stars is periodically checked between science exposures. The beacon is turned on and a pair of exposures are obtained. If necessary, the occulter is moved. Velocity matching is essential to mission performance. Stationkeeping may require ATCS thrusting during science exposures to maintain the necessary alignment if waiting for an exposure to complete is impractical, or more likely between science exposures to maintain alignment on the TTLOS.

Fine alignment and stationkeeping of the SPIDER on the TTLOS vector could be accomplished with cold-gas or xenon-ion thrusters. Cold-gas thrusters could be used if the luminosity of the xenon plasma cloud contaminates exposures. Xenon-ion thrusters could be used if propellant consumption is a lifetime issue.

The sequence of steps described above can be represented by a linear feedback and control system. The computed position and relative velocity (drift) of the SPIDER with respect to the telescope are sent to the SPIDER. These parameters are the primary feedback signal and form an updated state vector (USV). The USV is differenced with the occultation reference state vector (RSV), which is the ideal position for observation, to form the error signal which is transformed into the desired maneuver commands. Figure 5 presents a control block diagram depicting the target acquisition logic.[3]

3.4. Departure Maneuvers & Transit Between Targets

At the end of the observation phase, the occulter is articulated back to the transit configuration. The SPIDER is oriented and commanded to accelerate to the next station.

Once an occultation observation is complete, the occulting platform (SPIDER) then moves under low acceleration to rendezvous at a predetermined point in space for its next planned observation. If the transit time is long enough, which in general it will be, the telescope may slew to perform many other observations while awaiting the SPIDER's arrival on station. Approximately one half of the total mass of the SPIDER spacecraft should be propellant (xenon gas) to achieve a 6 year mission assuming continuous maximum acceleration between targets.

4. THE UMBRAS OBSERVING PROGRAM

The lifetime of the UMBRAS space mission depends upon the amount of propellant carried, thrust level, the distance between the telescope and occulter, the number of targets, and the rate of supported UMBRAS observations. For 100 unique targets scattered about the sky, the average angle between targets is $\sim 23°$. At a separation distance of 15,000 km between the telescope and occulter, the average SPIDER transit distance between neighboring targets is $\sim$3,600 km, resulting in an average transit time between targets of $\sim$5 days. This assumes an average low acceleration of 0.8×10^{-4} m s^{-2} (xenon-ion propulsion system) and accelerating half the distance to the new target location followed by deceleration to a stop. Assuming one visit per target, an N-Class occulter would only stop at 35 different targets per year. However, it is likely a target will be observed more than once over the lifetime of the mission. If every target is visited twice, then nearly 100 individual targets will be observed over the lifetime of the mission given the constraints stated above.[4]

4.1. Detection Possibilities

The actual projected area of the occulting screen in the field of view will depend on the viewing angle between the Sun, telescope and occulter. The screen must be oriented to present the "Sun Shade" toward the Sun with the Sun lying in the plane of the screen (see Figure 1). In some cases, this requirement causes the screen to be tilted rather than face-on to the telescope. For example, a 16×24 m screen at a distance of 15,000 km from a telescope would subtend a solid angle of $0.22'' \times 0.33''$ on the sky. For a face-on presentation, the screen edges would be between $0.11''$ and $0.17''$ from the star. The regions near the screen edges would be affected by the diffraction pattern, but even there the light from the primary star would be suppressed by a factor of 5 (nearly 2 magnitudes) in the bright fringes, and by a much larger factor in the dark fringes. The regions farther from the screen edge would be less affected by diffraction. In general, the screen will not be viewed face-on due to orientation constraints.

In Spitzer's discussion, an ideal location for detection of a planet is at a distance that is twice the angular separation from the occulted star to the edge of the occulting screen.[5] At this location for the example above, Spitzer's simplified model indicates the suppression of light from the occulted star to be about 7.5 magnitudes at an angular distance of $\sim 0.3''$ from the star. This is sufficient magnitude gain to detect a Jupiter-like planet in a 5 AU orbit about a star at 5 parsecs (an angular separation of $1.0''$). For comparison, the HST NICMOS coronagraphic hole has a useful radius of $0.4''$ and provides a direct detection gain of 5-6 stellar magnitudes.[6]

What does this buy us in terms of detections? Table 2 presents estimated visual magnitudes and maximum angular separations for planets in our Solar System if they were orbiting other stars. For the nearby stars α Cen A and τ Ceti, the angular separations are large and the planets would appear at relatively large distances from the edges of the occulter. Jupiter and Saturn would be fairly easy to detect, although Uranus is quite faint and would be very difficult. For the more distant stars 55 ρ^1 Cnc and β Pictoris, the inner planets would be behind the occulter or at its edge, and the outer planets would be close enough to be affected by the diffraction pattern. Jupiter and Saturn might be detectable, although Saturn would be a stretch at the fainter, though closer, 55 ρ^1 Cnc. One way to enhance detection possibilities during observations is to translate the SPIDER about the TTLOS and thereby move the occultation pattern to more favorable positions to detect planets.

Table 2. Estimated visual magnitudes/projected angular separations for planets in the Solar System as seen orbiting other stars from Earth. Planets about other stars are best imaged when near quadrature.

Planet	Sun		α Cen A (1.3 pc)		τ Ceti (3.7 pc)		55 ρ^1 Cnc (12.5 pc)		β Pic (18.2 pc)	
	mv	Distance								
Venus	-4.7	0.72 AU	23.1	$0.55''$	26.6	$0.19''$	29.1	$0.06''$	26.9	$0.04''$
Mars	-1.2	1.52	27.4	1.17	31.0	0.41	33.1	0.12	31.3	0.08
Jupiter	-2.9	5.20	21.0	4.00	24.7	1.41	27.6	0.42	25.0	0.29
Saturn	0.0	9.54	22.5	7.34	26.1	2.58	29.0	0.77	26.4	0.52
Uranus	5.7	19.18	26.6	14.75	30.1	5.18	32.7	1.53	30.4	1.05

4.2. Types of Targets

In recent years, Doppler observations of nearby solar-like stars have been used to detect at least 42 Jupiter-sized planets.[7–12] Doppler detection favors close, massive planets. UMBRAS has the potential to detect planets that are more distant from their parent stars than those detectable with current Doppler techniques. UMBRAS detection capability increases with star-planet separation while Doppler detections decrease. In addition, an N-Class UMBRAS mission should be able to detect a few of the currently 42 Doppler-detected planets which are at large separations from their parent star.

The UMBRAS space mission could be used to observe other low brightness targets which are lost in the glare of a much brighter object. These include low-mass stellar and brown dwarf companions to nearby stars, the surrounding nebulosity in planetary nebulae, astrophysical jets, the surrounding regions of the centers of galaxies, and the host galaxies of quasars.

In addition, several unique observing programs could be achieved using the SPIDER as a knife edge occulter. High-time-resolution exposures during scanning of the SPIDER across close binary stars could be used to measure small separations, while scanning across Kuiper Belt objects and asteroids could determine the sizes of these objects. In addition, scanning could also be used to map the surfaces of stellar photospheres.

5. SUMMARY

Studying terrestrial and giant planets about stars is one of the primary goals of NASA's Origins Program. The UMBRAS space mission could extend the field of planetary studies by providing numerous extrasolar planet detections and could advance our understanding about how planetary systems form by imaging circumstellar disks closer to the primary star than what has been achieved so far. Direct detection (imaging) of extrasolar planets may even be augmented with spectroscopic observations using UMBRAS.

The UMBRAS mission concept as described above is complex, requiring mission operations and long-range planning. During transit between targets, the SPIDER needs to be monitored for health and safety, fuel usage, acceleration level, and positioning. Rendezvous requires locating the SPIDER relative to the telescope, distance, orientation, and velocity matching. Target acquisition requires image processing on the telescope, data storage, centroiding software, and a communication link between the SPIDER and the telescope. Stationkeeping may require periodic imaging of the field to locate the occulter relative to the field stars and for adjusting its position. Since the occulter is not built into the telescope as an add-on instrument, any target in the telescope FOV can be occulted. The occulted target can be anywhere in the image plane, unlike classical coronagraphs. All science instruments onboard the telescope can be used with UMBRAS, imaging arrays and spectrographs. The study of extrasolar planet properties, photometrically and spectroscopically, could be achieved.

An N-Class UMBRAS mission has the potential to obtain revolutionary observations of extrasolar planets.

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