Imaging Planets About Other Stars with UMBRAS: Target Acquisition and Station Keeping

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ABSTRACT

We present a novel coronagraphic imaging technique and design for space-based telescopes. The Umbral Mission Blocking Radiating Astronomical Sources (UMBRAS) is a space mission design consisting of a free flying occulter, the Solar Powered Ion Driven Eclipsing Rover (SPIDER), and possibly one or two metrology platforms. The UMBRAS spacecraft operate in conjunction with a space-based telescope. The size of the occulting SPIDER is dictated by the size of the telescope with which it will work. The goal of UMBRAS is to provide "paleolithic" (i.e., non-focal plane) coronagraphic capability to enable direct imaging of extrasolar Jovian planets and other bright substellar companions such as brown dwarfs.

We discuss two aspects of the operation of a free flying occulter: acquisition of targets and station keeping. Target acquisition is modeled after the onboard schemes used by Hubble Space Telescope (HST) science instruments. For UMBRAS, the onboard commanding sequences would include imaging the field using instruments on the telescope, locating the target and the occulter in the field, and accurately positioning the occulter over the target. Station keeping consists of actively maintaining the occulter position in the telescope line of sight to the target.

Velocity matching of the occulter with the space-based telescope is essential to mission performance. An appropriate combination of solar electric and cold gas thrusters provide the ability to match velocities using position information derived from communication and from ranging data between telescope, occulter and any metrology stations.

The accuracy requirements for target acquisition and station keeping depend upon the science requirements, the occultation geometry, and the sensitivity of the science to changes in occultation geometry during an exposure sequence. Observing modes other than the ideal centered occultation of a target will be discussed.

Keywords: UMBRAS, free flying occulter, coronagraphy, extrasolar planets

1. INTRODUCTION

Coronagraphic occulters are used to block light from a bright source to enable the study of faint objects at small angular separation. The solar corona and prominences are familiar targets of coronagraphic studies. Other classes of astronomical objects which benefit from coronagraphic study include the host galaxies of quasars; the nuclear regions of galaxies, especially galaxies with point-like cores; dust disks around relatively nearby stars; low-mass, sub-luminous companions to nearby stars (i.e. brown dwarf stars and giant planets); orbit orientation in close binary

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stars; high-contrast ring studies around solar system planets. The study of stellar dust disks and extrasolar planets was recently adopted by NASA in its Origins theme,[1] which establishes the investigation of the birth and early evolution of stars and planets as one of the primary goals of the US space program in the coming decades.

Stellar disks are the birth places of planets, and have been the object of coronagraphic study since the visible light detection of the dust disk around β Pictoris[2] in the early 1980's. The β Pictoris disk was first identified from the star's excess emission in the infrared longward of 60 μm. Other stars with similar infrared excess have been searched in visible and near-IR wavelengths for evidence of disks, but the β Pictoris disk was the only one detected. The HST NICMOS coronagraph utilizes a coronagraphic hole with a useful radius of $0\farcs4$. Recent NICMOS observations have increased to 3 the number of dust disks directly detected around stars with infrared excess.[3–5] The discovery of the first confirmed extrasolar planet around a normal star in 1995[6] has been followed by an explosion of detections. These planets have been indirectly detected by using Doppler techniques to infer the presence of a planet from the reflex motion of the star as it orbits the common center of gravity. At this writing, 36 extrasolar planet detections are claimed for 33 solar-like stars.[7,8] None of these new planets can be directly detected using existing instruments, except perhaps the possible outer of the two planets around the star 55 ρ^1 Cnc,[9] which might be just barely accessible with the NICMOS cornographic aperture.

Classical coronagraphs include an occulting disc at the focal plane in the optical path of the instrument. These focal plane occulters impose structure on the point spread function that can be reduced only by highly accurate positioning of field stops and apodizing masks. Placing the occulter outside the telescope eliminates these problems. Non-focal plane occulters provide several advantages over focal plane occulters: (1) field stops and apodizing masks are not required; (2) the occulter can be used with any science instrument in the telescope; (3) light from the bright source is excluded before it ever reaches the telescope, significantly decreasing internally scattered light. Except in the naturally occurring case of occultation of an interesting object by an asteroid or the moon, a non-focal plane coronagraph external to the telescope is not practical for ground-based telescopes.

In 1962, Lyman Spitzer[10] expounded the idea of using a man-made occulting object to search for faint companions to stars. Spitzer showed analytically that such an occulter significantly increases the chance of detecting extrasolar planets. About a decade later, Gordon Woodcock confirmed Spitzer's analysis and outlined a design for such an occulter.[11,12] In the mid-1990s, Craig Copi and Glenn Starkman explored the use of space-based occulters with both space-based and ground-based telescopes.[13] In the late 1990s, in response to the call for innovative science concepts for the Next Generation Space Telescope (NGST), we independently derived a design for a free-flying occulter to be used with NGST, which we dubbed UMBRAS.[14,15] The previously cited studies rely on new, untested technologies, while the proposed UMBRAS design uses only existing technologies, albeit in new and interesting ways.

2. WHAT IS UMBRAS?

An *Umbral Mission Blocking Radiating Astronomical Sources* (UMBRAS) is a multi-craft mission, consisting of a space telescope, possibly one or two metrology platforms, and a Solar Powered Ion Driven Eclipse Rover (SPIDER), which is the free-flying spacecraft carrying an occulting screen. The purpose of the UMBRAS is to utilize a free-flying coronagraphic occulter with a space-based telescope. The papers in the UMBRAS series present conceptual design studies of various aspects of such a mission. The intent of these studies is to explore the scientific possibilities of a free-flying occulter, and to elucidate and propose solutions for the technical problems of spacecraft and mission design. All UMBRAS design studies have two requirements: the design must incorporate only existing, off-the-shelf technologies and the spacecraft must be compatible with current launch vehicle weight and volume limits. Studies to date indicate that UMBRAS could be built today.

The UMBRAS design is scalable over a large range of telescope sizes and mission goals. An overview of our current thinking on mission design, occulter spacecraft design, optical considerations, and science expectations for an UMBRAS operating with an 8-meter telescope observing in the infrared (NGST) was presented at the 1999 SPIE meeting in Denver.[14] Our current thinking on mission and spacecraft design are summarized in the following section.

2.1. UMBRAS Design Overview

The SPIDER and telescope need to be placed in solar orbit or near the Sun-Earth L-2 point, to minimize the differential gravitational forces between the spacecraft (see Section 4). The observing configuration for the SPIDER occulter and the telescope is illustrated in Fig. 1.

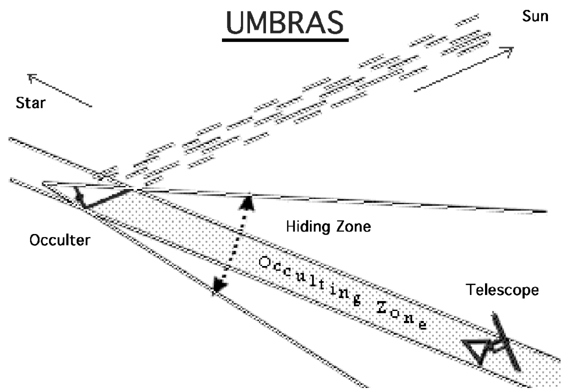

Figure 1. Relative placement and configuration of UMBRAS mission elements. The screen occults light from a star and hides the spacecraft bus from telescope view. The bus is oriented with the solar panels toward the sun. The screen is oriented with its normal perpendicular to the direction to the sun, to help keep the side toward the telescope dark. The screen is shaded to minimize light scattered toward the telescope. The bus-screen joint may be articulated to change the available sun angles of the hiding zone.

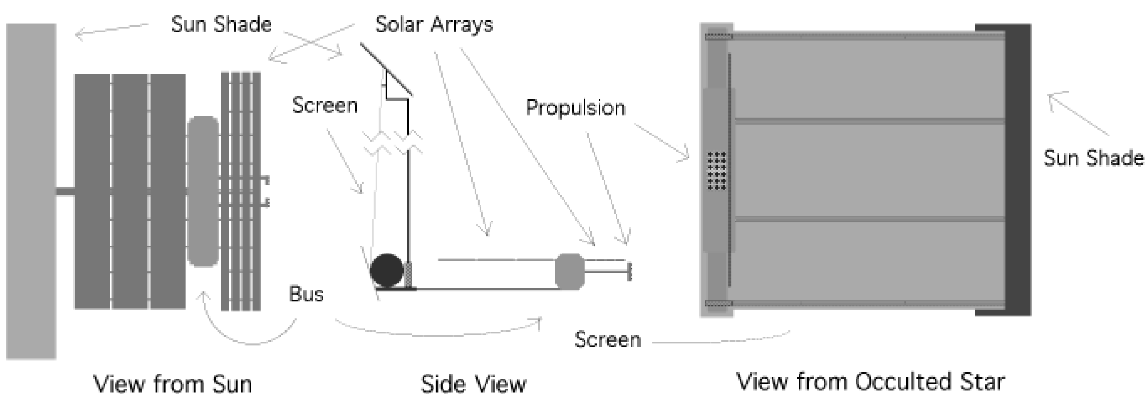

Figure 2. Three plan views of the SPIDER occulter showing the major components of the craft. The spacecraft bus, propulsion units, solar array panels, the occulting screen, screen boom, and the screen sun shade are all marked. The screen is initially deployed by unrolling it from the cassette and held in place by rigid masts. The joint between the screen masts and the boom from the bus is hinged to allow the screen-solar panel angle to be changed. In these views, the screen is articulated into the normal position for occultation, about 90° from the bus and solar panels. The shade shields the side of the screen facing the telescope from the sun.

The nominal physical separation between the occulting screen and the telescope is driven by the desired quality of the individual science exposures and the overall operational capacity of the mission. At very large separation, *spot mode*, the occulting screen is a barely resolved spot that blocks the smallest possible area around the star of interest. At small separations, *knife edge mode*, the occulting screen functions as a diffracting edge, a nearly infinite half-plane. The extremes of the operating range place different constraints on mission operations, especially target acquisition and station keeping.

The SPIDER serves to move the occulting screen from target to target and to keep the screen in position along the telescope-target line of sight (TTLOS) during observations. The main structural components of the SPIDER are shown in Fig. 2. The SPIDER will be powered by solar electric propulsion (SEP) thrusters using xenon propellant for long transits between targets. Cold gas thrusters and reaction wheels are used for station keeping and attitude control. Guidance, navigation and orientation in space will be controlled by a combination of gyros, inertial guidance devices, and fixed head star trackers (FHST).

The screen will be mounted on a hinged boom so that the angle of the screen to the spacecraft bus can be changed. This allows the occulter to accomodate a range of observing positions while maintaining a good sun angle on the solar panels and keeping the screen shade positioned to prevent sunlight from illuminating the telescope-ward side of the occulting screen. The screen shape is square. A square occulter creates a more interesting diffraction pattern than a disc, but it is easy to store for launch, easy to unfurl, and easy to support by a simple boom and mast arrangement.

The SPIDER design incorporates only off-the-shelf technology, although forecast improvements in certain technologies could improve weight or power constraints. The design has been studied in some detail for use with an 8-meter telescope observing in the infrared[14,15] (the N-class mission) and in this paper for a 1-meter telescope observing in the visible (the D-class mission). The largest SPIDER design studied to date, that for the N-class mission, can be fit into the payload bay of the shuttle or into a Titan IV fairing for launch.[14]

The basic operation of the telescope with the SPIDER occulter spacecraft can be broken down into phases: *Transit*, *Target Acquisition*, and *Observation*. When the occultation observation of a given target is complete, the *transit* phase begins. The SPIDER moves under low acceleration to rendezvous at a predetermined point in space for the observation of the next planned occultation target. While the SPIDER is in transit, the telescope can be used to make other science observations which do not require the external occulter. When the SPIDER arrives in the vicinity of the TTLOS, the *target acquisition* phase begins. During target acquisition, tracking and navigation information will be used to precisely locate the occulting screen relative to the telescope. The SPIDER will be commanded to move to place itself on the TTLOS so the target will be occulted as required by the science. After the occulting screen is correctly positioned, the *observation* phase begins. The SPIDER enters station keeping mode while the telescope makes the scheduled science observations. When the observation of that target is complete, the cycle begins anew. The purpose of this study is to examine in some detail the mission requirements for target acquisition and station keeping.

2.2. The 1-meter Design Reference Mission

A mission like UMBRAS has never been flown, so it makes sense to build a small version before attempting a large one. The target acquisition and control strategies required are also new, and should be tried at a small scale before we commit to a large mission. The operational differences between spot mode occultation and knife-edge occultation have a large impact on mission lifetime and fuel requirements.[14] The tradeoffs between these two modes need to be studied in a real situation before the design for a larger mission is fixed.

The smallest telescope with which useful coronagraphic science could be done is 0.5 to 1.0 meters in diameter. The smallest external occulting screen useful with a telescope has a linear dimension about 5 times the telescope aperture diameter.[10] We have chosen a 1-meter telescope and a 5-meter screen for the Design Reference Mission (DRM). The target acquisition and station keeping capabilities discussed here will be scaled, when necessary, to this 1-meter DRM.

Design Reference Mission:

Telescope aperture diameter: 1 meter (40 inches)
Science instrument wavelength sensitivity: 5000Å (3000-7000Å)
Resolution: $0.''125$ ($0.''075$-$0.''175$)
Square occulting screen, 5 meters on a side
Solar orbit or sun-earth L2 orbit
Fully capable maneuver, control, and communications

2.3. Science Capabilities of the 1-meter UMBRAS

Excellent science can be done with a 1-meter telescope and a 5-meter external occulting screen. The coronagraphic capability of this system would be a significant improvement over the current and proposed space based coronagraphs: the HST Near Infrared Camera and Multi-Object Spectrometer (NICMOS) coronagraphic hole and the HST Advance Camera for Surveys (ACS) High Resolution Channel (HRC) coronagraphic fingers.

The HST NICMOS coronagraphic hole has a useful radius of $0.''4$ and provides a direct detection gain of 5-6 stellar magnitudes.[16] The NICMOS coronagraph has opened up the study of dust disks around nearby stars[3–5] and has detected at least one previously unknown brown dwarf companion to a nearby star. The NICMOS is not currently functioning, although a new cooling system is planned for installation during the next HST servicing mission, currently scheduled for June 2001.

The 2001 servicing mission will also bring the ACS to HST. The ACS HRC features a coronagraphic mode which occults the uncorrected aberrated HST image. Two focal plane masks are available, the smaller having a radius of $0\farcs9$. The modeled performance of the HRC coronagraph shows a gain of 1-1.6 magnitudes between 2 and 4 arcseconds from the star.[17]

The capabilities of the UMBRAS occulting screen will depend on the occulter-telescope separation. At a separation of 1000 km, the 5-meter occulter screen has a radius of $0\farcs5$. At this separation, the occulter suppresses the light from the occulted star by a factor of 1000 in brightness (about 7.5 stellar magnitudes) (see equations 4 and 5 in Ref. 10). This is not a sufficient magnitude gain to detect a Jupiter-like planet in a 5 AU orbit around a star at 5 parsecs (the canonical detection example). However, this does compare quite favorably with the 5-6 stellar magnitude gain of the NICMOS coronagraph, and it is much better than the ACS coronagraph.

At increased occulter-telescope separations, regions closer to the star can be examined, but the light supression by the occulter decreases. At an occulter-telescope separation of 4000 km, the occulter radius would be about $0\farcs13$. At this distance the square occulting screen is a spot on the sky which, when centered, superscribes the area of the Airy disk of an unobstructed point source. The detection gain is about 2 stellar magnitudes, comparable with the ACS gain at 2-4$''$ from the occulted star, but at a significantly smaller separation angle. The region between $0\farcs4$ from the star and $0\farcs13$ from the star cannot be accessed by any current or planned occulter.

The 1-meter telescope-UMBRAS combination provides a direct detection gain of 7-8 stellar magnitudes at separations greater than $0\farcs4$ arcseconds, about 2 magnitudes better than NICMOS and more than 6 magnitudes better than the ACS HRC coronagraph. The region between $\sim0\farcs13$ separation and $\sim0\farcs4$ separation is the search space available to the 1-meter UMBRAS that is inaccessible to existing or planned space based coronagraphs. The detection gain in this region varies from 7 stellar magnitudes to 2 magnitudes. At least one of the currently known extrasolar planets should be accessible to the 1-meter UMBRAS: the second, outer planet which may exist about 55 ρ^1 Cnc.[7,9] Three others are within the angular capabilities of the 1-meter UMBRAS, but are unlikely to be bright enough to detect. Studies of previously inaccessible regions of stellar disks, quasar host galaxies, and the nuclear regions of nearby galaxies would be possible.

3. TARGET ACQUISITION STRATEGY AND CONSTRAINTS

Target acquisition as used here means the accurate positioning of the occulting screen over the intended science target. The proposed strategy utilizes the imaging capabilities of the telescope to locate both the science target and the SPIDER occulting screen. The design is based on our experience with the target acquisition and slew commanding capabilities of the HST science instruments, current and past.

The cameras and computers onboard the telescope will be used to locate the science target and the occulting screen, and to compute the spacecraft motion required to bring the SPIDER to the TTLOS. The motion command will be transmitted from the telescope to the SPIDER, which will compute the correct thrust commands and carry out the motion. The SPIDER's ion thrusters will be used until the required motion is around several 10's of meters, at which point cold-gas thrusters will be employed to make the final position corrections.

The design requires image processing and target location capabilities on the telescope, a command link between the telescope and the SPIDER, and repositioning calculation and control software onboard the SPIDER. The procedure should be automated, *i.e.* controlled in its entirety by software onboard the telescope and the SPIDER, which is initiated by the observing script loaded from the scheduling and commanding system on the ground. The mechanics of the target acquisition impose requirements on the design elements of both the occulter and the telescope.

The target acquisition procedure begins shortly before the end of the slew of the SPIDER from one target to the next. The SPIDER moves to position itself on the line of sight between the telescope and the target at the scheduled time of the science observations. Shortly before the SPIDER arrives in the line-of-sight vicinity of the target, the telescope will acquire the target and take a reference Target Acquisition (TA) image of the field, which is stored onboard. Once the SPIDER has arrived in the vicinity of the TTLOS, a pair of TA images will be made and also stored. This pair of images will be compared by the telescope with the initial TA image to determine the relative apparent positions of the occulter and the target, and with each other to determine the differential velocity of the occulter. The telescope uses the apparent position of the occulter on the sky, the angular velocity of the occulter, and the telescope-occulter distance, as determined from either radio or laser range finding, to compute a slew direction and distance in inertial space. This slew vector is transmitted to the SPIDER, which calculates and executes the thrust maneuvers necessary to make the traverse. Long traverses will be powered using the SEP ion thrusters, and traverses shorter than a few 10's of meters will be made using the station keeping cold gas thrusters.

Target acquisition is completed when the occulter is positioned in the instrument field of view to within the tolerances specified by the science. To search the space between $0.''13$ and $0.''4$ from a star, the edge of the occulter must be positioned accurately in image space to about 10% of the telescope resolution, or about $0.''013$. The telescope imaging system must be able to locate the science target and the occulter screen to that same resolution. This criterion requires that the telescope camera have a high resolution mode with pixel sizes of about $0.''004$, to sufficiently oversample the PSF. The image analysis must include flat fielding, cosmic ray rejection, plate scale calibration, field analysis, object identification, and point source and extended source centroiding algorithms to accurately locate the center of light for the target and the occulter screen navigation lights.

3.1. Control Theory Formulation

The sequence of steps formulated in the previous section can be cast in terms of classical control theory. The simplest representation of the system is by a proportional-derivative (PD) or proportional-integral-derivative (PID) controller. The position and velocity of the occulter as calculated by the telescope's acquisition imaging and reduction system (AIRS) determines the offset and rates used to iteratively bring the occulter closer and closer to the TTLOS and place it in the correct relative position for science observations to be conducted. Because of the finite time between imaging offset determinations, the system inherently forms a discrete-time, digital feedback control system.

Design by both analysis of HST (Hubble Space Telescope) STIS (Space Telescope Imaging Spectrograph) and NICMOS (Near Infrared Camera, Multi-Object Spectrograph) target acquisition strategies and by synthesis of new elements inherent to occulter engineering are needed to create a telescope-occulter-target automated guidance and station keeping (TOTAGS) system. Although the target acquisition strategy can be achieved with human interaction through downlinking the required data to the ground for real-time processing, a faster, better, and cheaper approach is to build an on-board target acquisition system which can perform as an automated functional element during the execution of the target observation sequencing specification.

In order to perform science observations, the required position and velocity of the occulter with respect to the TTLOS is computed during proposal development on the ground far in advance of execution and is referred to as the occultation reference state vector (RSV). This RSV comprises the desired position, uncertainty in position, and allowed velocity residuals which a given observation can tolerate. The reference state vector is used as the reference input in the feedback system and is transformed by the telescope image processing computer (TIPC) into image coordinates on the reference images taken before occulter arrival. The feedback elements of the system are the AIRS, and the reduced images taken of the star field around the target star both with and without the occulter in the field. The primary feedback signal is a position and velocity of the occulter, and uncertainties in each with respect to the TTLOS at a given time — the updated state vector (USV) — computed from differencing the images. This USV is differenced with the RSV (the desired optimal position and velocity of the occulter) to form the error signal which is the position and velocity relative to that desired.

This error signal is then transmitted from the telescope to the occulter's on-board computer. The occulter computer functions as a feed-forward control element by computing a sequence of thruster firings needed to offset the error. After this program (control signal) is executed by the occulter Attitude and Translation Control System (ATCS), new images are taken of the target field by the telescope and the process is iterated until the occulter state vector is within tolerances.

3.2. Imaging Detector Resolution and Field of View

During a traverse, the SPIDER will navigate and steer using inertial guidance and ephemeris information. FHSTs will be needed to control SPIDER's orientation in space, and it is possible that these can also be used to increase navigation accuracy. There will be some navigational error on the part of the SPIDER, which results in missing the TTLOS by some distance. The widest field of view on the telescope must be large enough to ensure the SPIDER is in that field of view. The spatial miss distance can be estimated by assuming the miss distance will be some fraction ξ of the distance traveled during transit. The average distance between targets can be estimated for a large number

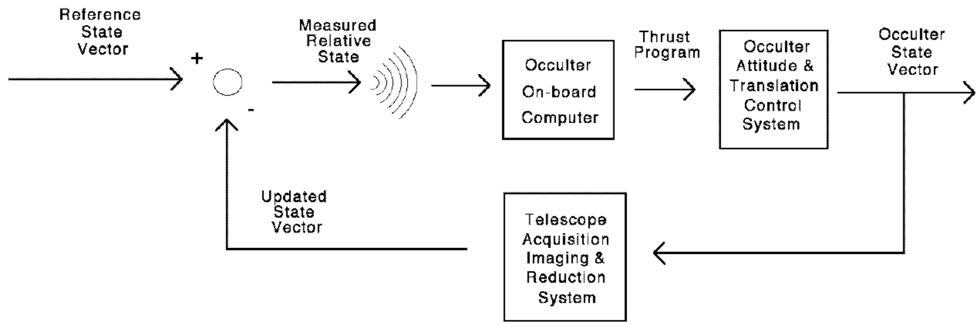

Figure 3. An elementary control flow diagram showing the elements of the telescope-occulter-target system and the steps required to produce target acquisition calculations and drive the occulter to the target.

of targets by assuming that the occulter operates at an average distance from the telescope, and approximating the surface area of that operational sphere as the sum of circular areas around the targets:

$$4\pi r^2 = N_T \pi (q/2)^2 \tag{1}$$

where r is the average occulter-telescope separation, N_T is the total number of targets, and q is the average travel distance between targets. For 100 targets[16] distributed approximately uniformly, the average angular separation q/r is 23°. Table 1 relates the navigational error ξ to the angular miss distance $\xi q/r$:

Table 1. Navigational error *vs.* approximate angular miss distance following the transit from a previous target separated by 23°on the sky.

ξ	30%	10%	5%	2%	1%
$\xi q/r$	7°	2.5°	1°=60′	30′	15′

The high resolution mode for the camera requires pixel resolution of about $0''.004$/pixel. The wide field mode might need to be as large as 7-14°. For a primary camera focal ratio of f/48, a single 1024x1024 CCD chip could have a normal image scale of $0''.05$/pixel and a total field of view of $102''\times102''$, or $1'.7$. The ACS Wide Field Camera[17] will have a total field of $202''\times202''$, or $3'.3$, provided by abutted 2048x4096 CCDs, with an image scale of $0''.049$/pixel.

The instrument field of view for a similar camera on the UMBRAS 1-meter telescope can be made to nearly span the required range by inserting movable mirrors into the optical path, as has been suggested for the proposed Near-Infrared Camera for the NGST.[18] When inserted into the main optical path, the mirrors would deflect the beam to alternate optical paths with different f/ratios. A focal extender to f/600 would provide the necessary high pixel resolution in a subsection of the CCD. A focal reducer to f/5 could widen the field of view to nearly 33′, which is just large enough to encompass a 1% navigation error.

There are many possible alternatives to the wide field requirement. The navigation error could be decreased by active navigation during the transits, perhaps using the Earth-based Global Positioning System (GPS) if the UMBRAS is close enough to Earth. The TA linear field of view could be increased by a factor of 3 to 5 by using a mosaic of several images in an overlapping spiral search pattern. Some means other than imaging by the telescope could be used to measure the miss distance after the primary transit to the TTLOS, such as imaging with a separate wide-field star tracker bore-sighted with the telescope optical axis or integrating a radio interferometer into the system. This is one area where detailed studies are required to determine the costs and benefits of different options.

The narrow field, high resolution requirement, however, is fixed by the requirements for accurate positioning of the occulter prior to making any the science images.

3.3. Occulter Screen Navigation Beacons

The telescope imaging detector must be able to locate the occulting screen in the field of view to a very high degree of accuracy. Navigation beacons will be required to enable the telescope to find the screen in the field of view. The beacon lights will be switched on during the target acquisition phases, and switched off otherwise. Failure modes for each circuit must leave the lights switched off. The beacons must be placed so that at least two independent lights are near any critical location, to provide redundancy. The quadrants of the screen could be distinguished by colored lights (requires extra target acquisition images in distinct filters), or by setting the lights in a pattern unique to each quadrant. Patterns will be useful only when the occulter is not operated in spot mode.

The beacon lights must be bright enough to be easily distinguished, but not so bright that they saturate the detector and compromise the target location algorithms. The brightness constraints need to be met across the expected range of physical separation between the occulter and the telescope. One solution is to set the lights to be about 5th magnitude when the occulter is at extreme spot mode range, and use neutral density filters on the telescope to reduce the magnitude of the navigation lights at closer range.

A set of three lights set at known locations in the occulting screen on the side towards the telescope would provide redundancy and sufficient information to locate the screen in space. The precise orientation of the screen relative to the telescope and on the sky will be handled by the FHSTs on the SPIDER.

4. STATION KEEPING STRATEGY AND CONSTRAINTS

Once the occulting screen is in place, station keeping begins. Station keeping requirements are based on assumptions about the tolerance of science exposures to drift in the occulter position. Drift along the TTLOS changes the apparent size of the screen and position of the screen edge, but the occulter will in general be far enough from the telescope that such changes will be negligible. Drift perpendicular to the TTLOS causes changes in the diffraction pattern at the telescope focal plane, and must be tightly controlled. There are two limits to consider:

1) Absolute drift: During an exposure, the occulter cannot drift more than some fraction of its own dimension perpendicular to the TTLOS. This ensures that the diffraction pattern produced by the occulter does not change significantly during an observation. This requirement is particularly important in *spot* mode, when all edges of the screen contribute equally to the diffraction intensity.

2) Angular drift: During an exposure, the occulter cannot drift in apparent angular position more than some fraction of the telescope diffraction-limited resolution. We assume that angular drift can be tolerated up to 10% of the resolution.

Both drift constraints depend on the size of the UMBRAS mission. The constraints are shown in Table 2 for the 1-meter DRM.

Table 2. Drift tolerance during a single exposure.

Telescope aperture = 1.0 m	Angular drift $<0\overset{\prime\prime}{.}013$
Screen dimension = 5.0 m	Absolute drift <5 cm

Drift is a function of both drift rate, which is controlled by the SPIDER propulsion units, and observation duration. In space, CCD exposure durations are primarily limited by cosmic ray flux. Individual exposures probably will have to be limited to 1000-3000 seconds. Thus the drift in Table 2 represents the maximum acceptable spacecraft motion perpendicular to the TTLOS in 15-50 minutes.

For a given absolute drift, the angular drift decreases linearly with increased separation between the occulter and the telescope. Thus the angular drift constraint will be the more restrictive at smaller operational ranges, and the absolute drift constraint will be the more restrictive at larger ranges. For the DRM, the cross-over point between these two regimes is about 800 km: the angular drift is more restrictive at distances smaller than 800 km, and the absolute drift is more restrictive at distances larger than 800 km.

The drift constraints translate into constraints on the thrust control systems of the SPIDER. We expect that the thrusters will be able to control the spacecraft position to within certain limits, providing an absolute drift rate at

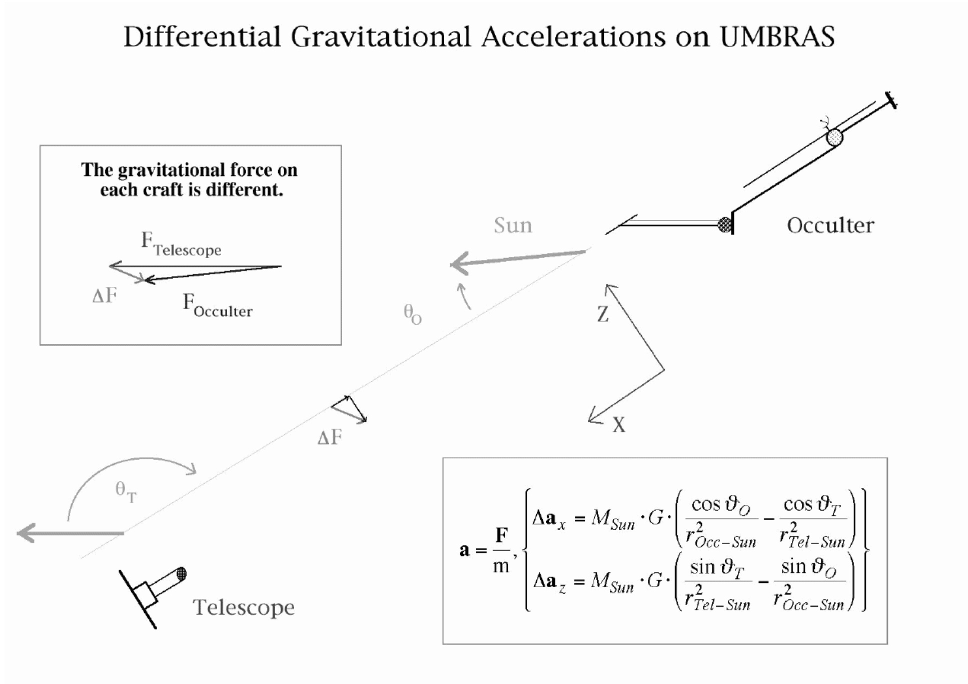

Figure 4. Simplified differential gravitational forces on the occulter and telescope produced by the sun. Similar modeling should be done for each body of significant effect (e.g., Earth, Luna, etc.) depending upon the orbit chosen for the mission. The occulter is shown with the screen articulated to allow operations away from the telescope-occulter-sun quadrature circle.

a given observing configuration. At this point, we expect that cold-gas thrusters will be used to maintain the drift rate. However, analysis of the expected perturbative forces on the spacecraft indicates that small ion thrusters could also do the job.

4.1. Modeled Perturbative Forces

The purpose of station keeping is to accurately control the occulter's position with respect to the TTLOS. The orbital motion of the telescope and any motion of the target will shift the TTLOS in space. The various perturbing forces on the occulter will shift the occulter away from even a stable TTLOS. An accurate model of the relative motion of all three objects must be used to compute the optimal position and velocity for the occulter at the start of a science observation.

For targets outside our solar system, the position of the target in inertial space is essentially fixed on timescales of the science exposures during a typical alignment. If the UMBRAS is being used to observe a target within the solar system, a model of the motion of that body must also be used in determining the occulter's desired state vector.

Two sources of perturbation are discussed here, with consideration to their relative sizes and how they can affect station keeping: differential gravitational forces and solar radiation pressure.

4.1.1. Differential Gravitation

The non-zero separation of occulter and telescope in orbit produces an apparent differential gravitational acceleration which will perturb the position of the occulter during an exposure. The situation is illustrated in Fig.4. The approximate controlling equation is

$$a_{\perp} = 2GM_{\odot} \times \frac{r_{to} sin(\theta) cos(\theta)}{r_{st}^3} \tag{2}$$

where $a_{\perp}$ is the acceleration across the line of sight, G is the gravitational constant, $M_{\odot}$ is the mass of the sun, r_{to} is the telescope-occulter separation, and r_{st} is the sun-telescope distance. The value of $a_{\perp}$ at representative telescope-occulter separations at 1 AU from the sun is shown in Table 3.

Table 3. Maximum differential gravitational acceleration across the TTLOS at 1 AU from the sun.

r_{to} (km)	500	1000	2500	5000
$a_\perp$ (ms^{-2})	2×10^{-8}	4×10^{-8}	1×10^{-7}	2×10^{-7}

Assuming the SPIDER mass is 1 tonne, the station keeping thrust required to counter the differential gravitational acceleration is only 2×10^{-4} N (200 microNewtons) at 5000 km, and correspondingly smaller at closer ranges. This force is small enough to be within the capabilities of small electrostatic propulsion systems (assuming specific impulses $\simeq$2000 seconds). Primary propulsion for the SPIDER is on the order of tens-of-millinewtons when using xenon ion propulsion systems (XIPS), in order to get sufficient speed for target-to-target transits.[15,19] This clearly indicates that the xenon required for station keeping would be a small fraction of the total required propellant. These fuel and thrust requirements are well within what is commercially available and feasible.

However, consider cold-gas helium, with a specific impulse $\frac{1}{20}$th that of XIPS. Cold-gas helium thrusters would require 20 times the propellant mass to achieve the same force, but this is still only about 0.2 milligrams/second. Station keeping would use only a few kilograms per year. Cold-gas thrusters are considerably lighter and simpler than ion thrusters and might be a better choice.

4.1.2. Solar Radiation Pressure

The solar array panels are face on to the sun during target acquisition and science observation phases, to charge batteries and maintain a positive power flow. The solar array panels for a SPIDER have a slightly smaller linear dimension than the occulting screen. For this DRM, the screen is a square 5 meters on a side. The solar panel array has an area about 22 m^2. This area yields 5.4 kW, assuming panels with 20% efficiency — enough to run two XIPS engines. Solar radiation pressure at 1 AU from the sun is about 4.5×10^{-6} N/m^2, or 10^{-4} N. For a 1-tonne craft, the acceleration is 10^{-7}m/s^2, the same order as the differential gravitational acceleration at 5000-km telescope-occulter separation (Table 3).

5. SUMMARY: WHY UMBRAS?

The UMBRAS design has several advantages over other types of coronagraphic designs. Since the occulter is not built into the telescope as an add-on instrument, scattered light is reduced due to fewer optical surfaces, there are no unwanted diffraction spikes resulting from coronagraphic supports, and the complexity of the instruments can be reduced. The screen can occult any target in the telescope image plane. All science instruments on the telescope, including spectrographs, could be used to make observations of the region around the occulted target.

The small UMBRAS mission examined here is proposed as a technology testbed for a larger mission. Even this small mission offers a significant improvement compared to the other space based coronagraphic detectors expected to be operational over the next decade. The small UMBRAS could outperform the NICMOS coronagraph by 2 stellar magnitudes at separation angles greater than $0''.4$. The small UMBRAS offers detection gains of 2-7 stellar magnitudes at separation angles between $0''.13$ and $0''.4$, a region which will not be accessible to any existing or planned space based coronagraph. At least one of the currently know extrasolar planets could be detected with the small UMBRAS mission, and studies of previously inaccessible regions of stellar disks, quasar host galaxies, and the nuclear regions of nearby galaxies would be possible.

Lessons learned from a small mission would make a large mission feasible. A large occulting screen working with an 8-meter or 10-meter telescope would truly revolutionize the study of the origins of stars and planets.

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