AIAA 2000-5230

UMBRAS: Design of a Free-Flying Occulter for Space Telescopes

Ian J. E. Jordan, Alfred B. Schultz, & Helen M. Hart
Computer Sciences Corporation, Baltimore, Maryland;

Fred Bruhweiler
Catholic University of America, Washington, D.C.;

John Hershey & Dorothy Fraquelli
Computer Sciences Corporation, Baltimore, Maryland.

AIAA Space 2000 Conference & Exposition
19-21 September 2000
Long Beach, California

UMBRAS: DESIGN OF A FREE-FLYING OCCULTER FOR SPACE TELESCOPES

Ian J. E. Jordan*, Alfred B. Schultz†, & Helen M. Hart‡
Science Programs, Computer Sciences Corporation, Baltimore, MD 21218
Fred Bruhweiler§
Catholic University of America, Washington, D.C. 20064
John Hershey¶, & Dorothy Fraquelli#
Science Programs, Computer Sciences Corporation, Baltimore, MD 21218

Abstract

A free-flying occulter used with a space-based telescope can enhance the contrast in the region close to a star, allowing extrasolar planet searches. An occulting spacecraft design, emphasizing configuration, control, propulsion, mass estimates, and power requirements, is presented requiring no extension of existing technology or exotic engineering solutions. The design is scalable for use with telescopes having 1 to 10 metre apertures. Several innovations are employed to block starlight and suppress scattered sunlight. A station keeping control method is possible using various thruster types. With scientifically interesting rates at which different stars are surveyed, solar-electric propulsion allows the occulting craft to be packaged on existing launchers with no on-orbit assembly.

I. *Nomenclature*

cm	=	centimetres.
F_j	=	spacecraft thrust (Newtons).
g	=	9.8 metres/second/second.
η_m	=	propellant utilization efficiency.
I_{sp}	=	specific impulse of fuel (seconds).
kg	=	kilograms.
km	=	kilometres.
kW	=	kiloWatts.
m	=	metres.
mN	=	milliNewtons.
M_{prop}	=	propellant carried by craft (kg).
μ	=	microns.
T	=	Time spent thrusting (seconds).
W	=	Watts.

* Space Telescope Science Institute, 3700 San Martin Drive; AIAA Member.

† Space Telescope Science Institute, 3700 San Martin Drive.
‡ Dept. of Physics & Astronomy, FUSE Project, The Johns Hopkins University, 3400 N. Charles Street.
§Professor, Depart. of Physics, 620 Michigan Ave.
¶ Space Telescope Science Institute, 3700 San Martin Drive.
# Space Telescope Science Institute, 3700 San Martin Drive.

II. *Introduction and Purpose:*

In 1962, Lyman Spitzer [1] expounded upon the idea, earlier expressed by R. Danielson, of using a man-made occulting object to search for faint stellar companions. A dozen years later, Gordon Woodcock [2] reconfirmed and extended Spitzer's analysis, presenting a rough design for an umbrella-like craft and ideas on how to accomplish the mission. However, in those early days of space astronomy, not many practical ideas arose for a mission with a wide scope. Over twenty years later, Craig Copi and Glenn Starkman [3,4] presented concepts for very large occulters requiring significant technological development. Others[5,6,7] have explored the technique and presented different occulter ideas. Analysis shows that diffracted light near the star could be suppressed by factors of 10 to 100+, increasing chances of direct detection of extrasolar substellar objects.

Derived independently, UMBRAS is a scalable, current technology occulter for use with 1-10 metre-class space telescopes [8]. We refer to this implementation of the occulter concept as *Umbral Missions Blocking Radiating Astronomical Sources* (UMBRAS). UMBRAS encompasses a combination of techniques that address design and operations challenges and requires no extension of existing technology. The occulting craft, the heart of the UMBRAS mission, is discussed here rather than the telescope or any companion metrology craft.

III. ***UMBRAS: A Scalable Design:***

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

Design driver	E-Class	D-Class	N-Class
Telescope Aperture	~ 1-metre	~ 2-metres	~ 10-metres
Screen Size	~ 5-metres	~ 10-metres	~ 45-metres
Mission Duration	~ 1-year +	~ 2-years +	~ 6-years

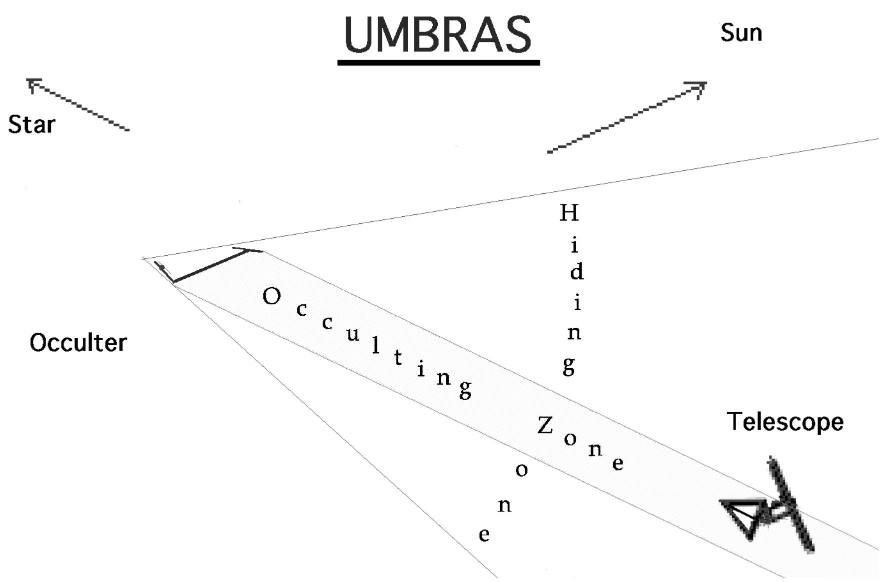

Figure 1: Relative placement and configuration of space-based occulting mission elements. The occulting screen blocks light from a star and hides the spacecraft bus from telescope view. The occulting screen is oriented with its normal perpendicular to the sun's direction, helping to keep the side facing the telescope dark. The screen is shaded to minimize light scattered toward the telescope. The bus is articulated to an appropriate angle to hide the spacecraft from view behind the occulting screen.

UMBRAS is a constellation of craft--telescope, occulter, and any companion metrology craft--used in an occulting mission. The occulter can be used with any telescope detector with targets placed anywhere in the focal plane, unlike classical coronographs. UMBRAS is designed to launch aboard existing boosters and deploy without on-orbit assembly. Tradeoffs between number of targets, observation rates, nulling efficiency, and mass are necessary. The UMBRAS occulter moves between targets at engine ratings which optimize mission objectives.

Central to the mission concept is the occulting craft--a *Solar-Powered, Ion-Driven, Eclipsing Rover* (SPIDER). If necessary, small metrology platforms are used for ranging, navigation, and station keeping between the telescope and occulter. We discuss occulters in the context of use with 1-metre (Explorer or "E-class", and Discovery or "D-class") to 10-metre (NGST or "N-class") aperture telescopes. Telescope aperture size and mission duration are primary design drivers. Table 1 shows approximate mission characteristics. The E-class occulter is a low-weight version of the D-class and lacks redundant systems, offering a limited, higher-risk mission. Differences in design between missions will be highlighted when necessary.

The SPIDER moves from one location to another at various ranges and directions about the telescope, maneuvering to block out light from astronomical sources (q.v. Figure 1). The occulter implements a separate shading component to minimize scattered sunlight from the *occulting screen*. The spacecraft bus and solar array are hidden by the screen through proper orientation of the occulter with respect to the telescope. The main SPIDER structural and functional elements are:

- Solar Arrays
- Spacecraft Bus
- Propulsion Module & Boom
- Occulting Screen
- Screen Shade.
- Screen Pedestal & Boom

Figure 2 shows the SPIDER's functional elements from different aspects in the observing configuration. The screen is depicted perpendicular to the array-bus, but need not be for observations (q.v. Section 5.3.1). During inter-station transits (not shown), the screen articulates down to lie in-line parallel with the bus-arrays in the x-y plane (E- and D-class), or perpendicular in the x-z plane (N-class)[9].

3.1 ***Solar Arrays:***

The craft shown in Figure 2 has multiple solar panels in two asymmetric "wings" with approximate dimensions given in Table 2. Wing "width" (y-direction) is limited by the need to hide the arrays from the telescope on the side of the occulting screen facing the target star.

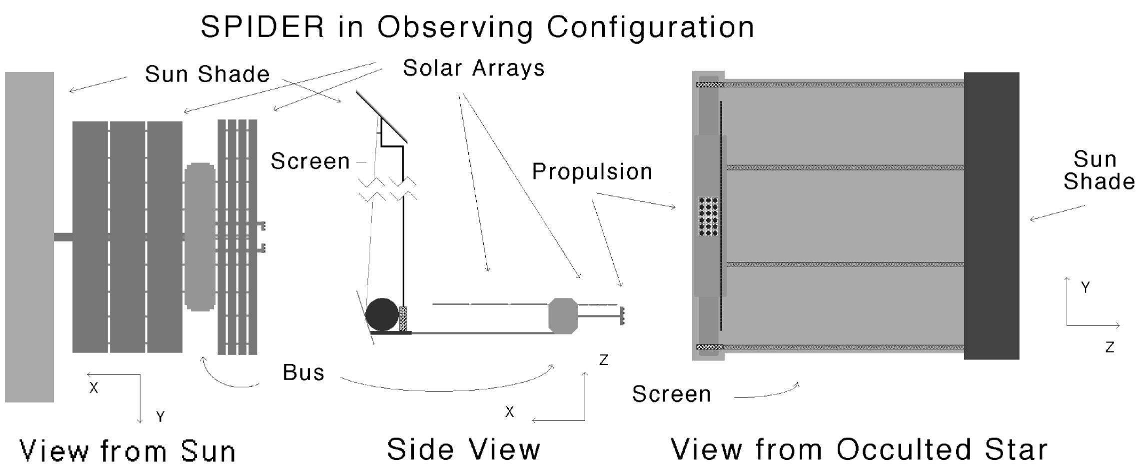

Figure 2: Several views of the SPIDER in an observing configuration. Bus-fixed x-, y-, and z-axes are adopted everywhere except for the screen and shade. The plus-z axis points perpendicular to the solar arrays toward the sun. The plus-x axis points from the bus along the bus-screen boom toward the occulting screen, which is also the direction of motion when moving between targets. The y-axis is defined as in a conventional right-handed x-y-z coordinate system. The "top" of the occulting screen is the end affixed with the shade. The right aspect shows the screen 'hiding' the bus and arrays (this side of the screen) from the telescope (on the other side of the screen). The shade prevents sunlight from illuminating the telescope-ward side of the screen.

Table 2: Characteristic Solar Array and Bus Sizes for SPIDER for various missions.

Mission	y-width	+x-wing	-x-wing	Bus
N-class	12 m	5 x 1.0 m	2 x 0.5 m	1.5 x 1.5 x 6-8 m
D-class	4 m	6 x 1.0 m	4 x 0.5 m	1.5 x 1.5 x 4 m
E-class	4 m	4 x 0.8 m	4 x 0.4 m	1.2 x 1.2 x 2 m

3.2 ***Spacecraft Bus:***

The spacecraft bus contains all command, control, communications, power management, and fuel storage. High data rates are not required for a SPIDER using optical navigation between targets, so a low gain antennae is chosen for all mission classes. One to six spherical, high pressure (100-200 atm) propellant tanks containing xenon are located within the bus. Batteries may be used for surge/peak-power times.

3.3 ***Propulsion Module and Boom.***

Solar-electric propulsion (SEP) is sufficient and the only option considered. With solar-electric thrust, the SPIDER is power-limited as a consequence of launch weight restrictions. Practical upper-limits to range and target observation rates result[10]. Electrostatic thrusters are used for primary propulsion and possibly the attitude and translation control system (ATCS). At least some cold-gas thrusters are used to avoid spacecraft charging induced when plasma exhaust would otherwise impinge upon the solar array, occulting screen, or shade (e.g., when SPIDER translates in the negative-x direction).

Primary propulsion thrusters and some of the ATCS are mounted on 2 pop-up booms projecting from the center of the spacecraft bus, pointing in the -x direction when deployed. Thruster booms move only once upon post-launch deployment. Exhaust plasma is directed away from all spacecraft systems, minimizing contamination, electrostatic charging, and plasma damage [11,12,13,14]. Before deployment, the propulsion booms are folded flat against the bus along the y-axis. Malleable metal tubing at the bending joint avoids flexible, degradable propellant lines.

High specific-impulse electrostatic thrusters discharge a tenuous high-temperature plasma. Charge flow, separation, and buildup in and around the SPIDER require consideration. Studies [12,15,16] of neutral and plasma component distributions in the exhaust of single and multiple thruster configurations appear compatible with the UMBRAS design. Exhaust products can modify exposed surfaces, changing thermal and optical properties [12,17]. Current SEP accelerator cathodes employ molybdenum which is sputtered into the exhaust and can contaminate glass surfaces, reducing solar cell efficiency. This is expected to be less significant with future long-life carbon-carbon cathodes. Plume shields on the propulsion booms can reduce contamination [17,18]. At 2.3 kW power consumption, a 17 kW array can sustain 4-6 NASA-Hughes' NSTAR engines yielding up to half a Newton of thrust.

3.4 ***The Occulting Screen:***

When in the observing configuration the occulting screen blocks light from astronomical sources, redistributes residual diffracted light *and* hides the remainder of the spacecraft from telescope view. The occulting screen might consist of a multi-layer blanket (MLI) with approximate dimensions of 16- to 45-metres square for an N-class occulter, or as small as 5-metres square for an E- or D-class craft. Multiple *layers* provide redundancy against screen tears or punctures.

The number, thickness, composition, and spacing of the layers determines thermal and optical insulation between the screen's bus-ward and telescope-ward sides. Screen layer composition requires separate analysis and is not considered here. To remain dark at wavelengths of 0.1-5 μ, several techniques are used to produce the darkest possible screen. Thermal behavior is important for telescopes observing in near-thermal infrared wavelengths. During observations, the screen is edge-on to the sun minimizing screen heating and sunlight reflected toward the telescope. Critical protection is offered by the *screen-shade* (q.v. Section 3.5).

Many choices of screen shape are possible. Here we consider a square or rectangular screen fitting within available launchers which is straightforward to deploy. A multilayer blanket can be unfurled in a manner conceptually similar to a roll-up window blind, tape-measure, or film cassette. Once deployed, it need never refurl.

Sizing the N-class screen for the space shuttle payload bay (18- by 4.6-metre usable cylindrical volume [19]) allows compatiblity with other large launch vehicle fairings. To package a *screen* larger than 16 metres wide into this linear restriction, a three-section, sliding-track, interleaved-layer design is chosen. *Layers* from different *sections* of the wide screen are interleaved when rolled within the cassette. After unfurling to its full *length* upon deployment, a sliding track system allows *layers* of the plus- or minus-y *section* to slide out together. Three interleaved 16-metre wide sections can spread out into a continuous 45-metre wide screen with 1.5-metre overlap between adjacent sections. By interleaving layers which overlap near their edges when unfurled, light leaking from bus-ward to telescope-ward sides of the screen is minimized.

A multi-layer screen is more complex to package than a single layer, and allowance for a rolled configuration must be made. A multi-layer screen wrapped around a drum must either have inner layers that 'crinkle' or contain overlapping *segments* in each *layer* otherwise outer layers will be longer than the inner layers. For example, a 45-metre screen with 22 turns around the drum and 3 cm spacing between monolithic inner and outer layers would have an outer length 4.2 metres greater.

Monolithic crinkling sheets may be used if they are not inflexibly attatched to each other along their lengths. If a 'crinkle' design is not chosen, the unrolling screen might have overlapping *segments* for the inner layers and a monolithic outer layer. The innermost layer lies bus-ward when deployed and the telescope-ward side is the monolithic sheet. The innermost layers could be comprised of wide segments, not subject to vacuum welding, where the top of one segment overlaps the bottom of an adjacent segment when rolled onto the cassette. Segments may be supported in place by a flexible rigging near each layer's y-edges. When unrolled, overlap decreases, but remains sufficient to provide a light-baffle from the bus-ward to the telescope-ward side of the screen.

To keep the screen rectangular and flat, lightweight masts unfurl with the screen, providing structural stiffness to prevent damage during operations. Several choices are available, such as the *astromast*--a coilable structure with very low mass-to-volume ratio--or collapsible bistem tubes [20]. Several masts spaced out across the screen, attached to the slide-tracks and shade support beam provide screen rigidity. The masts are placed on the side of the screen facing away from telescope view (thermal flux minimization for N-class). To complete the light shield the pedestal is blanketed on the telescope-ward side by a *cassette shroud* which functions as a continuation piece for the occulting screen by covering the cassette-pedestal.

3.5 ***Screen Shade:***

To achieve the darkest possible screen, a *shade* is placed atop the screen structure, designed and oriented to minimize sunlight falling on the occulting screen. To prevent light scattering from the bus or arrays to the telescope off the underside of the shade, a secondary shade projects down from the lower edge of the primary shade near the shade ends (not shown in diagrams).

Several techniques for minimizing scattered sunlight into the telescope from the illuminated edge of the shade can be combined. The top edge of the primary shade must be very sharp (radius of curvature < 10-100 μ), presenting a minimal illuminated cross section to the telescope. If the edge is highly polished, then reflected sunlight is preferentially scattered specularly, with intensity dropping inversely with distance. By ensuring that the edge of the shade is not perpendicular to the telescope-target line of sight, much of the reflected light can be directed away from the telescope. If insufficient, then vapor deposition of a micro-beading material or roughening of the edge will scatter sunlight diffusely with intensity diminishing as the inverse-square of occulter-telescope separation.

Figure 2 shows the slanted "shack roof" shade where only the underside of the shade is within view of the telescope. The shade must obtain a minimum projected width with respect to the sun to keep the screen in shade. Since the sun is approximately 0.5° wide at earth's orbit, the shade must project at least 10 centimetres away from the screen for each 12-metres of screen height. Minimum shade width also depends upon screen straightness. The shade slant angle, operational range of target sun-angles, and projected shade width are inter-related mission and design parameters to be optimized for specific missions and are not discussed further here.

For an E- or D-class SPIDER, these measures may be sufficient. To be useful in the infrared for an N-class mission, the screen must also be cold. Screen temperature depends upon radiation and conduction from the spacecraft structures as well as transient heat absorbed from the exhaust plumes and solar heating during transit and articulation. Whether UMBRAS is useful in the infrared due to the extent and shape of the diffraction features has only been investigated in a preliminary way [3,4,8], and deserves fuller treatment elsewhere.

A thermal analysis is a topic in itself, nevertheless one source bears brief mention. A 45-metre long shade presenting a 1-metre cross-section to the sun at 1 a.u., with 90% reflectivity on its sunward side absorbs ~6 kW of sunlight. Heat disposal with high conductivity mesh running from the shade down the inside of the occulting screen to the cold, shaded platform radiators may be possible. This mesh may also provide tear protection for the screen.

3.6 ***Articulating Boom***

A 'telescoping' boom joining pedestal and bus allows compact launch packaging. When extended, room for unfurling the +x solar array wing between the bus and screen is allowed. The boom contains an 'elbow' articulating mechanism near the base of the screen allowing rotations between transit and observing configurations. An astromast or bistem is used to minimize boom weight.

The articulating mechanism allows the screen and bus-array to be placed at various angles and orientations with respect to each other, allowing all spacecraft structures to hide from the telescope view over a wide range of viewing angles. During transit between targets, rotation to a symmetric configuration decreases attitude control complexity. For an N-class occulter which might be used for observing at near-thermal wavelengths, a second rotating mechanism allows rotations around the boom axis[9]. This enables the SPIDER to transition from an observing configuration to a transit configuration while maintaining minimal solar heating of the occulting screen.

Table 3: Estimated SPIDER maximum mass and power requirements for typical UMBRAS missions.

Design Element	**E-class** *5-metre screen* Mass/Power:	**D-class** *10-metre screen* Mass/Power:	**N-class** *45-metre screen* Mass/Power:
Payload:			
extensible screen	13 kg	52 kg	360 kg
shade	10 kg	20 kg	60 kg
screen cassette	20 kg	40 kg	90 kg
bus-screen boom	30 kg	30 kg	70 kg
metrology (beacons)	10 kg [50 W]	10 kg [50 W]	30 kg [50 W]
pedestal & masts	50 kg	100 kg	130 kg
Payload subtotal:	*133 kg*	*252 kg*	*710 kg*
Bus + Array + Propulsion:			
Structure:			
array support	12 kg	20 kg	50 kg
bus + propulsion boom(s)	75 kg	100 kg	300 kg
Battery : (450 W-hrs NiH_2)	10 kg	10 kg	10 kg
Power Production:			
Arrays (GaAs @ 18% BOL)	168 kg {4 kW}	280 kg {6.6 kW}	600 kg {15 kW}
Control & Conversion	175 kg	300 kg	680 kg
Propulsion:			
NSTAR (η_m=.85) [2.3 kW ea.]	17 kg (1 op of 1)	102 kg (2 op of 6)	408 kg (6 op of 24)
Power Conditioning/Control	30 kg [0.3 kW] (1 ea.)	120 kg [0.6 kW] (4 ea.)	300 kg [1.5 kW] (10 ea.)
Xe propellant tanks	30 kg (100 kg Xe)	130 kg (440 kg Xe)	1200 kg (4000 kg Xe)
Xe pressure/feed system	50 kg [100 W]	50 kg [100 W]	50 kg [100 W]
Attitude & position determination & control:			
sun sensors	4 kg [12W] (4 ea.)	4 kg [12W] (4 ea.)	4 kg [12 W] (4 ea.)
star trackers/optical nav. cameras	3 kg [40 W] (2 ea.)	6 kg [80 W] (4 ea.)	6 kg [80 W] (4 ea.)
gyros (MIMU)	8 kg [50 W] (2 ea.)	8 kg [50 W] (2 ea.)	8 kg [50 W] (2 ea.)
reaction wheels	26 kg [150 W] (4 ea.)	42 kg [150 W] (4 ea.)	142 kg [500 W] (6 ea.)
ATCS (16 UK-10)	120 kg [4 x 0.7 kW]	120 kg (4 x 0.7 kW)	120 kg (4 x 0.7 kW)
ATCS aux. (16 @5000mN)	40 kg [100 W]	40 kg [100 W]	40 kg [100 W]
N_2 tank + feed system	75 kg (+ 25 kg N_2)	75 kg (+ 25 kg N_2)	75 kg (+ 25 kg N_2)
Communications:			
Communications (low gain)	50 kg [70 W] (2 ea.)	50 kg [70 W] (2 ea.)	150 kg [170 W] (2 ea.)
Command, Control & Data I/O:	50 kg [50 W]	50 kg [50 W]	50 kg [50 W]
Thermal Control:	10 kg	20 kg	30 kg
Bus + Array subtotal	*853 kg*	*1527 kg*	*4223 kg*
Dry mass:	*986 kg*	*1779 kg*	*4933 kg*
Margin ~ 20% (total dry mass):	197 kg	356 kg	987 kg
Total mass (inc. propellant)**:**	**1308 kg**	**2600 kg**	**9945 kg**

IV. *UMBRAS Tips the Scales*

Spacecraft component masses and power requirements are standard elements of spacecraft design [15,21,22,23] except for the SPIDER's payload (occultation components). The values in Table 3 represent best-guess upper limits on what is required to build SPIDER. Discussion here is devoted only to the more unusual subsystems. It is currently unknown if separate metrology platforms will be employed or if existing positioning systems, such as GPS, are usable, so we have chosen inter-craft optical navigation for mass budgeting. Control of the occulter through the telescope's communications link with SPIDER is assumed when on-station. Power consumption estimates are provided in Table 3, however not all subsystems consume power simultaneously.

4.1 ***Propulsion System Mass.***

A 6-year N-class mission is longer than the nominal lifetime of a typical SEP engine, therefore redundancy is required. A NASA/Hughes NSTAR xenon electrostatic propulsion unit masses ~17 kg and the power conditioning and control electronics (PCCE) [24,25,26,27] masses about 30 kg. An operating thruster exclusively uses one PCCE, but a network topology of redundant, cross-switchable PCCEs serving more than one thruster serially in time avoids separate PCCEs for every thruster placed on board.

For an N-class craft with 6 thrusters operating simultaneously, 12 PCCEs (half assumed as backups) may be required in a network of 24 thrusters, depending upon the expected PCCE lifetime. Assuming NSTAR engines operating at 3000 seconds specific impulse and 85% propellant utilization efficiency over a 6-year mission (5-years thrust time), Equation 1 yields 3.4 tonnes of xenon required. If thruster lifetime is extended with the new carbon-carbon cathodes, then an 8-thruster (6 operating during transit) system saves over 300 kg.

$$M_{prop} = \frac{F_j \cdot T}{I_{sp} \cdot g \cdot \eta_m} \qquad (1)$$

The xenon is stored as high pressure gas in 1-4 spherical tanks less than 1.2 metres in diameter inside the spacecraft bus. Although titanium has the best tensile strength-to-mass ratio among metals, a very conservative margin requires tanks to mass about 30% of xenon with a safety factor of ~ 2 against tank failure at 30°C [15,21]. Tank failure due to accidental overheating is avoided with pressure relief valves. Woodcock notes that filament-wound tanks will reduce tankage mass [28].

4.2 ***Payload Mass.***

The *payload* consists of the shade, screen, masts, sliding-tracks, cassette, pedestal, articulating joint, boom, navigation beacons and booms, and any deployment mechanisms such as lanyards and motors. Major components are itemized in Table 3. A 45m x 45m screen is allowed 0.2 kg/m^2 density (75 µ equivalent aluminium thickness), while smaller missions are allotted twice this amount. Several different materials in multiple layers are assumed to be required for proper light and thermal baffling.

In specifying 'layers', the ~25 µ thickness allowance for each of 3 layers (N-class), includes tear-resistant weave built into each layer. Each 'layer' may consist of multiple sheets of different materials. Kapton is currently available at under 4 µ thickness and commercial packaging aluminium at 15 µ, so this assumed areal density allowance does not seem unreasonably small. Comparable areal densities are assumed for the shade, however the 'lead-edge' may need to be constructed as a more rigid razor-blade-like structure (q.v. Section 3.5).

V. ***UMBRAS Operations***

5.1 ***Launch:***

At launch, the panels in each solar array wing are folded against the bus along with propulsion booms, screen platform and furled occulting screen. This allows the SPIDER to fit within available large launch fairings or the shuttle payload bay (q.v. Figure 3). The folded SPIDER is oriented with the long y-axis pointing vertically within the launcher.

We find that an E-class occulter can be packaged with a small space telescope (SIRTF weight) for launch and delivery aboard a single Atlas II class launcher. D-class occulters can either be launched separate from the telescope aboard an Atlas II class booster, or tandem launched with the telescope on a single Titan IV class launcher. N-class occulters require a separate Titan IV class launcher, or larger.

5.2 ***Deployment and Delivery to Station:***

Options for delivering the SPIDER from its launch platform in low earth orbit (LEO) to its circum-telescope station depend upon configuration, size, and mass. The combination of station keeping requirements imposed by the science goals and the inherent low acceleration of the occulter mandate operation at least 500,000 km from Earth. An N-class SPIDER may be too heavy to place into a direct escape trajectory. For a 10-tonne N-class SPIDER, a Delta IV launcher is projected to provide enough boost for LEO escape.

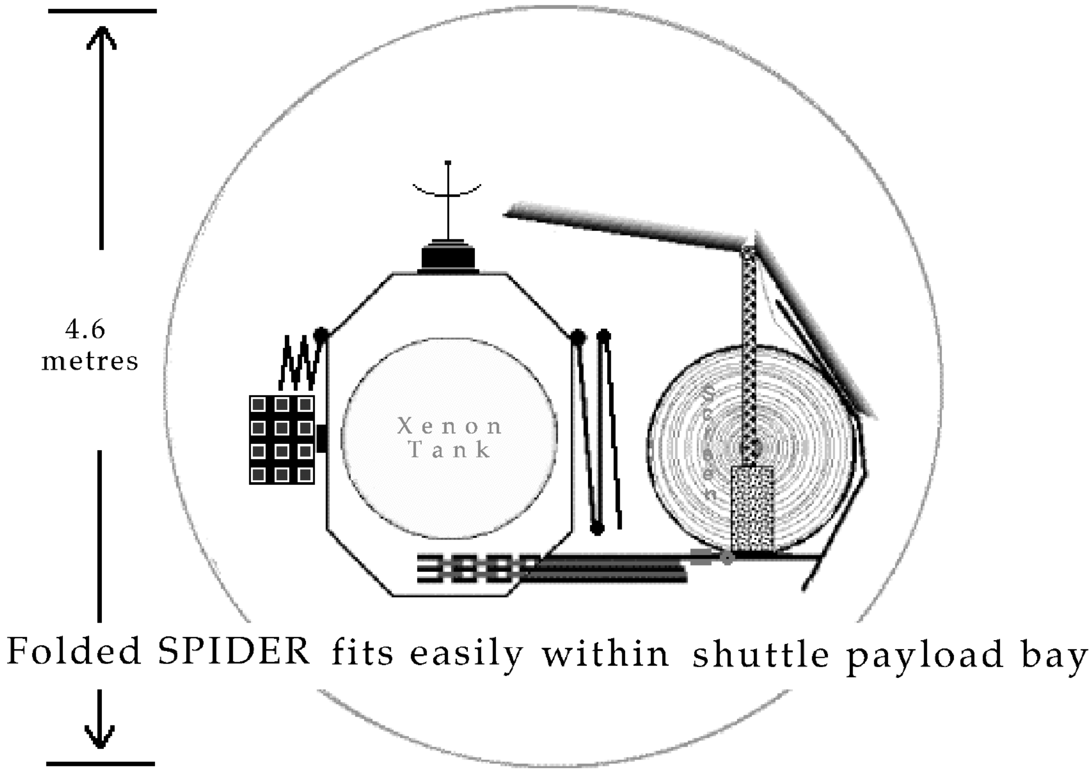

Figure 3: UMBRAS fits within existing payload size limits. Here, an N-class SPIDER is shown in cross-section, through the payload bay, fitting comfortably within shuttle and Titan IV restrictions. Components shown are (left to right, top to bottom) propulsion module, -x array, bus, propellant tank (internal cutaway), communications antenna, bus-screen boom, shade, +x array, screen cassette, rolled screen, screen pedestal, and cassette shroud.

One approach for delivering a 10-tonne N-class SPIDER launched aboard the space shuttle is to configure it with PAM D-II class perigee kick motors (PKMs) [30] mounted in staged pairs at opposite ends on the bus' long axis (four total). At 2 metres long, and 1.65 metres wide, stacked pairs nestle together between the folded solar array wings leaving room for the screen cassette in the payload bay. The total length of 4 stages is 9-10 metres, and if the spacecraft bus is under 8 metres, the entire stack may fit within the shuttle payload bay.

After initial deployment from the shuttle or Titan IV, each PKM is fired and staged sequentially. Each pair of staged PKMs 'face' in opposite directions and the SPIDER must slew 180° before a PKM on the opposite side is ignited. Four PKMs give a 10-tonne SPIDER nearly three-quarters of the speed needed for Earth-escape. Such a 4-burn sequence would place the SPIDER in an orbit with a period of about 9 hours and an apogee 30,000 km above Earth's surface. The remaining velocity can be gained by near-continuous SEP thrusting. Orienting the semimajor axis of the orbit perpendicular to the sun-earth line maximizes array solar exposure and therefore thrust. Such an orbit is not sun-synchronous, so clever planning of orientation and thrust vectors is necessary to precess the orbit axis accordingly. A 6-tonne SPIDER launched from the shuttle could achieve full escape velocity in approximately 1 year of SEP acceleration with this 4-PKM configuration.

Once the high-thrust phases of the delivery are complete, unfurling and deployment of SPIDER structures may commence. Deployment of the screen, propulsion module, and screen-boom have already been discussed in light of their design impact. The shade also requires deployment since it is folded to conform to the launcher's fairing. Motors to move the shade to the appropriate angle may be required.

5.3 ***Maneuvering***

Operations phases are discussed more extensively elsewhere [8,9,29], however translation and rotation are critical functionalities with direct bearing on design. The moment of inertia of E- and D-class SPIDERs about the y-axis is on the order of 1-4 x 10^4

kg-m^2. Several 25-mN SEP ATCS thrusters oriented perpendicular to the y- and x-axes at the end of the propulsion boom allows a 180-degree turnaround time under 1000 seconds. Large reaction wheels[31] can also meet this torque and slew-time goal. For a 10-tonne N-class SPIDER with a 45-metre screen, the moment of inertia is on the order of 10^6 km-m^2. A similar SEP ATCS thruster arrangement would require several hours for executing a turnaround maneuver. Tandem ATCS use with reaction wheels could reduce this maneuver time.

5.3.1 ***Station Keeping: Attitude Control***

The SPIDER's precise orient requirements mandate 3-axis stabilization. A model of mass distribution between bus, array, propulsion module and screen/shade shows the center of mass (CM) of the craft may lie between the bus and occulting screen (q.v. Figure 4). Few spacecraft have the CM outside the bus, and those that do have attitude control thrusters distributed sufficiently to "encase" the CM. Such distribution allows conventional roll and attitude control techniques.

In the SPIDER design, such encasement is highly problematic. ATCS placement to surround the offset CM would entail locating some on booms projecting toward the screen, or on or near the screen itself. Further complications result with trying to positioning thrusters not to point at the occulting screen, as well as supplying propellant and power to them. As a result, non-conventional ATCS techniques are employed.

These problems are avoided by placing groups of ATCS thrusters only on the bus and propulsion booms and firing them so as to produce "force couples". The magnitudes of the force couples are such as to yield zero net spacecraft rotation, yet result in a net translational force on the spacecraft. Figure 4 demonstrates the idea for zero rotation, non-zero net translation in the direction perpendicular to the occulter-telescope line and in the spacecraft bilateral symmetry plane (the S-T plane in Figure 4 which bisects the SPIDER spacecraft). The result is a translation along the S-axis using a non-rotational, oppositely directed force couple without having thrusters placed near the screen/shade.

Movement in the perpendicular direction (U-axis) is not as straightforward. A complication arises in that the CM of the SPIDER can vary its position in the S-T plane significantly depending on the angle between the occulting screen and the bus-screen boom. CM shifts also occur due to expenditure of propellant from the tanks. CM shifts along the U-axis can occur if propellant is unevenly depleted from the tanks. The directions of the force couple and the SPIDER's CM must all lie in the same plane else rotations are induced.

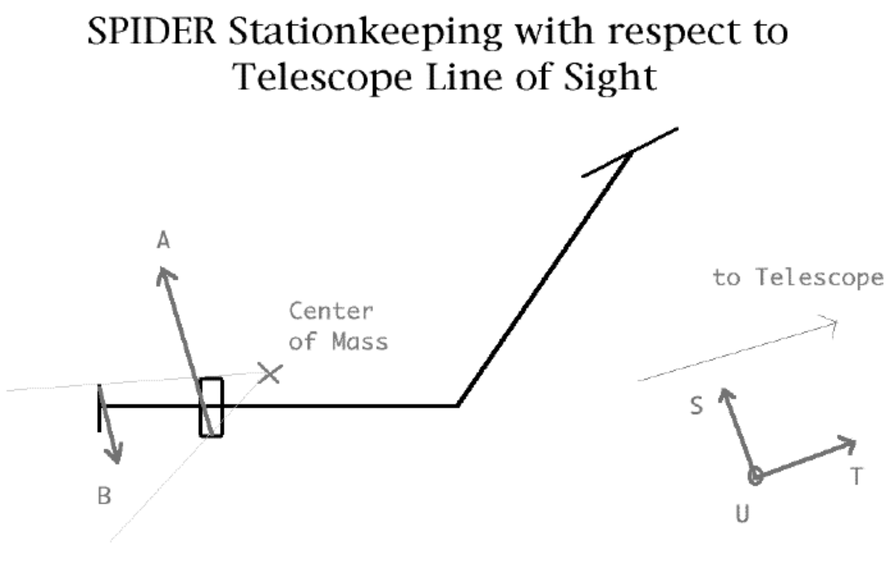

Figure 4: The SPIDER fine tunes its position across the telescope-target line of sight through force-coupled thruster firings oriented oppositely and offset asymmetrically from the center of mass. The magnitude of the forces A & B are such as to produce no net rotation--only translation along S, and possibly T. The S-T plane is parallel to the x-z plane (q.v. Figure 2).

For translations in the U-direction, the solution is trickier. An answer lies in accepting a T-direction translation component along with the desired U-direction movement. ATCS thrusters pointing out of the S-T plane are placed near the end of the spacecraft bus as well as on the primary propulsion module. By either gimballing appropriate thrusters on the spacecraft bus, or by firing more than one thruster in a cluster at each couple pivot point, the net forces can be oriented to be in the same plane as the CM and each other.

With an appropriate choice of direction and magnitude of each pivot-point's net thrust vector, the S-axis component of net-thrust may be nulled while net U- and T-axis components remain. While the U-axis component of motion is desired and necessary, the T-axis component is a benign side-effect. Since the SPIDER operates thousands of kilometres from the telescope, translations along the T-axis of a few tens of metres are acceptable as they produce only minute changes in apparent occulter size.

5.3.2 ***Station Keeping: Guidance***

An outstanding concern is how the occulter can be positioned without using metrology platforms and inter-spacecraft ranging: how can an "invisible" screen be accurately positioned? One solution is to use imaging of one craft (telescope or occulter) with respect to the background stars from the other craft[9,29]. If imaging is done from the telescope, allowance must be made for the 'dark' observing configuration of the occulter. For the N-class occulter, an articulating boom folds out from the bus in the -z direction into the telescope's view. At the end of this boom is an illuminated beacon which, when imaged by the telescope against the background stars, aids in determining the occulter position. Between science exposures, the boom "pops down" for position verification, and then folds back up out of view before resuming science exposures. For D- and E-class craft, which need not be concerned with any thermal sources, the beacon may be mounted on the screen pedestal or shade support.

Conclusions

A usefully sized occulting spacecraft appears constructable with current day engineering. Launch and delivery of small occulters can be achieved with existing medium boosters, while larger occulters require heavy lift capability. Solar-electric propulsion can be used for moving between targets and perhaps station keeping and attitude control. A conventional MLI occulting screen performs occulting duty with a shade shielding the screen from direct solar exposure. Such an occulter would open a new search regime around stars for extrasolar Jovians and other low mass companions.

Acknowledgments

I. Jordan and A. Schultz acknowledge partial CSC/STScI research support. Space Telescope Institute is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS5-26555. Appreciation is extended to Wayne Kinzel, Martin England, Forrest Hamilton, Chi-chao Wu, Al Holm, Conrad Sturch, Chris Sande, and Mark Kochte of CSC, Alex Storrs and Peter Stockman of AURA, Greg Wenzel of Honeywell, Mike DiSanti of Catholic University, Lisa Landenburger of the U.S. Geological Survey, Charles Brown of University of Colorado, T. A. Bond of Hughes Electric, Saskia Besier, and Linda Jordan Hughey of University of Canterbury for their insights, help and patience during provocative discussions and reviews.

References

[1] L. Spitzer, Jr., "The Beginnings and Future of Space Astronomy", American Scientist, v. 50, pp. 473-484, 1962.

[2] G. R. Woodcock, in Future Space Transportation Systems Analysis, Contract NAS9-14323, Dec 11, 1974.

[3] G. D. Starkman, C. J. Copi, "The Improved Resolution and Image Separation (IRIS) Satellite", *Proceedings of SPIE:* Space Telescopes and Instruments V, ed. P. Y. Bely, J. B. Breckinridge, v. 3356, pp. 608-621, August 1998; q.v. http://erebus.phys.cwru.edu/~boss/.

[4] C. Copi, G. Starkman, "The Big Occulting Steerable Satellite", Astrophysical Journal, v. 532, p. 581, 2000.

[5] J.I. Elliot, "Direct Imaging of Extra-solar Planets with Stationary Occultations Viewed by a Space Telescope", Icarus, v. 35, pp. 156-164, 1978.

[6] H. S. Hudson, "The Pinhole Occulter Facility", Advanced Space Research, v. 2, pp. 307-314, 1983.

[7] J. Schneider, "SCODOTEP: A Class of Mission Concepts for the Detection and Study of Terrestrial Extra-solar Planets by Coronographic Imaging in Space", *Detection and Study of Terrestrial and Extrasolar Planets* workshop, Boulder, CO, May 15-17, 1995.

[8] A. B. Schultz, D. Schroeder, et. al., "Imaging Planets About Other Stars with UMBRAS" *Proceedings of SPIE*, Infrared Spaceborne Remote Sensing VII, v. 3759, pp. 49-58, July 1999; q.v. http://www.stsci.edu/~jordan/umbras/

[9] A. B. Schultz, "Imaging Planets about other Stars with UMBRAS II", SPIE 45th Annual Meeting, San Diego, CA, July 30-August 4, 2000.

[10] I. J. E. Jordan, A. B. Schultz, D. Schroeder, et. al., "Enhancing NGST Science: UMBRAS", NGST Science & Technology Exposition, Hyannis, MA, October 1999. E. Smith and K. Long, eds., ASP Conference Series CS-207, p. pub. pending, 2000.

[11] M. R. Carruth Jr., E. V. Pawlik, "Interactions Between a Spacecraft and an Ion Thruster-Produced Environment", *Progress in Astronautics & Aeronautics:* Electric Propulsion and its Applications to Space Missions, ed. R. C. Finke, v. 79, pp. 787-798, AIAA, 1981.

[12] R. I. Samanta Roy, D. E. Hastings, N. A. Gatsonis, "Ion-Thruster Plume Modeling for Backflow Contamination", Journal of Spacecraft and Rockets, v. 33, no. 4, AIAA, pp. 525-534, July-August, 1996.

[13] R. I. Samanta Roy, D. E. Hastings, N. A. Gatsonis, "Numerical Study of Spacecraft Contamination and Interactions by Ion-Thruster Effluents", Journal of Spacecraft and Rockets, v. 33, no. 4, AIAA, pp. 535-542, July-August, 1996.

[14] R. I. Samanta Roy, D. E. Hastings, "Three-Dimensional Modeling of Dual Ion-Thruster Plumes for Spacecraft Contamination", Journal of Spacecraft and Rockets, v. 33, no. 4, AIAA, pp. 519-524, July-August, 1996.

[15] R. L. Sackheim, R. S. Wolf, Sidney Zafran, "Space Propulsion Systems" in Space Mission Analysis and Design, W. J. Larson, J. R. Wertz, ed., Kluwer, pp. 637-664, 1992 .

[16] N. J. Stevens, "Computed Voltage Distributions Around Solar Electric Propulsion Spacecraft", *Progress in Astronautics & Aeronautics:* Electric Propulsion and its Applications to Space Missions, ed. R. C. Finke, AIAA, v. 79, pp. 826-840, 1981.

[17] J. L. Power, "Measuring the Spacecraft and Environmental Interactions of the 8-cm Mercury Ion Thrusters on the P80-1 Mission", *Progress in Astronautics & Aeronautics:* Electric Propulsion and its Applications to Space Missions, ed. R. C. Finke, AIAA, v. 79, pp. 813-825, 1981.

[18] J. R. Beattie, "A Model for Predicting the Wearout Lifetime of the LeRC/Hughes 30-cm Mercury Ion Thruster", *Progress in Astronautics & Aeronautics:* Electric Propulsion and its Applications to Space Missions, ed. R. C. Finke, AIAA, v. 79, pp. 127-158, 1981.

[19] S. J. Isakowitz, International Reference Guide to Space Launch Systems, AIAA, p. 254, 1991.

[20] H. M. Briscoe, "Spacecraft Mechanisms" in Spacecraft Systems Engineering, P. Fortescue, J. Stark, pp. 467-492, J. Wiley & Sons, 1995.

[21] J. B. Moss, "Propulsion Systems" in Spacecraft Systems Engineering, P. Fortescue, J. Stark pp. 143-180, J. Wiley & Sons, 1995.

[22] E. Reeves, "Spacecraft Design and Sizing", in Space Mission Analysis and Design, W. J.. Larson, J. R. Wertz, ed., pp. 285-337, Kluwer, 1992.

[23] R. Turner, "Spacecraft Structures" in Spacecraft Systems Engineering, P. Fortescue, J. Stark, pp. 237-279, J. Wiley & Sons, 1995.

[24] D. G. Fearn, "The Ulysses Mission: the Ion Propulsion Alternative", Journal of the British Interplanetary Society, v. 49, no. 5, British Interplanetary Society, pp. 181-192, 1996.

[25] H. Gray, P. Smith, D. G. Fearn, "UK Ion Propulsion System Development", Journal of the British Interplanetary Society, v. 49, pp. 163-172, British Interplanetary Society, 1996.

[26] D. C. Byers, "Characteristics of Primary Electric Propulsion Systems", *Progress in Astronautics & Aeronautics:* Electric Propulsion and its Applications to Space Missions, ed. R. C. Finke, v. 79, pp. 99-122, AIAA, 1981 .

[27] M. W. Crofton, "Evaluation of the United Kingdom Ion Thruster", Journal of Spacecraft and Rockets, v. 33, no. 5, AIAA, pp. 739-747, September-October 1996.

[28] G. R. Woodcock, private communications, January-April 1999.

[29] H. M. Hart, I. Jordan, A. Schultz, et. al., "Imaging Planets About Other Stars with UMBRAS: Target Acquisition and Station Keeping", at *International Conference on Application of Photonics Technology,* 14 June, 2000, Quebec City, CA.

[30] J. P. Loftus Jr., C. Teixeira, "Launch Systems" in Space Mission Analysis and Design, W. J. Larson, J. R. Wertz, ed., pp. 665-692, Kluwer, 1992.

[31] J. S. Etermo, R. O. Zermuehlen, H. F. Zimbelman, "Spacecraft Subsystems: Attitude Determination and Control", in Space Mission Analysis and Design, W. J. Larson, J. R. Wertz, ed., pp. 340-366, Kluwer, 1992 .