NOME: Modifying Nexus into an Occulter for use with NGST

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Free-flying external coronagraphs for space telescopes have been studied many times since the 1960s, but few schemes have been generally viewed as yielding a mission with an acceptable cost. Results of a design study are presented on modification of the Nexus L2 mission to perform as an occulter for NGST. Such a mission would have a much smaller cost than previous occulter ideas. A suitably configured spacecraft, incurring only a small percentage mass increase, can be transformed into a free flying occulter capable of performing unique science in conjunction with a space telescope. The `mission extension' concept serves as an example applicable to other missions.

Keywords: Extra-solar planets, free-flying occulter, high contrast imaging, spacecraft design

1. Introduction

A major problem with directly detecting extrasolar planets by reflected light lies not only with their faintness, but also with the contrast between the planet and the diffracted light from their parent stars. For example, a Jupiter-sized planet five astronomical units from the star τ Ceti (11.9 light-years away) would shine at 25th magnitude in the optical and appear over 1 arcsecond away for more than half of its orbit around the star. The Hubble Space Telescope (HST) can routinely observe objects this faint, so why haven't such objects been seen? Even if HST's optics were perfect, such a planet would be over a thousand times fainter than the diffracted light from the star. The starlight is a billion times greater, scattering through imperfect optics, making it virtually impossible to discern faint objects from the noise.

Occulters offer space-based telescopes an aid for detecting faint objects around nearby stars in a manner akin to a conventional coronagraph, except that the occulting mask is placed outside the telescope rather than in the focal plane. The key advantage over internal coronagraphs is a reduction in scattered light internal to the telescope. The benefit over radial velocity (RV) techniques, which have netted the bulk of extrasolar planet candidates, is that *direct imaging*, photometry, and spectrometry of extrasolar planetary systems is possible. Potentially, a new class of Jovian and sub-Jovian planets having orbital radii greater than those of the RV candidates is detectable with this technique. Such planets are more representative of planetary systems like our own.

During the past several years, the authors have explored design, operations, and science goals which exploit free-flying occulters. Nexus was to have been an engineering test of key technologies needed to ensure the success of the *Next Generation Space Telescope* (NGST), but was cancelled in late 2000. Prior to cancellation, a feasibility study was undertaken to see if Nexus could be modified to perform as an occulter upon conclusion of its primary mission. The *Nexus Occultation Mission Extension* (NOME) concept would have allowed NGST--which is not slated to carry an internal coronagraph--to enhance its ability to detect and measure faint companions at visible and near-infrared wavelengths by suppressing a star's light. In such a mission, four major concerns arise:

- impact on Nexus' primary mission,
- design,
- operations,
- achievable science performance.

This article expands upon results of a study of these issues originally presented at the American Astronomical Society's 198th meeting [1]. The NOME study is presented as though it were still a possibility with the hope of inspiring similar multi-use mission analyses, and demonstrating critical features that have already been identified for occulter missions. This article does not concentrate on justification and explication of the occultation technique, as that is detailed extensively in other publications cited throughout this work. Instead, we concentrate on the new aspects addressed in the original study—the modifications necessary to turn the Nexus spacecraft into one capable of performing the auxiliary occultation mission. Implicit is the understanding that proposed solutions may not be optimal, but appear to address the major concerns. By introducing an occulter as a "piggyback extension", mission costs are only a fraction of a separate occulter spacecraft. NOME serves as a paradigm for other such extended mission occulter possibilities. The Herschel (FIRST), Plank, GAIA, and even SPICA missions have been identified as potential carriers of an occulter package.

The NOME concept, in essence, is simple: the occulting elements are carried as an auxiliary payload which are not deployed until the primary mission is complete (~3-6 months duration for Nexus). The Nexus/NOME spacecraft is then placed in a subsistence mode until NGST reaches its Earth-Sun L2 station, whereupon the active part of the NOME mission begins.

Nexus subsystems need to be enhanced to allow controlled occultations. The proposed changes entail no structural modifications that would otherwise interfere with the prime mission, and requires only modest subsystem hardware alterations. Hardware changes to NGST were not needed and software enhancement appears to be a manageable component of NOME costs.

2. Mission Design Overview

Before describing the modifications needed to the Nexus spacecraft, it is useful to briefly summarize the elementary aspects that define occulter constraints and how they aid in studying faint objects at very small angular distances away from bright astronomical sources. No occulter missions have yet flown, however the technologies required to enable their use have matured in the past 40 years. Figure 1 shows the basic arrangement of the important elements of a "free flying" occulter-telescope space mission.

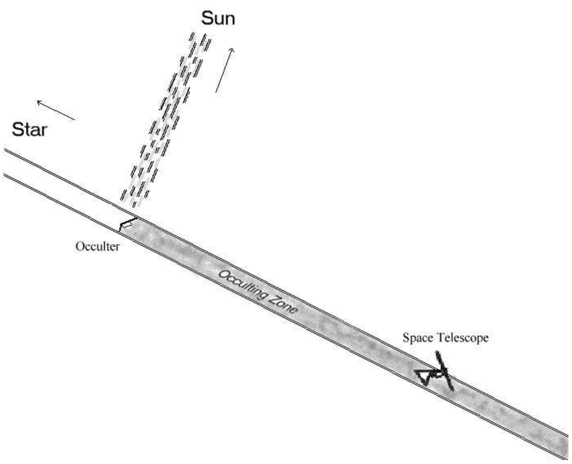

Fig 1: Main elements of an occulter space mission are shown above. The occulter is aligned along the line of sight between telescope and target star, and flies in formation with the telescope. Target selection is constrained to minimize sunlight scattered from the occulter toward the telescope.

An occulter mission employs separate telescope and occulter spacecraft which are positioned far enough away from massive gravitational bodies (such as the Earth) that an occulter spacecraft can maintain a "stationary" alignment between a telescope and a target star. When appropriately positioned, the occulter spacecraft blocks bright starlight from reaching the focal plane, but allows light from faint nearby sources to be relatively undiminished in intensity. For this to work, the occulter must have an occulting "screen" size larger than the telescope aperture. In order not to block light from the sought-for faint bodies around the stars, the separation between occulter and telescope must be great (typically thousands to tens of thousands of kilometres), depending upon the size of the telescope aperture, the occulter's screen dimensions, and the observing wavelength. Diffraction of the starlight around the occulting screen into the telescope aperture plays an important role in determining the efficacy of the technique.

While on station between target and telescope, the occulter must maintain formation alignment over the course of science observations. The occulting craft must be able to compensate for the drift across the target-telescope line of sight (TTLOS) caused by differential gravitational and solar radiation pressure induced accelerations between the telescope and occulter. In addition, the occulter must be able to compensate for the torque from solar radiation pressure caused by non-alignment of center of pressure and center of mass with the sun.

Once observation of a given target (star) is completed, the occulter is moved to a different target. Because the target-to-target distances are very large, high-efficiency (specific impulse) thrusters are required, otherwise propellant would be exhausted after survey of a relatively small number of targets. Solar electric propulsion is typically discussed as the propulsion method of choice. Since inter-target transit time can take many days, the telescope is free to observe targets that do not require the use of the transiting occulter.

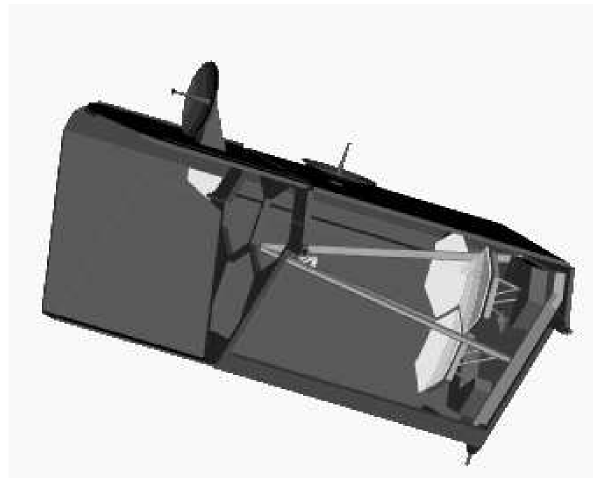

Fig 2 Interior/exterior cutaway diagram of an early version of the Nexus spacecraft [2] which the NOME concept study used as a test bed. The sunshield, where most NOME components are mounted, is on top where both Nexus and Redeye HGAs (conceived before the change to an L2 mission) are visible. Approximate sunshield dimensions are 3 x 6 metres.

3. Occulting Screen

We assume the following minimum performance requirements for NOME:

1) Five (5) astronomical magnitudes (100x) of starlight suppression in the I-band,
2) Apparent occulter semi-diameter < 1-arcsecond,
3) Uninterrupted exposure times up to 1000 seconds,
4) One-year science mission.

Given these requirements, a screen with a 10-metre minor-axis dimension is needed which can travel around NGST at distances from 1000 to 2000 km.

To minimize added payload mass, severe restrictions are imposed on performance and composition. The NOME screen design does not reflect a common heritage with previous free-flying occulter screens [3] which assumed heavier, thick MLI construction. Thick screens are not strictly necessary and many performance characteristics are retained with a thinner multi-screenlet design.

3.1 The Screen: Configuration

During occultations, NOME would be placed in an attitude such that the Nexus optical telescope assembly (q.v. Fig. 2) is on the shadowed side of the occulter screen obliquely facing NGST. Minimizing illuminated structures within view of the telescope is critical. Various screen configurations are possible, however we adopt a hybrid planar/cupped layout with piecewise overlapping screenlets (q.v. Fig. 3) where the screen self-shades and shadows all structures on the side facing NGST (this differs from occulter configurations such as those discussed in [3]).

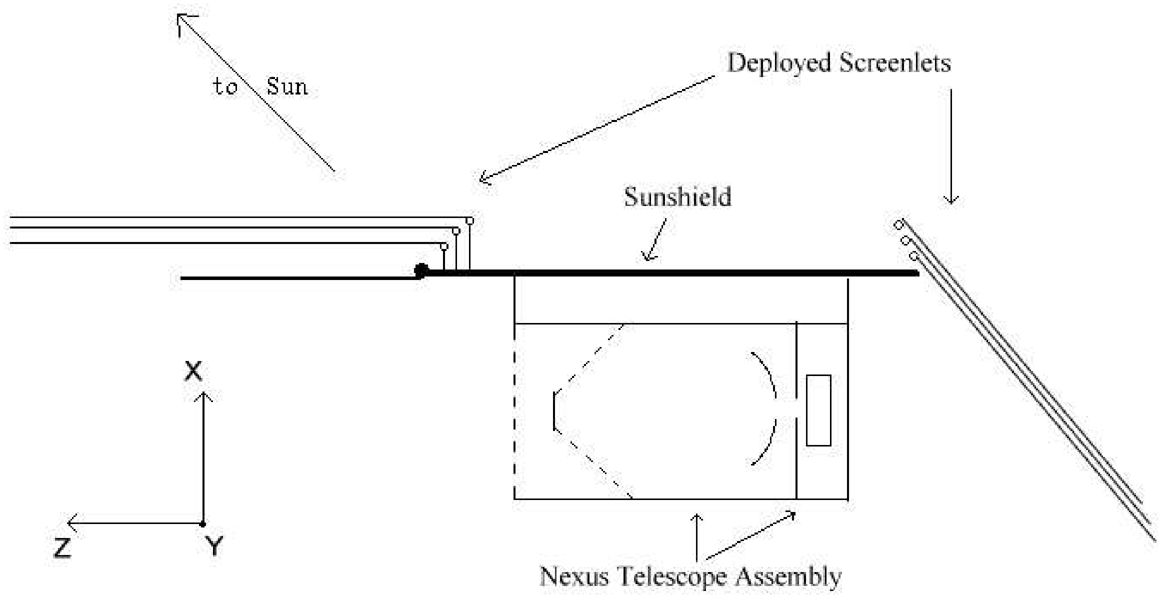

Fig 3 The general configuration of NOME's +/- Z-directed screenlets and screenlet canisters is shown superposed on this side-view/cross-section through the Nexus spacecraft. Screenlets also project in the Y-directions (into and out of the page), but some are not shown, nor are their screenlet canisters. The overlapping screenlets form a continuous occulting screen that blocks starlight and shades the spacecraft underside (negative-X) from sunlight. In this observing configuration, NGST is toward the lower left and in the plane of the page. The spacing between screenlets is exaggerated for clarity.

A lightweight, self-shaded screen can be used at optical wavelengths, but precludes science observations beyond $\lambda \sim 2$ µm due to thermal emission from the screen. The Sun-NOME-NGST angle, NOME's tilt angle, and its orientation are major factors in determining the required ratio of the lengths of the short- to long-axis (also, q.v. Section 5.2) of the rectangular occulting screen.

\`Planar', \`Cupped', and Aperture Door Emplacement Options

We chose a screen deployed "planar" parallel with the sunshield and cupped around one side of the spacecraft to shield it from solar exposure. "Cupping" allows:

- less screen material than in the "planar" configuration,
- reduced force from solar radiation pressure on NOME,
- greater tilt range with respect to the sun.

If the degree of screen cupping is adjustable, the force from solar radiation pressure can be varied for a given apparent size of the occulter as viewed from the telescope, and therefore allow control of cross-TTLOS accelerations. The drawback with variable cupping is that additional mechanisms are required.

Screenlets may also be mounted on the Nexus aperture door. One possibility has two screenlets on the door, with the door used as an element in the occulting screen structure.

Baseline Configuration & Design

A coordinate system is useful to visualize configuration and deployment of the screen with respect to Nexus. The Z-axis of the Nexus/NOME spacecraft is the optical axis of the Nexus payload. The X-axis points perpendicular to the sunshield in the sunward direction. The Y-axis is defined as in a conventional right-handed Cartesian coordinate frame.

To create an occulting screen, a nine-segment screen is employed in a 3x3 overlapping array, with eight segments composed of unfurlable multi-layer mylar-aluminium insulation surrounding the rigid central sunshield (q.v. Fig. 4). For launch packaging, the eight segments, called *screenlets*, are stowed in rolled *canisters* mounted on the +X side of the Nexus sunshield. The sunshield is assumed to be 3 x 6 metres [4] in accordance with early Nexus/REDEYE configurations (Redeye was an Earth Observing mission for which hopes to combine two missions into one spacecraft were subsequently abandoned).

Screenlet Deployment

Two short-spindled screenlets unroll in the + and -Z directions, defining the length of the occulting screen. Four long-spindled screenlet canisters swivel 180-degrees out into the + and -Z directions (imagine unfolding your doubled arm by rotation at the elbow), one from each corner of the sunshield. These four canisters, along with two unarticulated ones running the length of the sunshield on each +/-Y side, unroll their screenlets into the + and -Y directions to provide the remaining occulting screen width.

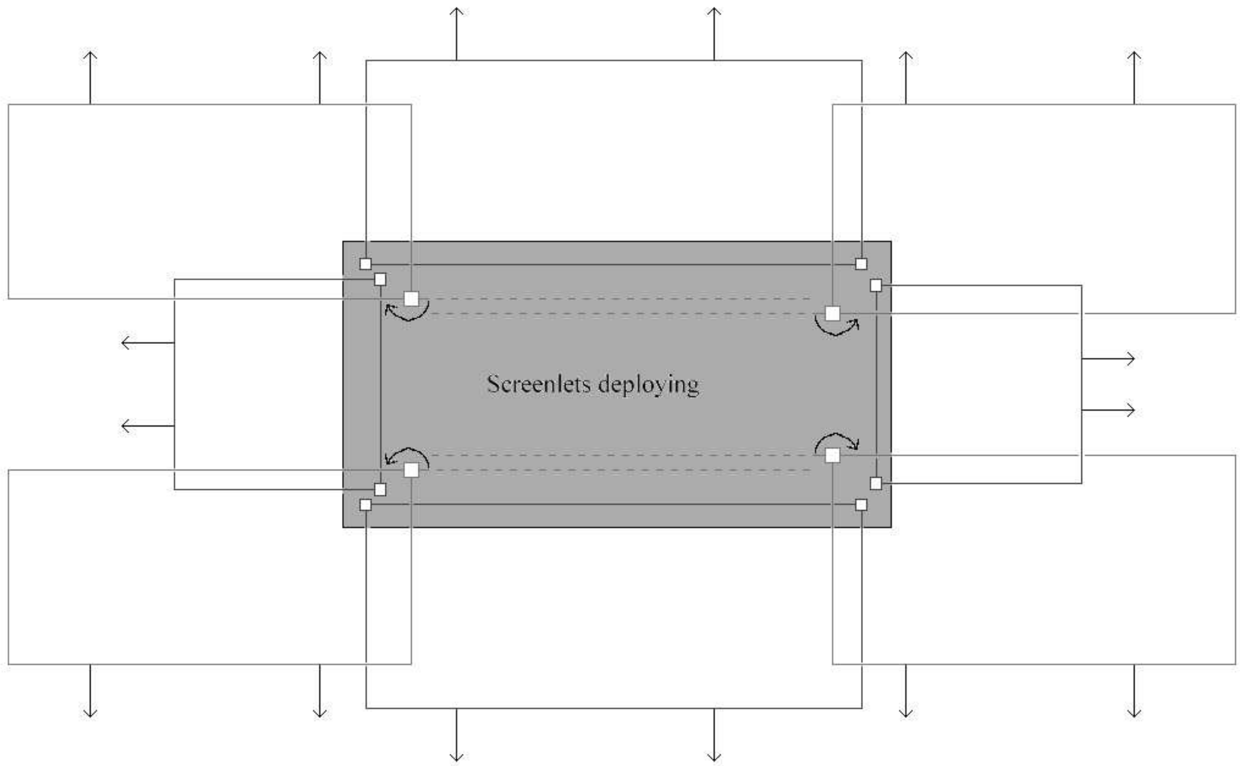

Fig 4: The diagram shows how the screenlets deploy and overlap to form the larger occulting screen with the NOME/Nexus sunshield (shaded rectangle). The hatched arms show the stowed position of the four corner screenlets. Note how screenlets overlap to yield a "continuous rectangular 14m x 10m screen.

The three unfurled screenlets at the -Z end of the sunshield tip in the -X direction at an angle from the Y-Z plane to produce the "cupping". Figure 3 shows the screens in the cupped configuration. Figure 4 is a schematic of the screenlets during deployment as viewed looking back in the –Z direction on the spacecraft.

The result is a 14.25-metre long, 10-metre wide semi-cupped occulting screen formed from the overlapping screenlets. Space (25 cm) is allowed between each canister as well as between the canisters and sunshield edge (12 cm). The area in the middle of the sunshield not occupied by screen structures (1.5 x 5 metres) is sufficient for other subsystems, such as HGA, solar array, and ion propulsion unit. Special attention during construction would require robust engineering solutions to minimize light leakage around these separate segments (q.v., Section 3.3).

3.2 The Screen: Composition

Mylar is commercially available as thin as 2.5 μm. We adopt a 3-layer (or *sheets*) construction within each screenlet and allow ~ 20% overlap between adjacent screenlets, yielding a total of ~ 450 m^2 of Mylar [5] (q.v. Fig. 5, and Table 2 for mass estimates for this and subsequent screen discussion).

Optical Densification

The transparent Mylar needs a coating to block starlight and prevent sunlight from scattering through the screen toward the telescope. Assuming an extinction coefficient of k = 7 - 10 between λ = 0.6 - 0.9 μm (q.v. Eq. 1) for vapor-deposited aluminum, with attenuation factors of 1000 (τ ~ 7 optical depths) per layer, the required thickness is about d = 0.1 μm [6,7]. We assume d = 0.2 μm to allow for nonuniformities in the coating process plus binding polymers.

$$d = \frac{(\tau \cdot \lambda)}{(2\pi \cdot k)} \qquad (1)$$

All 3 layers combine to produce a light attenuation factor of 10^9, well in excess of the required 10^2 - 10^3, providing redundancy in case of damage to one or even two layers.

Aluminum has a very high α/ε ratio and therefore a high equilibrium temperature, making potential melting of the Mylar substrate a concern. However, aluminum paint has $\alpha/\varepsilon \sim 1$, and may be used if it does not degrade over the mission life. The aluminum paint could be placed on the "backside" (away from the sun) of the Mylar to allow the Mylar itself (higher emissivity) to dissipate heat away from the screen. S-13GLO [8], with low α/ε, white paint, or Indium-Tin-Oxide coating of the sunward side could be used to protect the sunward side of the Mylar. Other factors have an effect on choice of the ordering of layers (q.v. Section 3.4).

Mylar is susceptible to erosion from atomic oxygen, so time spent by Nexus/NOME in low-earth orbit should be minimized. The effect of solar wind, cosmic rays, and UV on the thin layers needs further characterization to confirm materials selection. Further study is needed to quantify how this design is constrained.

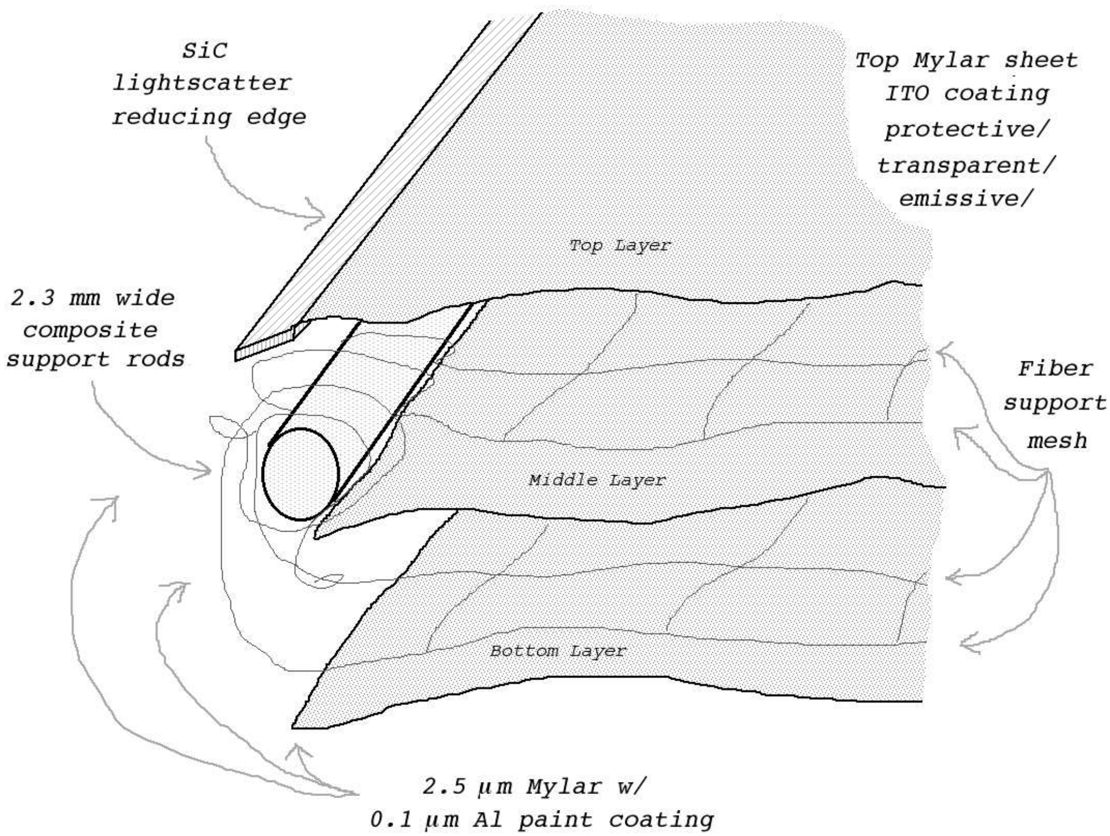

Fig 5: Conceptual cross-section of the edge of one screenlet showing the screenlet layers, fibre mesh support, deployment rods, and sharp light scatter-reduction edge. The rod and scatter minimization edge are not drawn to scale.

Screenlet Support Rods & Deployment Motors

The occulting screenlets must be flexible to allow unrolling from the spindles. Composite rods formed of polysulfone, S-glass, and graphite, having a lineal mass density of 7.4 g/m and diameter of 2.3 mm, run the perimeter of each screenlet [9] to provide rigidity. For 8 screenlets, ~ 115 metres of rod is required.

Two motors are allocated for each screenlet spindle, plus 2 more for each corner screenlet deployment arm. One motor should be sufficient, however a second is added for redundancy.

Screen Support--Load Alleviation

To prevent loads from being placed on the aluminized Mylar sheets by the support rods, a wide-spaced fibre mesh connects the screen support rods within each screenlet, with the mesh sandwiched between each pair of layers.

3.3 Scattered Sunlight

Because of the screen structure's flexibleness, and the piece-meal packaging for launch stowage, attention must be given to scattered sunlight leaking from the sunward- to the telescopeward-side of the screen in the deployed configuration, particularly from two concerns:

- the overlap regions between the screenlets,
- from the illuminated edges of the occulting screen.

One path for light leakage is sunlight bouncing between overlapping screenlets to the telescope-ward side of the screen. Several techniques may be employed to minimize this. One approach is to apply a dark coating in the overlap areas reducing the amount of sunlight reflecting through to the telescopeward side of the screen. Another way to close the gaps between screens is to include a thin-filament lanyard system connecting adjacent screenlets that is tensioned after unfurling the screenlets. One possible way to augment closure is to place small electromagnet coil couple pairs on adjacent screenlets spread out along overlapping edges in the support mesh. Running a current through the circuit activates the coils and pulls the screenlets tightly together, reducing the gaps. A Velcro-like addition near each coil could latch the closure, avoiding continuous current flow.

Scattered sunlight from the illuminated screen edge has been considered [10] and appears manageable. If the screen edge is very sharp, the illuminated area visible to NGST is minimized. Silicon-carbide blades could be used along the inflexible outer screenlet edges. For the edges curled on the canisters, flexible metallic strips would be used instead.

3.4 Screen Integrity

Screen integrity can be compromised from several sources over the mission life:

- meteoroid damage,
- photonic and particle radiation damage,
- unforeseen rips, tears, or delamination,
- improper or incomplete deployment.

Each phenomenon in turn can impact science utility based upon two concerns:

- unblocked starlight,
- scattered sunlight.

Allowable Screen Damage

Limits on screen damage are derived from science requirements. Extrasolar planets 20-24 astronomical magnitudes fainter than their primaries are the prime targets for NOME science goals. As a result, the faintest target stars for extrasolar planet searches must be in the range m_V=5-9 assuming a faint object detection limit of m_V~29 and S/N ~ 5[11].

The integrated angular area of screen perforations near the TTLOS must not exceed a fraction of the angular area of the Airy disk as viewed from the telescope. For the Nexus/NOME sunshield, no such perforations should arise and the Airy disk is well blocked. By specifying 5 magnitudes of starlight suppression in the design, the total perforated area on the screen must be less than ~ 1%. (~ 1 m^2).

Of greater concern is sunlight reflecting toward the telescope from torn, punctured, or ripped material flaps. A 7 cm^2 diffusely reflecting patch uniformly scattering sunlight appears as approximately a 14th magnitude object at 1500 km, which is comparable to the brightnesses of faint target stars after having been reduced in brightness by the occulting screen. Two factors make this zeroth-order limit unrealistically over-restrictive:

- patches are likely to be specular reflectors, not diffuse scatterers,
- most science targets will not be at the faint end of the target range.

Specular reflections are problematic if their direction is toward the telescope, but can be alleviated with small rotations of NOME if bright specular areas swamp initial target acquisition images. Any real surface is not purely specular and has a diffuse component. Assuming 10% diffuseness yields an allowed area of such patches to be ~ 10-times greater.

Since most intended NOME target stars are brighter than 7th magnitude, an additional factor of 10 or more in patch brightness may be tolerable. When combining increase factors from specular and target selection arguments, an illuminated patch area of ~ 0.1 m^2 should be acceptable. This estimate is roughly in accord with values arrived at from a different model [12].

Likely Damage

Actual damage that the occulting screen would incur depends upon when it is deployed relative to commencement of science activities since perforations accumulate linearly in time with the exposed cross-section. Two deployment time possibilities are:

- upon conclusion of nominal Nexus operations,
- sometime later, before NGST arrives on station.

If kept stowed until NGST arrival, meteoroid and radiation damage could be diminished. The downside of delayed deployment is the risk that nearly a decade of storage could see vacuum welding between rolled screen layers, embrittled coatings, or other deployment system failures.

Table 1: Expected Meteoroid Impacts on Screen

Impactor Size	Number of Hits (10 years)
1 mm	1
200 µm	100
30 µm	10,000
2 µm	100,000
0.5 µm	1,000,000

Exposure of the screenlets to the natural L2 environment is not without risk. The effects of L2 meteoroid damage on membranes of similar composition (although significantly thicker) to NOME screenlets has been explored for NGST. The thin NOME screenlet membranes allow smaller and higher numbers of meteoroids to penetrate than does the NGST sunshield. Table 1 summarizes the order of magnitude number of impacts on the NOME screen likely to cause perforations over a 10-year period (adapted from [13]). The approximate integrated perforation area is on the order of a few tenths of a square metre. Since only a small fraction of holes appear aligned from the telescope's view, the net viewable perforation area would likely be much less than the perforated area of each screenlet. A more sophisticated trade study is needed, including likely damage from grazing impacts, to determine the optimum deployment time.

Also important is the associated meteoroid damage caused by `petalling' and blowout of secondary and tertiary layers. Damage to films and multiple layers for the thickness proposed for the NOME screenlets needs further study. However, there is no clear indication that meteoroid damage will prevent a viable mission using a NOME-type occulter.

3.5 Screen Mass Summary

Table 2 contains a summary of screen components and mass budget. While there are many components listed, it is remarkable to note that ~ 14 kg is sufficient for this triple-layer, multi-screenlet piggyback mission.

Table 2: NOME Occulting Screen Mass Budget

Screen Component	Type/Quantity	Element Mass
Mylar	3 layers, 2.5 μm, 150 m^2	1.8 kg
Aluminium coating	7 optical depths one side, each layer	0.3 kg
Composite support rods	2.3 mm diameter, 115 m	0.9 kg
Screen canister spindles	38 m hollow 1 cm Al tube (0.5 mm)	0.2 kg
Reel guides	~	0.5 kg
Spindle mounts & tie-downs	~	1 kg
Mylar grommets	~ 56	0.75 kg
Fibre support mesh	0.1 mm diameter	0.5 kg
Motors + mounts	e.g., Emoteq Q01700 (x 24)	2 kg
Wiring	~	1.4 kg
Protective cover & mounts	~	0.6 kg
Light suppression canister covers	8	0.2 kg
Anti-reflective & protective coatings	ITO & various paints	0.4 kg
Light scatter suppressing edge	10 μm thick SiC and Al strips	0.2 kg
Screenlet closure coils/lanyard/motors	~	2.0 kg
Control electronics	~	1 kg

4. Propulsion System

To function as more than a serendipitous occulter, NOME must move around the telescope. The Geissen RIT-10 radio frequency xenon ion thruster [14] is baselined for the task. Nominally operating at 15 mN and consuming ~ 600 W of power, the engine is de-rated to 10 mN for NOME, drawing 400 W, buying several advantages:

- less power control/conversion per unit mass required,
- increased thruster lifetime.

The power control unit (PCU) mass scales approximately as the operating power, so instead of 12 kg, the de-rated RIT-10 would require only ~ 8 kg for power control & conversion. The lower propellant mass-flow rates result in longer engine component lifetimes [15].

Lightweight plume shields prevent direct ionic bombardment of sensitive spacecraft components. Spacecraft charging from engine operation must be carefully controlled, but is not considered further here. Depending upon Nexus design, a pop-up propulsion power-augmentation solar array could be integrated in with part of the primary Nexus solar array, or could be left separate. Deployment of the augmentation array helps optimize power for transits, which requires the spacecraft thrust vector to lie approximately in the X-Z plane. Deploying the solar array away from the sunshield at an appropriate angle allows optimum power generation. Table 3 provides a summary of the subsystem mass budget.

Table 3: NOME Primary Propulsion Mass Budget

Component	Mass
RIT-10	2 kg
PCU	8 kg
Supercritical Xe tankage	2 kg
Pressurization & feed	2 kg
Xenon propellant	16 kg
Plume shield, mounts, & wiring	1 kg

5. Attitude/Translation Control System

Controlled occultations require translations with respect to the telescope's inertial frame [16]. Since this differs from the requirement levied by simple attitude control, new features are needed on NOME/Nexus. Full attitude and translation control system (ATCS) capabilities use additional ACS/ATCS thruster clusters, and modifying them to include a parallel set of pinhole-sized ATCS exit nozzles. Two distinct station keeping and formation flying functions of the upgraded ATCS are identifiable:

- station keeping within L2,
- formation control with respect to NGST amidst science observations.

5.1 L2 Station Keeping

An L2 orbit is unstable with periodic velocity adjustments required to keep spacecraft from drifting out of the region. Lubow [17] has shown that burns of magnitude 25 cm/s every 3 weeks are sufficient to maintain the craft in the L2 region for the likely NGST orbit. The resultant $\Delta V \sim 39$ m/s required for a 9 year lifetime could be done either with primary propulsion or the ATCS system.

If the ATCS were tasked for these burns, the extra propellant required would be 1.75% (~ 16kg) of the total spacecraft mass. If instead, the RIT-10 is used for these station-keeping activities, a substantial mass savings is achieved with the RIT-10 operating less than half-a-day every 3 weeks. The required propellant would be 1.3 kg for an assumed 900 kg Nexus spacecraft. A likely minimum of 1 doppler and radiometric tracking session per week from ground spacecraft tracking networks will be required to quantify the required trajectory correction maneuvers.

5.2 NGST-NOME Formation Control

Several forces act to cause NOME and NGST to inertially drift apart. In [16] these are discussed in terms of their effect upon operations and science with the results applied here. For NOME's operating regime, relative accelerations due to *differential gravitation* (DG) become less significant than relative accelerations due to *differential solar radiation pressure* (DSRP). Radiation pressure on NGST must be factored in for determining drift in the Target-Telescope pseudo-inertial frame (not discussed in [16]). For NOME, DG ~ 10^{-7} m/s^2, and DSRP ~ 10^{-6} m/s^2. Since NOME operations with respect to NGST occur close to the `quadrature ring' (where the occulter-telescope line is perpendicular to the sun-telescope line), the DSRP will largely act to push NGST and NOME out of alignment across the TTLOS.

The proposed 14.25-metre semi-cupped screen is compatible with NGST from a formation flying perspective [18]. The likely areas, masses, and compositions of the NGST sunshield were used as input parameters to model the effect of DSRP. With a 45-degree tilt of NOME to the NGST line of sight, an approximate 10-metre square cross-section is presented to the sun as well as the telescope. A DSRP mismatch can arise if more than one of the following obtain:

- the NGST mass-to-sunshield area is lower than projected,
- the ratio of reflectances of NOME occulting screen to NGST sunshield is low,
- the mass of Nexus is very high.

Options for accommodating these possibilities include:

- increasing the occulting screen width (undesirable for operations),
- enable articulation of the trailing 3 screenlets up or down into the X-direction,
- reduced margins for canister placement on the sunshield (i.e., longer screens),
- altering canister placement design to allow "canister overlap" (i.e., longer screens),
- increasing Nexus sunshield length.

The last option may not be a major problem because for each additional 1 cm of Nexus sunshield length, an increase in the NOME occulter length by 3 cm is realized.

Arguments can be made [16] that point-spread function stability should be kept to the 1% level. This is crudely equivalent to maintaining occulter position to ~ 1% of its own dimensions. Therefore, a maximum 10 cm drift over a 1000-second science exposure (project goal) implies a maximum tolerable differential acceleration of ~ 2×10^{-7} m/s^2 (q.v. "Ballistic Smear Reduction" later in this section). DSRP drift will be a function of the differing area-to-mass ratios of the two spacecraft as well as the reflectances of the NGST sunshield and the NOME occulting screen. The differential acceleration (Δa) between the telescope (*T*) and occulter (*O*) will be on the order of

$$\Delta a \approx P_S \cdot \left[\frac{A_T}{m_T}(1+q_T) - \frac{A_O}{m_O}(1+q_O) \right] \qquad (2)^*$$

where the areas A_i are those projected with respect to the sun, m_i are spacecraft masses, q_i are the shield/screen reflectivities, and P_s is the solar radiation pressure.

With non-optimal choices of *A/m* (inverse ballistic coefficient) or *q*, formation flying might be needed during observations in order to achieve 1000-second uninterrupted science integrations. Several choices for formation flying come to mind, each with a significant possible consequence: *cold gas* thrusters, ACS/ATCS (*hydrazine*) thrusters, *solar electric* propulsion, A/m matching, and *ballistic smear reduction*.

Cold Gas and Hydrazine Options

Cold gas thrust is ruled out due to the large required system mass. In order to counter the acceleration during all science integration time for a 1-year mission, approximately 15 kg of N_2, plus 54 kg of tankage are required.

Only ~ 1 µg/s of hydrazine monopropellant is needed to maintain formation alignment. However, hydrazine exhaust has a flame temperature of ~ 1100 C and the glow could contaminate science exposures. This is posed as a problem for further investigation with several possible solutions (q.v., for example, Section 5.3).

Solar Electric Option

Small 1-mN solar electric thrusters can maintain TTLOS alignment. A wide variety of thrusters are available in this class, but a suitable choice, as with hydrazine thrusters, may depend upon the glow characteristics of the exhaust products. With higher specific impulse than chemical propulsion, the cloud dissipates faster and the required mass flow rates are smaller. Electron-ion recombination in the exhaust primarily produces discrete emission lines and not a continuum [19], so spectral filtering at the telescope could reduce science exposure contamination. Interaction between neutral Xe leaking around the ATCS thrusters and plasma exhaust may be another glow source along with charge backflow bombardment. Accurate characterization and resolution of these problems is beyond our present scope.

Precision Active A/m Matching

The yardstick NGST design [20] has a ~ 270 m^2 sunshield area and an observatory mass of ~ 2500 kg. Depending upon the target observed, the projected area with respect to the sun can fluctuate between 90 and 100% of the full shield size. Both the TRW and GSFC-yardstick preliminary NGST models have *A*, *m*, and *q* values likely to allow NOME and NGST to match DSRP acceleration to within 10%. NOME's design must not rely on this close match, but be adaptable enough to operate whatever the likely values. NGST's configuration could change between the design of NOME and the construction of NGST, so NOME design should assume worst-case mismatch with NGST.

One way to get accelerations of occulter and telescope to more closely match would be to make the trailing 3 screenlets articulatable (6 extra motors + mounts on the screenlets) such that they can be moved to increase or decrease the area presented to the sun. We refer to this technique as *active A/m matching*. Matching may only need to be performed during the initial rendezvous calibration observations with NGST, as *q* of NGST should be well characterized and not change significantly before most of the science targets are observed.

Ballistic Smear Reduction

Instead of starting an observation with zero cross-target velocity at a centered-position with respect to the target, starting offset with a non-zero cross-field velocity allows twice the integration time for a given drift acceleration. For example, suppose the occulter is offset 5 cm in the direction of the drift but with a velocity of 0.4 mm/s toward the center. Instead of the two spacecraft drifting 10 cm in 500 seconds when starting from zero relative velocity in a centered configuration, it would decelerate 10 cm across the field coming to a halt after 500 seconds, and then drift back to the starting position 500 seconds later. Higher accelerations become acceptable for the same science integration times by using this *ballistic smear reduction* (BSR) technique.

Table 4: NOME ATCS Additions Mass Budget

Component	Type/Use	Mass
Active A/m matching motors & mounts	6	0.5 kg
Additional Hydrazine tankage	~	0.2 kg
ATCS feed lines & valves	~	1 kg
ATCS Thruster cluster blocks (x8)	10 mN thrusters	2 kg
Inter-science station keeping propellant (hydrazine)	Recenter & velocity null, 3500 firings	1.5 kg
L2 station keeping propellant (Xe)	I_{sp}=3400, 75% efficiency, 1.3% s/c mass	2 kg
Additional Xe tankage	~	0.2 kg
Target acquisition propellant	Initial TTLOS alignment	0.2 kg

BSR requires precise placement of NOME across the TTLOS to the sub-5 cm level, and to gauge relative velocity to a suitably small amount. It is relevant to consider whether this is possible from a control standpoint. The technique used for control of the occulter with respect to the TTLOS is outlined in [16]. At 0.6 μm wavelength, the half-width of a 6-metre NGST PSF is about 24 milliarcseconds. At 1500 km, this corresponds to ~ 18 cm.

Although not in itself meeting the 10-cm control level and exceeding the desired BSR control level, the problem is overcome by centroiding the position of NOME to achieve greater accuracy than the PSF width. Small beacons or lights [3,16] may be placed on the spacecraft or screen to assist with accurate position determination. These beacons are turned on for target acquisition and alignment and between science exposures to measure the drift and drift rates. Formation flying translations are then used to correct for the drift. Beacon design needs to consider NGST imager pixel scale and beacon signal-to-noise ratio at the focal plane to ensure NOME can be guided to a suitable level, but is not considered further here. An additional complication arises if NGST is diffraction limited only at 1.5 μm, where 18 cm resolution would not likely be achieved.

5.3 ATCS Spacecraft Modifications

Here we assume that BSR and *A/m* & *q* matching will allow accelerations to be matched within ~ 10-20%. A parallel ATCS system to perform the required translation maneuvers is used between science integrations. To arrive at an estimate of required propellant, the following science mission activities are assumed:

- 20 distinct targets each with 2 separate visits,
- ~ 2 days time on TTLOS for each visit,
- The maximum allowed 10 cm drift and drift velocity occurs between science exposures,
- TTLOS restored between exposures in < 1000 seconds using hydrazine ACS burns,
- Inefficient oppositely directed thrust-couples are not required [3].

Thrust-couples are a design option which can be used to mitigate glow from thruster firings that was posed in Section 5.2. This technique would employ ATCS thruster clusters placed on a deployable boom projecting out from the Nexus/NOME sunshield in the +Z direction. In such a configuration, thruster plumes would be partially hidden from NGST's direct view behind the occulting screen.

To counter torque produced by solar radiation pressure, momentum wheels keep NOME stable during observations with momentum dumps between exposures as necessary. No new requirements are envisioned for momentum wheel performance. Table 4 gives a breakdown of the required subsystem masses.

6. Power System Modifications

Extra power is required for primary propulsion. Assuming 2.75% degradation/year for GaAs [21] over 9 years, cells initially 18% efficient at converting solar energy into electricity have 14.3% efficiency at end-of-life. For the L2 regime, 2.1 m^2 of cells are required to provide 400 W at end of life (q.v. Fig. 6).

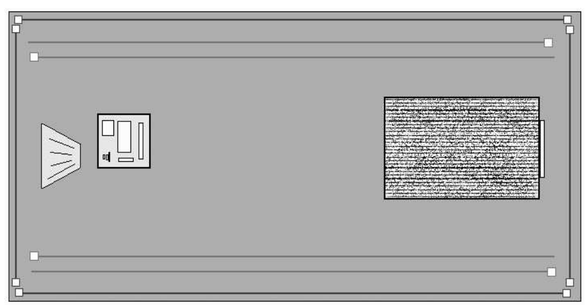

Fig 6: One possible placement of screenlet canisters, ion engine, and undeployed solar array on the back of the Nexus sunshield. The ion thruster points up out of the plane of the page to the left with the thrust vector pointing through the center of mass. A plume shield protects the screen and other spacecraft elements from contamination and ion-bombardment damage. A high fill-factor GaAs solar array is shown in its undeployed position. The +Z axis is to the left, and the +X axis points out of the page.

Table 5: NOME Power System Additions Mass Budget

Component	Mass
GaAs cells	16 kg
Wiring	2 kg
Mounting & Deploy mechanism	2 kg

An additional 2 kg of wiring and 2 kg of attachments and deployment mechanisms are assumed for an array articulating upward away from the bus to maximize power generation during nominal inter-target transits. If the spacecraft operates near the quadrature ring, then a single solar array deployment motion should suffice. Table 5 provides the subsystem mass estimate.

7. Lifetime Issues

We have made a pessimistic assumption that NOME will need to be placed in a subsistence state for roughly ten years until NGST's launch and arrival on station. Requiring NOME to live nearly a decade beyond its originally conceived lifetime of under 1-year is no small task. A number of Nexus' primary spacecraft subsystems may require enhanced lifetime or redundant components. Since Nexus spacecraft design was never finalized, it is difficult to identify which components require upgrading. Nevertheless, an attempt is made to budget for this.

Since Nexus must have a low probability of a crippling failure during its prime mission, many components would have had redundancy and high-grade parts. Some critical systems having lifetime issues that are essential to NOME are:

- onboard computer & electronics,
- gyros & momentum wheels,
- batteries & power distribution,
- pressurant for the (presumed) hydrazine propellant,
- optical navigation camera (ONC).

8. Operations

A long hibernation period is required between the end of nominal Nexus operations and arrival of NGST. L2 station keeping maneuvers were addressed in Section 5.2. In allowing for a long NOME hibernation period, we assume that NOME operations need not begin at the onset of NGST operations, but can be delayed until potentially higher priority NGST mission objectives are well under way or completed.

A simplified target observation rate model indicates that NOME has a limit of 40-50 targets per year with no other operating constraints. A more conservative estimate of 10-20 targets is arrived at by allowing for:

- at least two visits to each target,
- non-ideal convergence to the TTLOS,
- delays for synchronization with NGST's schedule.

The general operations strategy outlined in [16,22] is largely compatible with NOME. Issues unique to NOME are:

- the dynamics of the NOME occulting screen,
- lack of a shade for the occulting screen.

The screen may flex significantly when performing attitude maneuvers in and around the TTLOS or near turnover between targets. Some settling time would be required to allow screen vibrations induced by ATCS thruster to be damped out between science exposures.

NOME does not rely on a separate shade to shield the occulting screen from light. Instead, spacecraft operations must ensure that NOME is placed in an attitude where all structures are either shielded from view by the occulting screen or in its shadow. This allows some freedom for NOME to roll about the TTLOS (unlike shades defined in [3]) and pitch in the Sun-NOME-Telescope plane. The pitch freedom allows adjustments for DSRPA as well as the apparent size of the long axis of NOME as seen from NGST.

Automated mission operations would include software developed to allow a closed-loop control scheme similar to that outlined in [16]. A low-gain RF communication link between spacecraft has power requirements estimated at about 1 W. The control method uses the NGST science instruments to locate the occulter within or near the target star's field of view. The derived relative position is used by the occulter as an error signal for commanding a translation closer to the TTLOS, with iteration until the occulter is appropriately aligned. Once aligned, the drift rate is monitored until relative position, velocity and accelerations are well enough determined and corrected to allow science observations to commence.

For navigating NOME to target, we consider only a wide-field ONC on NOME having the responsibility of imaging the area around NGST. The NOME ONC images are then used by NOME to determine the relative direction between the vehicles and yield the amount by which NOME must move before beginning the target acquisition sequence (techniques which may be employed are discussed in [16] and might adopt strategies discussed in [23, 24]). The estimated impact on the vehicle mass budget is provided in Table 6.

Table 6: Navigation Components

Item	Mass
Beacons	0.25 kg
ONC upgrade	0.5 kg
Wiring	0.25 kg

9. Summary

With available Nexus mass and projected configuration, one arrives at promising estimates for the NOME impact on Nexus. The subsystems considered here, along with the proposed screen, add as little as 75 kg to a 900 kg vehicle. Significant margin may well be needed for component upgrades to meet lifetime increases required for mothballing NOME until NGST arrival. Table 7 summarizes the results of previous sections.

Table 7: NOME Mass Budget Summary

Subsystem	Mass
Screen	14 kg
Propulsion	31 kg
ATCS	8 kg
Power	20 kg
Navigation	1 kg
Nexus component redundancy/upgrades	20 kg
Margin (20%)	19 kg

Operations and design of NOME do not appear to be incompatible with Nexus goals, nor have unsolvable problems been posed. A screen design appears possible, although detailed evaluation of meteoroid and radiation effects on screen components are needed. The add-on mission that NOME represents could have contributed significant and new science at relatively small cost. Other L2 missions could well have configurations compatible with an occultation mission extension given that Nexus was the first mission examined for compatibility.

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* Subscript on 2nd term's numerator in equation 2 has been corrected from the erroneous published version.