Planning and Scheduling External Occulter Space Missions

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Abstract

This paper introduces the reader to a new class of space science missions employing a telescope and one or more mobile external occulters. Issues important for proper science and mission planning are discussed in light of the inherent mission constraints. Recommendations for software to analyze and optimize mission efficiency and construct integrated long-range plans are provided.

Introduction

External occulter space missions are a class of space science astronomy missions whose primary purpose is to obtain imaging and spectroscopy of high-contrast, faint targets such as extra-solar planets. The general concept is implemented by deploying a starlight-suppressing screen far out in front of a telescope. The screen must be small enough to allow planets (which are less than an arcsecond away from their parent stars) to be distinguished from the star's glare, but larger than the telescope aperture. These two requirements imply a very great telescope-occulter separation to allow the exoplanets to be viewable beyond the screen edge. The great separation drives system placement into space and far from earth.

The concept has been described and refined extensively over the last 5 decades, with a wide range of occulter sizes, shapes, telescope-occulter separations, and mission designs (Spitzer 1962, Woodcock 1974, Marchal 1985, Copi and Starkman 2000, Schultz et.al. 1999, Cash 2005). Perhaps foremost, a *Discovery* mission proposal to fly an external occulter in concert with JWST was submitted to NASA in the spring of 2006 (Semeniuk 2006).

External occulter missions introduce a unique set of constraints on mission planning driven by the technology. Since a free-flying external occulter mission has never yet flown, we begin by introducing the reader to the general concept of an external occulter space mission and point out important constraints. Then, discussion will turn to the elements defining the planning and scheduling topology of likely external occulter missions.

External Occulters: Fundamental Mission Constraints

The fundamental constraints driving the design of proposed external occulter space missions are the same as those affecting other space science missions: science requirements, cost, launch vehicle constraints, space dynamics, orbital geometry, communications, power, and propulsion. Like any space science mission, they combine to limit the feasible possibilities and sculpt the appearance of mission designs.

The science requirements define the basic capability needed in external occulter missions. Here, we consider only extra-solar planet investigations. Extra-solar planets are intrinsically faint (6-12 or more powers of 10 times fainter than their host stars) and conventional telescopes have not been able to isolate them for spectroscopic study except for a very small class of such objects. In order to obtain adequate signal on exoplanets like those in our solar system, moderately large aperture telescopes (1-metre-plus) are required.

However this alone does not solve the high-contrast problem. With telescopes smaller than 20-30 metres, it is essentially impossible to resolve conventional exoplanets without extraordinary means to suppress the diffracted and scattered starlight. External occulters offer a way to achieve this without requiring near-perfect optics simply because the starlight is blocked prior to entering the telescope aperture, where its control would otherwise be a significant technological problem. This technique offers an alternative to more conventional architectures such as internal occulters (coronagraphs) and long-baseline interferometry (Beichman, Woolf, and Lindensmith 1999).

The required scale of the external occulter-telescope system drives the placement of the system into space (Figure 1). External occulter concepts for exoplanet studies on the moon and ground-space configurations have been discussed, but we will focus on systems placed far from the earth-moon system, but not so far as to

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introduce data downlink rate issues. Cost and launch vehicle limits further constrain the basic requirements for the telescope(s) required to perform the science mission and the size and packaging techniques for the occulter.

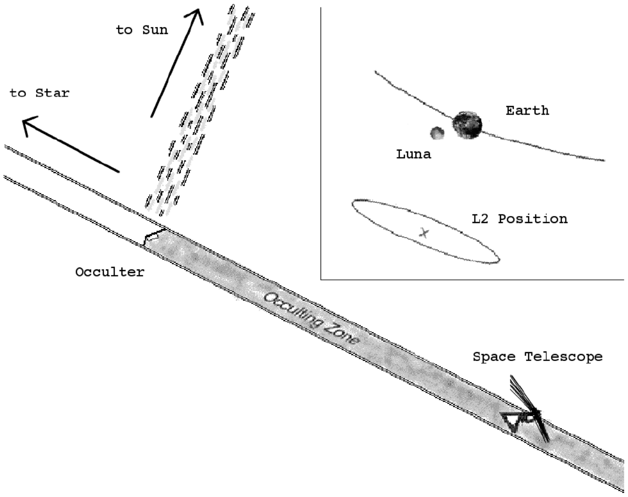

Figure 1: The general (not to scale) layout of the important components and aspects of an external occulter mission are portrayed in the above two panels. In the upper-right inset, the oval orbit shows a track relative to the earth-moon upon which the space telescope is likely to lie for near-term external occulter missions. The remainder of the cartoon shows a zoomed view on the orbit of the occulter in-line with a target star and the telescope (not to scale). The occulter casts a shadow of the star onto the telescope while remaining oriented to keep scattered sunlight to a minimum.

With a science requirement of telescope and occulter separated by tens of thousands of kilometers and a need to realign the two for each sequentially observed target widely separated on the sky, propulsion capability becomes a major factor defining the number of targets and mission duration. To move the occulting screen around the telescope and observe a large number of targets periodically in reasonable spans of time requires expenditure of a large fraction and quantity of propellant. To minimize propellant use, *solar-electric propulsion*-(SEP)-which then power-limits such a mission—may be employed. One way around the stressful power and propulsion requirements is to opt for multiple occulters. However, the mass-savings due to relaxed propulsion requirements is partially offset by greater launch and manufacturing costs.

Typical Occulter Mission Designs

Despite the tradeoffs involved, a number of reasonable occulter mission designs have been put forth. A few examples of external occulter missions will help illustrate the planning and scheduling issues:

- ASA+O (*Apodized-Square-Aperture* + *Occulter*)
- NWD (*New Worlds Discoverer*)

ASA+O (Jordan, et.al. 2004) was a concept for using simple, low-performance rectangular occulters in conjunction with specially shaped telescope apertures (square, unobstructed off-axis design) to achieve sufficient light suppression to allow a search for and study of terrestrial planets around the nearest stars. ASA+O employs at least two occulters launched in tandem with a 4-metre class space telescope. By using more than one occulter, the propellant demands on any single occulter are lowered, driving down each individual occulter's launch mass (Jordan, et.al. 2003).

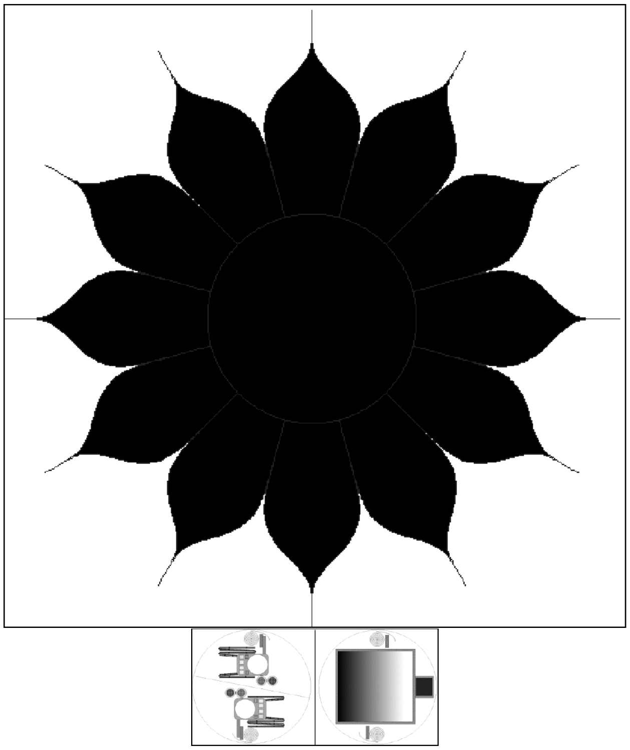

Figure 2: Two possible external occulter mission hardware sets are portrayed above. At top is one possible screen shape (shown in a deployed configuration) for an external occulter that might fly with JWST to search for earthlike planets around the nearest stars. At bottom are two fairing cross-sections (for a single launch vehicle) for two occulter spacecraft (left panel), and a 4-m diameter, square aperture telescope plus the two rolled rectangular screens (right fairing cross-section) for each occulter. The two diagrams are disproportionate in size to show approximate relative-scale for these two different architectures.

NWD (Cash 2006) is a proposed high-performance occulter that would fly with JWST (James Webb Space Telescope). A conceptual screen design similar to that proposed is shown in Figure 2. Figure 3 shows a similar, elongated screen that is a candidate for use in extended spectroscopic observations of extra-solar planets.

Although these screen designs span the range of starlight suppression performance, and the techniques for packaging differ, each has an expected mission profile similar enough to be encompassed by the discussion that follows. Figure 3 shows an advanced screen design that might be used for a follow-on mission specifically for characterizing atmospheres of objects found with earlier external occulter missions.

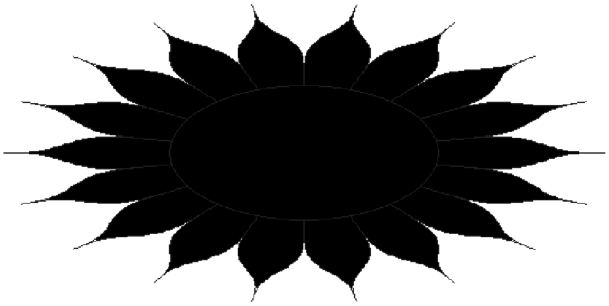

Figure 3: This advanced, elongated, starflower screen is designed to allow up to 4 months of continuous spectroscopic observations on ecliptic target stars. The screen may be as large as 100 metres across.

External Occulter Mission Planning Topology

Most external occulter missions are driven by technology requirements to suppress scattered sunlight, which places restrictions on spacecraft and occulting screen design. These requirements constrain the operating geometries between telescope, occulter and bodies such as the sun, earth, and moon. As a result, most occulter missions require the sun-telescope-occulter angle to lie within some limited range of 90-degrees. Few realistic external occulter concepts can have sun-telescope-occulter angles near 180-degrees because the telescope-ward side of the occulting screen cannot be shaded from the sun (an anti-solar avoidance zone), except with the use of a separate shading spacecraft—such as has been suggested by Woodcock. Additionally, there is an inherent telescope solar-avoidance zone to be obeyed.

The telescope-occulter range may also have limits, which—combined with the other restrictions—creates an annular shaped region known as the *quadrature ring* (QR) wherein the occulter must lie during target observations. The QR is not inertially fixed, but instead rotates about the ecliptic axis with a period commensurate with the telescope-occulter's solar orbit. Figure 4 conceptually shows the QR.

The QR defines the basic topology of scheduling—the occulter must move from one location to another within the QR, arriving at a given *target-telescope line-of-sight* (TTLOS) in time to perform the observations while the ring still intersects the TTLOS. Occulter system architectures, which allow large QR widths, are preferred as they allow more flexible scheduling.

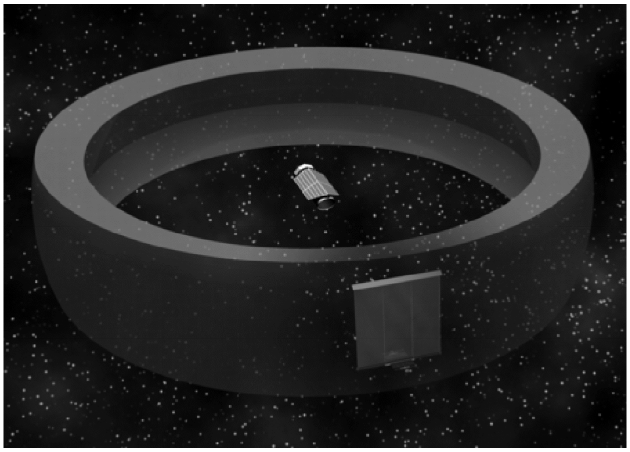

Figure 4: The QR of allowable operations is conceptually shown here (not to scale), courtesy of E. Rowles. The tire-shaped ring defines a region where the occulter could be placed to occult targets for the telescope. The sun is in the direction directly above.

Occulter missions conceived for the foreseeable future employ chemical or electric propulsion to transit between sequential TTLOSs. With such mission concepts, the occulter propels itself between targets while the telescope remains in a free-fall orbit, changing only its pointing. Because of the large distances the occulter must travel (thousands to tens of thousands of kilometers or more) and the science requirement that observations be in near-stellar-inertial reference frames, significant amounts of propellant and/or long transit times between sequential TTLOSs result.

Advanced mission planning for optimizing the number of *lines-of-sight* (LOS) visited is then very important. This requires some ability to plan what the best sequence of some set of targets which may have differing desired observing cadences based upon previous observing histories, stellar properties, and geometry (Brown 2006). Some targets will require only a single observation —which may be unknown in advance—while others will need two to four or more during the discovery phase of the mission, with the number depending upon what is discovered during each visit to the target.

Occulter Science Mission Phases

It is important to introduce the notions of differing mission phases. An occulter mission may have two or more distinct phases—*discovery* and *characterization*. Here, 'discovery' refers to a search for interesting objects, and 'characterization' means that any interesting objects are revisited for extended study. Discovery observations may require only days on target station, while characterization could last for many weeks. Any target may have both of these two phases, but a given target may have no characterization phase at all. The discovery phase will vary in length depending on the system properties determined during the discovery phase. Most systems may start out in the discovery phase of visitation. Discovery and characterization are thus interleaved, with most characterization occurring nearer to mission end.

Target-to-Target Cadence

For the occulter, there is also a different class of mission phases characterized by how the occulter spends its time—either in transit or on-target. There are significant periods of time where the occulter cannot be used for science observations (inter-target transits). During these periods, other science programs may execute onboard the telescope. Figure 5 shows the reconfigurations and phases that one type of occulter spacecraft goes through.

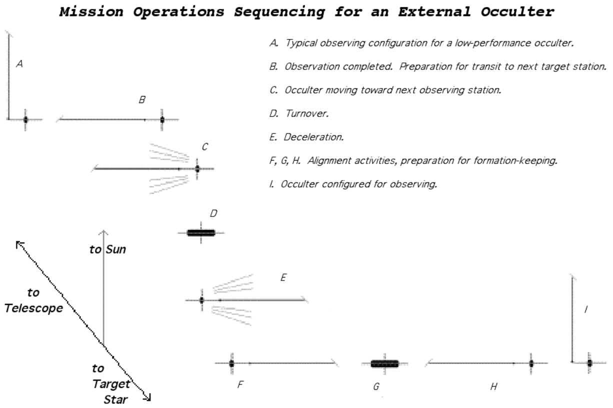

Figure 5: An external occulter will have its own operations flow. Above, one example occulter is shown at sequential operational phases as it is moved from observing one target to another. At phases "A" and "I", the occulter is on-station at different target lines of sight with respect to the telescope. Phases in-between illustrate possible reconfigurations and movement between the two TTLOSs.

As a result, the occulter observations are interleaved with other science. When constructing a science plan in advance based upon some periodic planning *Cycle* (a period in which approved observing programs are densely packed in expectation of execution. E.g. HST's yearly guest observer time allocation award and subsequent integrated year-plus science plan), planning 1-2 years of the occulter observations in advance may be desired. With each occulter observation, however, the long-term planned use of the occulter may be subject to change.

The reasoning here is that there are two fundamental limits on occulter operations—fuel consumption, and mission duration. These two constraints in some sense oppose each other: One would like to perform as many *LOSs* as possible, however due to fuel limitations, performing them over the maximum possible mission time is preferred. On the other hand, planned mission duration and a race against hardware failure dictate performing the LOSs as quickly as possible. This latter desire results in much faster fuel consumption rates. This conflict sets up a science mission optimization problem.

The number of surveyable targets is fundamentally limited by the amount of propellant carried and by the life of the mission. Target-to-target cycling defines the character of occulter missions and drives many constraints. Moving the occulter from one target to another must be done efficiently to maximize the number of targets visited during the mission and minimize propellant usage. Careful planning of the sequence of visits to targets is needed. Once observations on a target are complete, the occulter is commanded to move to its next destination.

Previous Evaluations of Mission Operations Planning Tools

It has been suggested that three software components are needed to facilitate planning and scheduling of occulter-telescope observations (Kochte, Hart, Fraquelli, et.al. 2004):

- a *Visibility Predictor* (VP),
- an *Accessibility Predictor* (AP), and
- a *Sequence Planner* (SP).

All three of these tools were posited as necessary during the mission operations phase for planning target-to-target sequencing in order to maximize the use of the occulter. The VP, given any date, provides target visibility for the occulter. The AP will provide fuel estimates and transit times on a per target basis given a particular set of configurations of the telescope-occulter.

The most complex of the three tools would be the SP. The SP determines if the occulter can stay longer on the current target and how that may affect a subsequent target. The SP should be able to generate, rank, and display different target sequencing scenarios. Over the course of 6 months the entire sky will pass through the QR, although the entire sky is never instantaneously accessible.

Although it was stated that it might be necessary to update and/or modify the observing plan on timescales of a few days, subsequent examination of the planning problem suggests that this may not be necessary for some occulter missions. If the time on target is lengthened, the tools outlined earlier will help mission operations determine how to maximize efficiency.

New Science Optimization Tools and Paradigms

In addition to previously discussed planning tools, applying mission planning tools in advance of operations can help optimize different observing and target sequencing strategies. With such tools, the goal would be to provide the capacity to statistically assess various different occulter use strategies. One approach would be to run multiple usage simulations and apply scoring metrics to each simulation. This would allow assessment of how best to employ the occulter both from a general strategic standpoint for long-range planning, and from specific conditions during the mission. In this way, one would be able to evaluate the impact of possible changes to the usage plan and construct optimal plans. Such tools may use the AP, VP, and SP as components.

It is likely that the science team will have more targets on their wish list than can be observed during the occulter mission, and a subset will need to be chosen for execution. Each simulation of target and visit sequencing could change working assumptions such as telescope-occulter operating range, thrust level between LOSs, specific target sequencing, target subset selection, and differing operation wait-times. Using different scoring algorithms would also allow the science team to judge which strategy and algorithm was best applied at different parts of the occulter mission.

Perhaps the greatest benefit in having this capability in the near-term would be in providing a science team the opportunity of optimizing the design of an external occulter mission in advance of its proposal or hardware definition phases. Performing many simulations with different subsets of targets would allow a search for the theoretically optimum use of the occulter. Because the science capability of the telescope-plus-occulter system is intimately intertwined with the mission architecture, being able to examine different scenarios in advance may also be useful for architecture optimization as well.

The science optimization problem is driven by a number of basic factors:

- optimizing science (function of T-O range and queuing)
- optimizing number of visits to each target
- optimizing number of targets surveyed
- target-to-target ‘slew’ rate of the occulter-telescope
- propulsion capability

The impact of each of these will be discussed in the following sections in the context of an example of modifying an existing planning tool, and how some of these factor into constructing a science plan.

Application of Existing Planning Packages

Many space astronomy planning packages and tools exist which might be adapted to external occulter mission planning. Here, we will discuss conceptually how one particular tool could be adapted to help construct optimal science plans. Comparatively minor modifications to the SPIKE (*Science Planning Intelligent Knowledge Engine*) software package (Johnston and Miller 1994, Giuliano 1998, Kramer 2000, Zimmerman and Asson 2002, Ferdous and Giuliano 2006) would transform it into a long-range planning tool for external occulter missions. An enhanced SPIKE would allow integrated planning of external occulter observations along with other science programs that do not require use of the occulter. In effect, these changes would allow the current software architecture of a single-spacecraft planning tool to be transformed into a simultaneous single-plus-multiple spacecraft observation planner.

An occulter *Design Reference Mission* (DRM) provides context for discussing how occulter observations would be integrated with non-occulter observations. The *Occulter DRM* (ODRM) would consist of a subset of desired targets having visit and linkset specifications. The occulter DRM visits would likely consist of a special identifier to single out planning for algorithm checks unique to the occulter component of the science mission, and for stepwise, coherent integration with the non-occulter DRM. Visit specifications would consist of minimum and maximum times required on target, minimum and maximum allowed Telescope-Occulter separations, and timing-link spacings and tolerances between repeat visits to individual targets, or period-phase constraints to emulate desired discovery-space mapping. Other user specifications might be applied with lesser impact on general plannability of the visits, such as roll specification.

The targets and observation pool would then be fed to the long-range planning software to plan concurrently with other science observations or separately. SPIKE modifications would include--effectively--a slew-constraint between adjacently planned occulter pointings to capture the minimum transit time for targets widely separated on the sky. During planning of individual occulter observations, the planning software would compute accessibility of sequential occulter observations to ensure that constraints such as the ability of the occulter to move from one target station to the next and adequate QR intersection times are obeyed.

Resource Consumption: Fuel, Time-on-Target, and Transit-Time

Addition of an algorithm to integrate fuel consumption for different transit profiles would allow the planning tool to keep track of the fuel constraint and provide a measure of remaining fuel after planning the existing target pool. This would be particularly useful for allowing the science planners to assess the best of several different plans generated as it would allow project managers to decide between prime and extended mission science trades.

As noted earlier, in addition to consuming telescope time, fuel carried by the external occulter is an important resource that must be tracked. Besides fuel for transit between stations, external occulters also expend fuel for formation-keeping activities during the intervals that individual targets are being observed. At least part of this consumable use can be predicted in advance for a given geometric configuration between telescope, occulter and the major solar system objects (the gravitational influence of which are major factors).

For inter-target solar-electric propulsion (SEP), occulter spacecraft design could have an impact on inter-target thrust-levels. Movement of the occulter may be further power-constrained if the spacecraft solar arrays cannot be pointed directly at the sun to gain maximum power for propulsion for particular target sequences. As a geometry problem depending upon spacecraft design and target-occulter-sun geometries, this would presumably be straightforward to implement as well.

Fuel consumption per target, acceleration level, and transit time are intimately related. The type of propulsion also plays a role: SEP will likely be characterized by long periods of acceleration, with very little inter-target coasting. Chemical propulsion will likely be the opposite, because of efficiency in either fuel-per-target, transit-time, or distance traveled. Solar-electric propulsion is not able to produce the large accelerations that chemical propulsion can because of the enormous solar-array-size requirements, but solar-electric propulsion is inherently more fuel-efficient, particularly when fuel mass–fraction is large.

Other built-in parameters that characterize the transit algorithm might be ‘turnover time’, maximum occulter transit velocity, arrival and departure configuration times, and possibly alignment tolerancing. Modeling spacecraft characteristics such as directed propellant leak rates, and photon pressure acceleration would be enhancements for more sophisticated simulations.

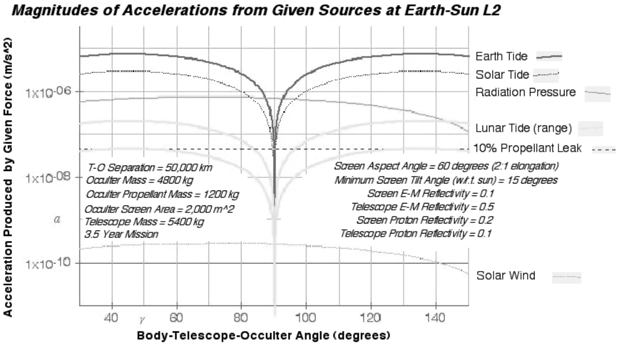

Figure 6: Time spent formation-keeping (on-target time) does require fuel consumption and cannot always be ignored. The consumption rate depends upon the geometry, separation, and design characteristics of the telescope and occulter. In the figure above, the magnitudes of the individual components of cross-TTLOS accelerations for a particular occulter mission as a function of sun-telescope-occulter geometry are plotted.

In Figure 6, the magnitudes of the cross-TTLOS accelerations (which are far more important for the science mission than the along-TTLOS accelerations) are shown for a particular telescope-occulter mission design. The most significant accelerations are the gravitational tides (*an expression for which is given in Eq. 1, where G is the Newtonian gravitational constant, theta is the body-telescope-occulter angle, z is the telescope-occulter separation,* M_{body} *is the body mass,* $r_{Tel\text{-}body}$ *is the distance to the body, and* $a_\perp$ *is the cross-TTLOS acceleration*) and solar radiation pressure. The tidal force grows linearly with telescope-occulter separation, so formation-keeping thrust is proportionately higher at greater ranges (more expensive propellant-wise). However, angular rates--as seen from the telescope--due to tides are independent of range and only a function of distance from the gravitating body. For the region where solar radiation pressure is important, its magnitude is independent of range.

$$a_\perp = \frac{3GM_{body}\sin(\theta)\cos(\theta)z}{r^3_{Tel-body}} \tag{1}$$

New criteria to score different possible observing windows for individual visits could be implemented such as one for fuel consumption and target observing rate. Planning an occulter mission concurrently with other science could necessitate differences in operational software use. One might wish to plan guaranteed time occulter observations stretching over a longer duration than normal Cycle-based occulter-less science observations.

Telescope-Occulter Range Optimization: Science vs. Fuel

In a previous section, the issue of minimum and maximum range between telescope and occulter was brought up in terms of the DRM. One could ask, 'why not operate the occulter at its minimum distance if doing so would maximize the amount of fuel available for the mission?' There is a drawback to this because a smaller telescope-occulter range yields a larger apparent size of the occulter and larger inner working angle (IWA), which may result in more objects of interest being blocked by the occulter. For certain targets, such as stars furthest from our sun--whose planets are therefore proportionately closer in apparent separation--this could seriously degrade the mission's achievable science.

$$n^3 v^4 z^2 F_{\max}^2 \propto f\left(obs\_strategy, M_{init}, M_{final}, I_{sp}\right) \qquad (2)$$

In Eq. 2, stated without proof is a statistical-dynamic trade relationship that is derivable between mission and spacecraft parameters for a large class of external occulter missions. Mission parameters such as the number of targets visited 'n', the number of visits per target 'v', the mean telescope-occulter separation, 'z', and the inter-target thrust F_{max}, appear on the left while details of the observing strategy, initial and final spacecraft mass, and propulsion system efficiency (I_{sp} , specific impulse) appear on the right.

The importance of this relationship is not its exact validity, but to indicate the usefulness of general relationships for assessing mission trades. Mission duration does not appear explicitly in Eq. 2, and is not conserved when varying any of the quantities, but varies approximately as the square root of the telescope-occulter separation. As an example of how such trade relationships are useful, if one were to choose greater separations, then without changing the propulsion system or observing strategy, either number of pointings or acceleration between targets would have to decrease to compensate. Exploring such relationships will allow evaluation of mission planning trades. Later, results of a detailed implementation of this approach are given in order to provide a semi-quantitative feel for the approximate expected values of some mission parameters affecting the science capacity of external occulters.

If the occulter operates closer to the telescope, more of the region of interest around the target star is blocked. In doing so, more visits to the target are required in order to achieve the same level of 'completeness' in a search of the target system. Because the benefits of range (fuel) and discovery efficiency offset each other, a careful evaluation of the net benefit based upon actual target subsets and specific sequencing strategies is indicated to optimize the science mission plan. Figure 7 shows the effect of the degree of obscuration on the need to revisit for approaching a given completeness level.

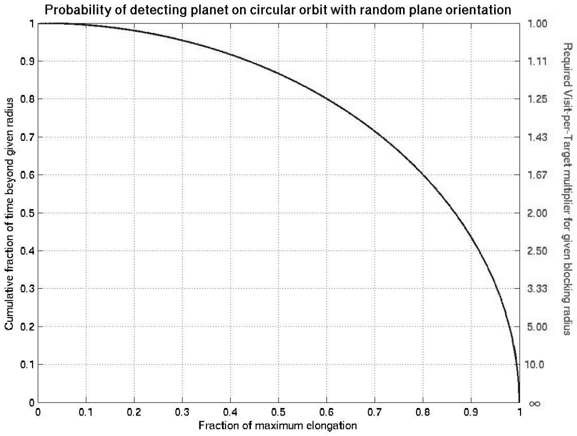

Figure 7: Science capability of external occulters is sensitive to separation between the telescope and occulter and similarly the apparent size of the occulter. The plot above shows the fraction of time a planet on a randomly oriented circular orbit would appear beyond the occulter edge, with the x-ordinate representing the ratio of the apparent radius of the occulter to the apparent semimajor axis of the planet. The y-axis on the right gives the multiplying factor by which one would need more than the minimum number of independent observations to determine the orbit of an extra-solar planet versus the apparent-occulter-radius-to-semimajor-axis ratio assuming that the planet is lost behind the occulter for the corresponding fraction of time.

Target Queuing Strategies

An efficient visitation strategy is important in order that time and propellant are not wasted flitting back and forth across the sky. Over the mission lifetime, propellant mass will be shed, increasing available acceleration, decreasing necessary thrust, or decreasing travel time between targets. Since transit time is proportional to the inverse square root of the acceleration (SEP constant acceleration missions), mass shedding does not provide a tremendous performance gain except for craft having a large propellant mass fraction. In the next section, we compare efficiencies of two possible queuing strategies to demonstrate that mission planning is a critical aspect of occulter operations and utilization.

An important point is that an ideal queuing strategy from a fuel consumption standpoint is probably not optimal from a science perspective. If the occulter observes near-ecliptic targets only as the sun-telescope-target angle decreases, only particular 'phases' of the stellar orbital environment are sampled. In the case of a sun-like star with a planet having an orbital period near 1-year, there is a significant probability that it would be missed in the survey because the observation spacing of the small number of visits would have an in-built bias near 1-year. For more complete time- and orbital- parameter-space sampling, it may be necessary for the occulter to ‘hop’ to the other side of the QR to observe a target that was observed about 6 months earlier. These long transits are fuel-per-target inefficient, so minimizing their frequency likely increases overall science mission efficiency.

Planning a complete occulter mission without frequent changes to the targets and their sequencing is unlikely. As an example of why changes might occur, consider the knowledge state of an initially evaluated high-priority target after one or two visits: there will either be features of interest around it or there will not. If no objects of interest exist because exozodiacal background is higher than expected, precluding detection of objects of interest, the target may be dropped from the repeat list or reduced in re-visit priority and replaced with another target. In this case, characterizing the targets as well as possible prior to selection enhances mission planning stability. The changing knowledge state of the targets is an important reason why the science plan will change and require both a dynamic response and tool-suite to handle the mission planning (Zimmerman, Asson, 2002).

Priority-based Scheduling: Examples and Comparison of Efficiencies

The general importance of sequencing target visits to overall mission efficiency can be demonstrated by comparing two different queuing schemes. Suppose that 14 targets are chosen as highest in priority, and 10 targets of lower priority. To simplify analysis, suppose that 3-4 visits (e.g., 84 total stops) to the targets are planned. If the targets are scattered uniformly (which they will not be in actuality) over the sky, then there would be, on average, ~47° of arc between nearest neighbors. To simplify analysis and make a fair comparison, assume that the mean telescope-occulter ranges are the same between the two compared schemes.

In a scheme of *Monolithic Priority-Based* (MPB) scheduling, the highest priority targets are to receive visits prior to lower priority targets. The average separation between nearest neighbor high priority targets is 61° and the average separation between low-priority targets is ~72°. The MPB scheme does not provide the optimum time and propellant usage and this can be demonstrated by comparison with another mission planning concept.

In many ways, multiple visits to all of a randomly distributed subset of targets before moving on to a fresh subset is a poor choice--the occulter could more efficiently survey different parts of the sky sequentially, clustering targets for greater productivity. In such a *Sequential Regional Survey* (SRS) scheme, high-priority targets in some regions of the sky are delayed until later in the mission in favor of clustering targets in time which are also clustered in sky direction--including those of lower priority--to minimize total transit time (propellant consumed). With SRS, the occulter makes shorter hops between clustered targets before a longer jump to another region of the sky, where it would visit a cluster of targets before moving on. In this way, less average time is spent in transit, with more targets reached over the long term.

Since the two examples differ by ~30-50% in mean effective target separation, the MPB scheme would require the occulter spending about 14-22% longer in transit and consuming more propellant. This comparison demonstrates that some queuing strategies are inherently more efficient than others. A drawback with the SRS approach is that some high-priority targets do not get visited at all until late in the mission. Areas of the sky could be prioritized to offset this shortcoming. Planning tools to help characterize the relative clustering of subsets of targets could also help planners converge on finding optimum target selections for the science mission.

This type of quantification is subject to the caveat that target densities and target-to-target cycling times are such that other observing constraints do not significantly alter the efficient sequencing of successive targets. So, in actuality, the ideal may not hold and a careful study to map out the efficiency space of different possible queuings should be undertaken.

Mission Science Capacity Example

Comparing performance of different queuing strategies with extensive simulations is beyond the introductory nature of this presentation. However, to step beyond the crude descriptions provided so far, efficiency can be examined using the analytic statistical-dynamic model posed in Equation 2 between relevant mission parameters. A detailed derivation of this model is also beyond the present scope (in preparation for a future publication), but some results from it are provided in Figures 8-9. Many other instructive parameter variations could be shown, but space is not extensive enough.

Some important caveats should be kept in mind when reviewing these figures. The model does not reflect either the MPB or SRS queuing strategies, but instead treats all targets as equal. The results are for a specific -- but not necessarily representative of those expected--single-occulter mission. Because this is not a detailed simulation and only a first-order statistical model, the precise values it predicts are not necessarily those to be expected. A more important lesson is the relative magnitude of the effect produced by changing one variable compared with another within certain regimes. It should be noted that changing the assumptions in the model can change the results for a particular contour set in important ways.

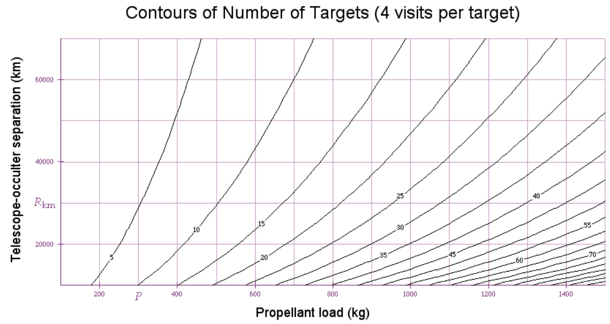

Figure 8: Contours of number of targets are shown as functions of propellant load and telescope-occulter separation. Mission duration varies in this plot. Thrust is fixed at the maximum ion thruster rating.

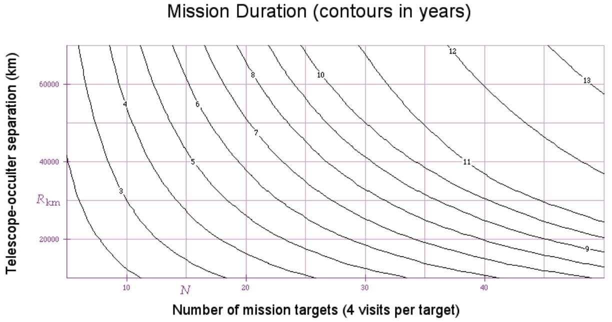

Figure 9: Contours of mission duration are shown as functions of number of mission targets and telescope-occulter separation. Propellant load is kept fixed at 1200 kilograms, however the average thrust level decreases for the longer duration contours.

In this scenario, the fixed spacecraft launch weight for a 2 NSTAR thruster (SEP) occulter is 4800 kg, with tankage and propellant allowed to vary for contour generation. Time on station for each visit is 3 days, and number of visits per target is assumed to be 4. The angular direction of travel between targets is restricted to one quarter of all possible directions, and distance of travel is ~ 22% further than nearest neighbor. These conservative assumptions were made in order to approximate realistic conditions whereby the occulter must either keep up with the rotating QR, or hop to the other side periodically.

The above strictly applies only to single occulter missions, but can be used to estimate the gain expected with multiple occulters. For example, in a mission with n_o occulters, assume that the number of targets is increased by the same factor. Average separation between targets decreases by $\sqrt{n_o}$ and transit time (at the same SEP thrust) decreases by the fourth-root of n_o, shortening the mission (chemical propulsion missions scale differently). The gain may alternately be distributed by shrinking the thrust level by $\sqrt{n_o}$, doubling the number of targets with the same mission duration. This also decreases required power and propellant, or allows increased number of targets. Additionally, occulter hops to opposite sides of the QR are needed less frequently for adequate search protocols around some target stars.

Other Scheduling Issues

The coordinated, simultaneous scheduling of external occulter and space telescope presents unique challenges characteristic of multi-spacecraft operations. Perhaps most importantly, optimum efficient use of the telescope demands that time not be wasted waiting for the occulter to follow the operational timeline. As a result, sufficient scheduling pads need to be built into the joint flight schedule, but not so much as to expand the science timeline unacceptably. A solid understanding of the operations and science constraints of the two spacecraft is necessary to create realistic schedules. Having this knowledge as far in advance of flight as possible is important for evaluating their impact on mission effectiveness in achieving the science goals.

Some occulter missions have been defined such that the degree of cooperative feedback between occulter and telescope is relatively small (such as the *New Worlds Discoverer*), while with others the degree of interaction is greater (*ASA+O*). The reliance on inter-spacecraft interaction will be an important factor in defining the scheduling issues. If, for example, as was defined in the original ASA+O mission scope, the occulter alignment is controlled in an active feedback through telescope observations, then a cooperative scheduling system will need to be defined in the overall mission planning.

Conclusion

Important interrelated parameters in designing an occulter mission are telescope-occulter range, target observation rate, spacecraft mass, thrust, power available, and propellant specific impulse. An operations model coupled with knowledge of occulter capabilities can be implemented to study science mission efficiency with modest extensions of existing planning software. Understanding proper target sequence planning is important for maximizing occulter science and possibly choosing among candidate architectures. Long-range science plan comparisons with different target subsets offer a way to maximize science mission efficiencies.

Acknowledgements

The author would like to extend particular thanks to Helen Hart, JHU/APL, Mark Kochte, CSC/JHU/FUSE, Wayne Kinzel, Merle Reinhart, and Dorothy Fraquelli, CSC/STScI, and Alfred Schultz, GSFC for their extensive discussions of space mission operations as applied to existing space telescopes and external occulter missions, and screen nulling performance. Appreciation is extended to Carey Myers and an anonymous AAAI reviewers who supplied suggested improvements.

Special thanks to Gordon Woodcock, Gray Research, Dr. Glenn Starkman, CWRU, Dr. Webster Cash, U. Colorado, Dr. Christian Marchal, ONERA, Dr. Richard G. Lyon , GSFC, Jon Arenberg and Amy Lo, NGST, for their contributions to understanding external occulter architectures and nulling performance.

Support for this work includes that provided by Computer Sciences Corporation, Greenbelt, MD, and by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

References

Beichman, C. A., Woolf, N. J., Lindensmith, C. A., eds., 1999, The Terrestrial Planet Finder. A NASA Origins Program to Search for Habitable Planets, JPL Pub. 99-3, May 1999.

Brown, R. A., 2006, “Chasing Earth-like Planets”, Space Telescope Science Institute 2005 Annual Report, STScI, pp. 24-26, 2006.

Cash, W., 2005, NASA Institute for Advanced Concepts Phase I report, http://www.niac.usra.edu/files/studies/final_report/999Cash.pdf , 2005.

Cash, W., 2006, “Detection of Earth-like planets around nearby stars using a petal-shaped occulter”, Nature, v.442 pp.51-53, July 6, 2006.

Copi, C. J., Starkman, G. D., 2000, “The Big Occulting Steerable Satellite (BOSS)”, The Astrophysical Journal, vo1. 532, pp.581-592, March 2000.

Ferdous, N., Giuliano, M., 2006, “Validating Resource Usage in Least Commitment Planning “, *5th International Workshop on Planning and Scheduling for Space*, Baltimore, MD, October 22-25, 2006.

Giuliano, M., 1998, "Achieving stable observing schedules in an unstable world.", Proceedings of the *NASA Workshop on Planning and Scheduling for Space*, Astronomical Data Analysis Software and Systems VII, ASP Conference Series, Volume 145, ed. R. Albrecht, R. Hook, H. Bushouse, pp.271-274, 1998.

Johnston, M., Miller, G., 1994, "SPIKE: Intelligent Scheduling of Hubble Space Telescope Observations", in Intelligent Scheduling Fox, M., Zweben, M., eds., San Francisco, Morgan-Kaufmann, pp.257-289, 1994.

Jordan, I. J. E., Starkman, G. D., Lyon, R. G., Copi, C. J., Schultz, A. B., Hart, H. M., Kochte, M., 2003, "The advantages of multiple coronagraphic vehicles in occulter missions", AIAA 2003-6300, Space 2003 Conference proc. Sept. 2003, ISBN#1-56347-647-9.

Jordan, I. J. E., Lyon, R. G., Schultz, A. B., Hart, H. M., et.al., 2004, “Apodized Square Aperture Plus Occulter Concept for TPF”, SPIE v.5487, no. 194, Glasgow, UK, July 2004.

Kochte, M., Hart, H. M., Fraquelli, D., et.al., 2004, “External Occulter Mission Operations”, SpaceOps 2004, AIAA, Montreal, CA, 2004.

Kramer, L., 2000, "Generating a long range plan for a new class of astronomical observatories", *2nd International Workshop on Planning and Scheduling for Space*, International Conference on Artificial Intelligence Planning and Scheduling, AIPS 2000.

Marchal, C., 1985, “A space telescope able to see the planets, and even the satellites around the nearest stars”, Acta Astronautica, vol. 12, no. 3, 195, 1985.

Schultz, A. B., Schroeder, D., et. al., 1999, "Imaging Planets About Other Stars with UMBRAS", Proceedings of SPIE, v.3759, July 1999; (q.v. also UMBRAS external occulter website, http://www.umbras.org).

Semeniuk, I., 2006, “Starshade will let alien planets shine”, New Scientist, p.14, March 11, 2006.

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

Woodcock, G. R., 1974, in Future Space Transportation Systems Analysis, Appendix to Contract NAS9-14323, December 11, 1974.

Zimmerman, L., Asson, D., 2002, "SPIKE: A dynamic interactive component in a human-computer long-range planning system", *3rd International Workshop on Planning and Scheduling for Space*, Houston, Texas, October 27-29, 2002.