The Advantages of Multiple Coronagraphic Vehicles in Occulter Missions

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Abstract

Free-flying external coronagraphs for space telescopes have been studied since the 1960s, but cost/benefit analysis has not proved convincing for skeptics. A single space vehicle carrying an occulting screen can increase the contrast between a star and its orbiting extrasolar planets for a suitably designed space telescope. However, a number of advantages ensue when replacing the single occulter with a fleet of lighter-mass occulters. Target observation rates can increase in proportion to the number of coronagraphic free flying vehicles devoted to a mission. At the same time, mass requirements for individual vehicles is dramatically reduced. Mission lifetimes can at the same time potentially increase, and the risk of independent catastrophic failures onboard an occulting vehicle eliminating all science productivity for the mission are effectively vanish. Per-unit vehicle costs are substantially lower than for production of a single unique craft.

1. Introduction

Multiple occulter missions (MOMs) employ more than one occulter or external coronagraphic spacecraft to perform as external coronagraphic vehicles for a space telescope. MOMs differ from *single occulter missions* (SOMs) which have been discussed extensively by investigators of the free-flying occulter technique [1-11].

The role of an occulter or *coronagraphic vehicle* (CV) in an occulter mission is to station itself along the line of sight between a telescope and a target star, blocking a significant fraction of the light[1]. The benefit derived is an increase in the contrast of objects surrounding the star, making them more easily observable. In order to be useful for more than a single such occultation, the CV must be able to move from one *target-telescope line-of-sight* (TTLOS) to another [2]. The parameters of scientifically interesting missions dictate that telescope-occulter separations need to be on the order of thousands to tens of thousands (or even more) of kilometres [3,5]. In addition, the telescope and occulter must be placed on the order of a million kilometres or more from earth or other planets [4,5].

Here we consider employing more than one occulter for use with a space telescope placed far from earth [12] for the purpose of comparing the operational efficiencies of a single (1) occulter mission with a multiple (N) occulter mission in which the telescope characteristics will remain the same.

2. Basic Kinematics of Single Occulter Mission Operations

The amount of time required for an occulter to travel between observing stations (T_1) can be broken down into discrete phases: departure preparation (T_{dp}), acceleration toward next target (T_a), turnover time (T_{turn}), deceleration toward arrival at next target (T_d), and arrival setup (T_{as}). The resulting time of transit for a single CV between targets is then

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$$T_1 = T_{dp} + T_a + T_{turn} + T_d + T_{as} \qquad (1)$$

For CV masses on the order of 1 tonne which use solar electric propulsion, analysis shows that turnover time and departure preparation are smaller than typical times spent accelerating or decelerating between target stations. Spacecraft acceleration and deceleration will usually be of similar duration to ensure minimum transit times, with the time spent in each, therefore, approximately the same. To simplify, we assume that arrival setup times are also small compared to the total time. Equation 1 then simplifies to

$$T_1 \approx 2 \cdot T_a \approx 2 \cdot T_d \qquad (2)$$

From simple kinematics, we know that

$$S_1 = 2 \cdot \frac{a_1 \cdot T_a^2}{2} = \frac{a_1 \cdot T_1^2}{4} \qquad (3)$$

where S_1 is the distance the CV must travel between science targets, and a_1 is the acceleration of a SOM CV.

3. Multiple Occulter Mission Operations

Suppose the single occulter is replaced with a fleet of *N* occulters scattered around the telescope, each operating at an average distance from the telescope comparable to that of the single occulter. This preserves similarity in the kind of basic science capabilities between SOMs and MOMs in order that direct comparisons between the two kinds of missions can be made.

Furthermore, let us assume that the average required transit time between science targets for each CV in the MOM is to be the same as that for the single CV in the SOM:

$$T_N = T_1 \qquad (4)$$

Analysis of SOMs shows that only a relatively small fraction of telescope time can be used for external occulter science since an occulter spends most of its time transiting between targets [6]. From the assumption expressed in Equation 4, which is not necessarily optimal for a mission (e.g., when science integration time on a target is long compared to occulter transit times), the number of science targets observable by a MOM will be as much as *N*-times that of the SOM. As we shall see, there are further important operational benefits to employing more than one occulter.

In the SOM, the single occulter moves from target to target around the telescope, first visiting one TTLOS and then another. A more extensive unpublished analysis has shown that target observation rates on the rough order of a score per year can be expected depending upon mission parameters.

Because of operational restrictions on the sun-telescope-occulter geometry [6,7], the occulter must remain within an annular, wedge-shaped region around the telescope which has a symmetry axis passing through the sun. This target availability annular wedge rotates against the sky about an axis perpendicular to the orbit about the sun. In the case of a near-earth mission, the annulus rotates with a period of 1 year and the occulter must move about the telescope from target to target visiting only those targets at suitable sun angles within the 'ring'. Targets near the ecliptic poles are observable for much longer durations than those near the ecliptic plane. Elsewhere, we dub this annular ring the *quadrature ring*. The ring width is a function of occulter design specifications and mission parameters that are beyond the scope of this discussion, but are on the order of 30-90 degrees.

For target observation rates on the order of a score per year, the average angle between targets (as viewed from the telescope) would be on the order of 20-40 degrees, depending upon the frequency of repeat observations of a target each year. As such, it is unlikely that single-occulter mission's occulter craft would be used to observe targets on opposite sides of the telescope sequentially. Instead, it would likely zig-zag back and forth somewhat in ecliptic longitude between targets, steadily sweeping either upwards or downwards in ecliptic longitude (although perhaps on occasion reversing direction against the general latitude 'flow' to visit particular targets) with the path resembling a thin, crumpled ring. A target region near the ecliptic plane could potentially be visited at roughly 6 month intervals.

4. Implications for Occulter Propellant Consumption

If the width of the quadrature ring is small and the average distance between targets is larger than the average separation between occulters circumferentially around the quadrature ring, then the distance between target stations will vary inversely in proportion to the number of occulters. However, a more likely situation is that the ring is broad, and occulter angular separations are larger than the average angle between targets. In such a case, the distance between target stations (*S*) varies inversely with the square root of the number of occulters as long as the mean target separation is less than the separation between CVs.

$$S \propto \begin{cases} \frac{1}{N}, & \text{Narrow quadrature ring;} \\ \frac{1}{\sqrt{N}}, & \text{Typical, broad quadrature ring.} \end{cases} \quad (5)$$

This has implications for the required acceleration of MOM CVs compared with SOM CVs.

$$\frac{S_N}{S_1} = \frac{1}{\sqrt{N}} = \frac{a_N \cdot T_N^2}{a_1 \cdot T_1^2} = \frac{a_N \cdot T_1^2}{a_1 \cdot T_1^2} = \frac{a_N}{a_1} \quad (6)$$

or

$$a_1 = \sqrt{N} \cdot a_N \quad (7)$$

So, by increasing the number of occulters, and keeping the transit times between targets the same, the target observation rate of the mission is *N*-fold higher and the required acceleration of an individual occulter decreases by root-*N*-fold.

5. Implications for Occulter Masses

This result is all the more remarkable when one considers the consequent impact on the operational lifetime of the occulter flotilla. For a spacecraft of a given fixed mass with a propulsion system having a fixed specific impulse (propulsion efficiency), the acceleration is proportional to the mass expulsion rate. Given the assumption in Equation 4 and result in Equation 7, this implies that the amount of propellant required for an individual transit between targets would be inversely proportional to the square root of the number of occulters. For our not necessarily optimal case, we might express this two alternate ways:

- MOM occulter lifetime ~ $N^{1/2}$ times that of a SOM occulter.
- MOM occulter propellant consumption rate ~ $N^{-1/2}$ of a SOM occulter.

The first of these is straightforward and requires little further comment, other than the assumption that the MOM CV is built to the same specifications as the SOM CV. It is important to note that the advantage of extending the lifetime of the occulter mission by a factor equivalent to the square root of the number of occulters is in addition to the earlier identified increase in target observation rate.

The second possibility is naïve and needs to be expounded upon. The simple estimation that propellant consumption is 1/✔*N* times that of the SOM CV assumes that there are no additional mass savings in building an occulter spacecraft with a smaller propellant load. This is in fact not the case and many subsystems onboard the spacecraft will benefit from a reduced overall mass due to the reduction in required propellant.

Table 1: Scaling Relations for Occulter Subsystem Masses for Propellant Requirement Reduction

Subsystem	Subsystem Scaling Factor
Solar Arrays	$m \propto 1/(\sqrt{N})$
Batteries	$m \propto 1$
PCU[a]	$m \propto 1/(\sqrt{N})$
Propulsion & Tankage	$m \propto 1/(\sqrt{N})$
C&DH & Comm	$m \propto 1$
ATCS[b]	$m \propto 1$
Structure	$1 < m < 1/(\sqrt{N})$
Thermal Control	$1 < m < 1/(\sqrt{N})$
Payload (screen, etc.)	$m \propto 1$

a. Power Control Unit
b. Attitude and Translation Control System.

One can compute the approximate scaling function of the mass of a MOM CV (relative to its SOM cousin) as a function of the number of CVs in the fleet. If we take as an example of occulter design the E-class vehicle described in AIAA-2000-5230 [9], and apply the scaling relations for the mass of the subsystems stated in Table 1, a model of the combined subsystems yields the relative occulter total masses for MOM occulter fleets of N=2, 3, 4, . . . vehicles. Table 2 contains estimates of MOM CV masses without iterating for the savings produced by lowered propellant expulsion rates derived from still lower CV masses. It is important to note that occulter mass estimates for the E-class vehicle are now considered conservatively high based on more recent occulter design studies [10].

Table 2: Individual and Aggregate Coronagraphic Vehicle Mass Estimates for Various Multiple Occulter Missions

# (*N*) of Occulters in Fleet	Occulter Relative Mass[a]	Fleet Relative Mass[a]
2	0.81	1.62
3	0.73	2.19
4	0.68	2.73
5	0.65	3.25
6	0.63	3.76

a. SOM coronagraphic vehicle = 1.0

6. Additional Advantages

The increase in target observation rate and reduction in size of each occulter are not the only advantages gained from deploying multiple CVs. Although all of the bonuses identified below are included in but a single section of this paper, the brevity of the discussion should not be taken as an indication that they are of necessarily lesser importance.

- per unit cost for building one of many occulters is lower than for a single vehicle.
- flight qualification program of MOM CV may be relaxed compared with SOM CV.
- failure of one CV does not terminate the science mission but only degrades the rate and amount of data collection.
- potential for flotilla or inter-occulter state vector metrology.

It is well understood that an assembly line approach to building multiple identical spacecraft reduces the per unit cost. Since we are discussing occulter flotillas of the quantity whereby the observation rate increases in proportion to the number of occulters, the per-observation cost also decreases.

With an increased number of independent CVs in the multiple occulter mission, the reliability of components and of the complete vehicles need not be held to the same level of a single occulter mission. Because there are multiple occulters, the loss of redundant vehicles after mission deployment does not terminate science collection, but merely reduces the amount and rate at which observations can be made. Because of this high-level redundancy [13] and its benefit to mission success, the extent of low-level redundancy within subsystems in each CV may be open to review.

Some early team concepts of occulter missions employed metrology platforms in an attempt to address the problem of maintaining alignment of the occulter along the TTLOS. Subsequently, an imaging-based scheme was adopted obviating the need for extra platforms. However, if occulter missions move toward adopting multiple CVs, there is every reason to consider enabling the occulter vehicles with means to measure the relative positions of individual CVs with respect to the other CVs and even the telescope. The possibilities are quite complex, but we provide one example of the possibilities below.

One typical sequence which follows on from [7] finds the occulter occasionally taking optical navigation images of the region of the sky containing the telescope as it travels from one target to another. Depending upon the specific design of the occulter, this may require interruption of the otherwise continuous thrust employed between targets. Once arriving near enough to the desired TTLOS, imaging exposures by the telescope are required to refine the knowledge of the CV's position and velocity in order to bring it into precise alignment.

With a MOM employing inter-craft metrology, it is conceivable that interruptions in the acceleration/ deceleration sequence by the CV can be avoided through radio ranging triangulation between the transiting CV and other CVs in the flotilla as well as the telescope. This same radio-ranging capability could be used to more accurately fix the position of a CV which has arrived near enough to its TTLOS to begin the final target acquisition alignment phase requiring imaging by the telescope of the target field.

7. Summary

Increasing the number of coronagraphic vehicles in an occulter mission has many benefits:

- Target observation rate is proportional to the number of craft.
- Required acceleration for each craft is reduced.
- Required reliability of the craft and subsystems is lower.
- Subsystem or craft failures only degrade science--not end it.
- Per-unit cost of occulters is lower.
- Inter-craft metrology becomes possible.

These benefits translate into increased science potential, enhanced chance of mission success, and higher science-per-unit cost output.

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