Appendix J: Trajectory Design and Orbit Determination

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The two NWO spacecraft will orbit about the libration point created by the Sun and Earth/Moon barycenter at the far side of Earth from the Sun, commonly known as the SEM L2 libration point. This location, ~1.5 million kilometers from the Earth, was selected as optimal, providing the science payloads the most environmentally stable location while meeting mass, communication and lifetime constraints. The L2 libration point orbit (LPO) is easily reached through a direct transfer from the Earth to the SEM L2 region with minimal delta-v cost and stationkeeping using an Atlas IV 550-series class launch vehicle. The two spacecraft, baselined to launch 6 months apart, will inject into the same medium-sized Lissajous-type orbits about L2. This orbit was selected over a 'halo' orbit (when the out of plane and in-plane magnitudes are similar, creating a circular repeating pattern as seen from the Earth) because it allows more flexibility in launch dates during the year.

The baseline trajectory is designed so that the L2 orbit injection delta-v cost is minimized; the spacecraft essentially falls into an orbit about L2. Selecting this type of orbit allows for launching the telescope spacecraft approximately 24 days each month. The spacecraft cannot launch directly towards the L2 point when the Moon is 'in the way', thus giving the ~4 day blackout period. The launch energy required for this type of orbit is approximately -0.5 km^2/s^2. Expected launch vehicle dispersions from the Atlas V are along the order of 3 m/sec, easily accounted for during the first 36 hours of the mission. Another advantage of the LPO orbit is that very little stationkeeping is required: 4 maneuvers of ~1 m/sec/year is required.

A schematic of the telescope spacecraft's LPO is shown in Figure 1. The semi-major axis of the orbit, as measured from the L2 point, is approximately 800,000 km, with a period of 180 days. The transfer trajectory is designed so that it avoids the shadow created by the Earth and Moon; these eclipses can be hours or days long and must be avoided. The initial orbit for the telescope spacecraft is selected so that the spacecraft is in an opening orbit as seen from the Earth, to ensure the spacecraft avoids the Earth shadow for as long as possible. The baseline trajectory will not cross the Sun-Earth line directly for at least 10 years (the minimum lifetime requirement is 5 years).

Figure 2 shows the mathematically integrated trajectory with respect to the Sun-Earth L2 rotating libration point coordinate system. The origin of the system is at the L2 point and the axes are defined by the Sun-Earth-L2 line and the ecliptic plane.

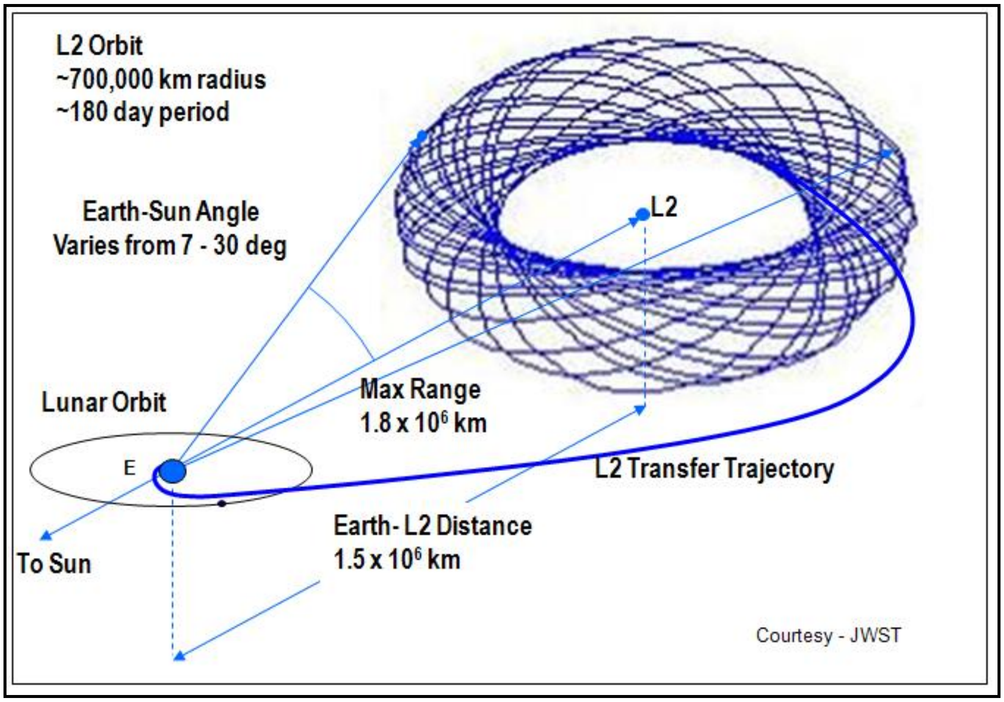
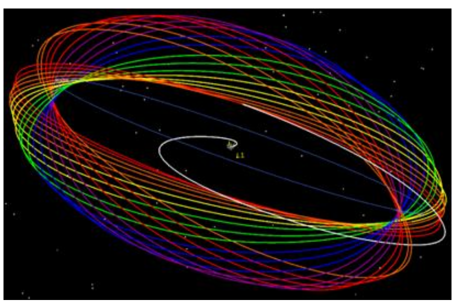
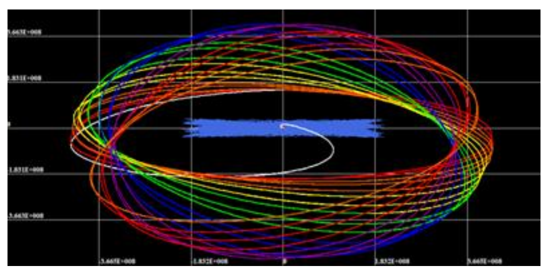


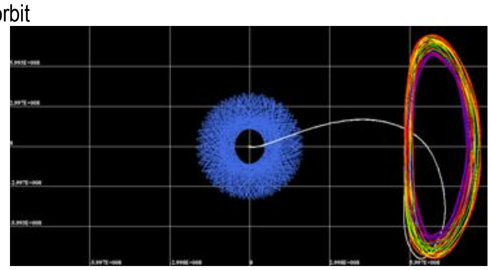
Figure 1: Schematic of Telescope Spacecraft Lissajous Orbit



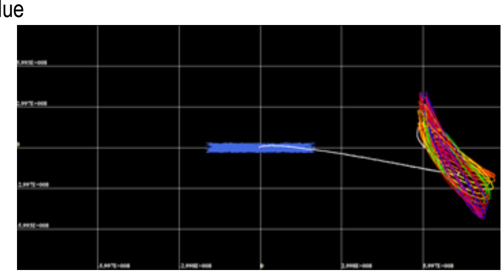
Isometric view, transfer trajectory is white, showing also (rainbow colors) the 10-year mission in the Lissajous orbit



SEL2 Y-Z view (looking towards the Sun with Earth and L2 at origin), the horizontal axis is the ecliptic plane; lunar orbit is blue



SEL2 X-Y rotating view, looking down on the ecliptic plane, with the horizontal axis fixed in the Sun-Earth direction (the sun is to the left and L2 to the right near Lissajous orbits center)



SEL2 X-Z side view, with Earth at the origin at launch and the horizontal axis being the ecliptic plane with "up" towards the north ecliptic pole; the Sun is to the left and L2 to the right

Figure 2: Telescope Reference Orbit Example- Launch Nov 1, 2018

Once the telescope spacecraft has injected into the L2 orbit, it will not perform any maneuvers with the propulsion system, excluding the momentum management (delta-H) and orbital stationkeeping maneuvers. The small delta-H maneuvers are expected to occur no more frequently than every 14 days. SEM L2 libration point orbits are meta-stable, and can be maintained through small, infrequent orbit maintenance maneuvers. Nominally the telescope spacecraft will perform four 1-m/s stationkeeping maneuvers per year.

NWO Trajectory – Starshade Spacecraft

The starshade spacecraft will be in a quasi-libration point orbit, flying a trajectory approximately 80,000 km from the telescope spacecraft. Unlike the telescope spacecraft, the starshade will perform propulsive maneuvers frequently to move from target to target and to maintain alignment with the telescope during exoplanet observations. The retargeting maneuvers are accomplished with the solar electric propulsion system (SEP), while the formation flying maintenance is done using the bipropellant system.

The starshade will launch from Kennedy Space Center on an Atlas IV spacecraft, between 1 and 7 months after the telescope launches. The baseline scenario is to launch 6 months after the telescope and reach the L2 region within 3-4 months. While further analysis is needed, the launch window for the starshade spacecraft is expected to be similar to the telescope launch window. Any launch vehicle errors imparted to the starshade spacecraft will be corrected using the SEP system, as will the injection into a rendezvous orbit with the telescope. Like the telescope spacecraft, the starshade spacecraft must avoid long eclipses; the trajectory will be designed so that the starshade does not encounter Earth or Moon shadows during its transfer to and for at least 5 years at the SEM L2.

Figure 3 illustrates a possible scenario, showing the two trajectories phasing at the L2 point. The starshade spacecraft is called Occulter in this figure.

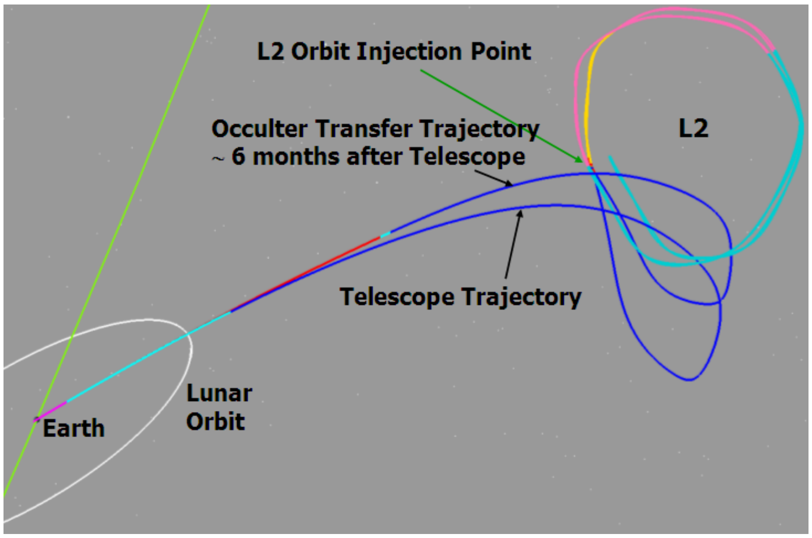


Figure 3: Starshade and Telescope Transfer and Phasing Trajectories

Once the spacecraft have achieved formation and are ready to begin exo-planet observations, the starshade spacecraft will perform propulsive thrusting almost continuously, using the SEP to reach each new exoplanet target location, and the bipropellant system to maintain the starshade's alignment along the line of sight from the telescope to the target star system.

Figure 4 depicts the two spacecraft's trajectories using a sample target list for a 12-month observation period. It is clear from the illustration that the starshade spacecraft does not follow the same trajectory as the telescope, and is maneuvering from libration point orbit path to path between exoplanet observations. This maneuvering between orbits is necessary to maintain the distance of ~80,000 km between the spacecraft, and accounts for the majority of the starshade

SEP delta-v required for the mission. The maneuver sequence can be seen in this Figure, but is better shown in Figure 5. The starshade engages the SEP system to accelerate, reaches roughly the half way point, turns off the SEP system, and coasts for a few hours while obtaining telemetry to ensure it is on the correct orbit. The starshade then performs a 180 degree rotation and engages the SEP to decelerate. This sequence is designed to have the starshade arrive at the desired alignment location to the telescope with zero relative velocity.

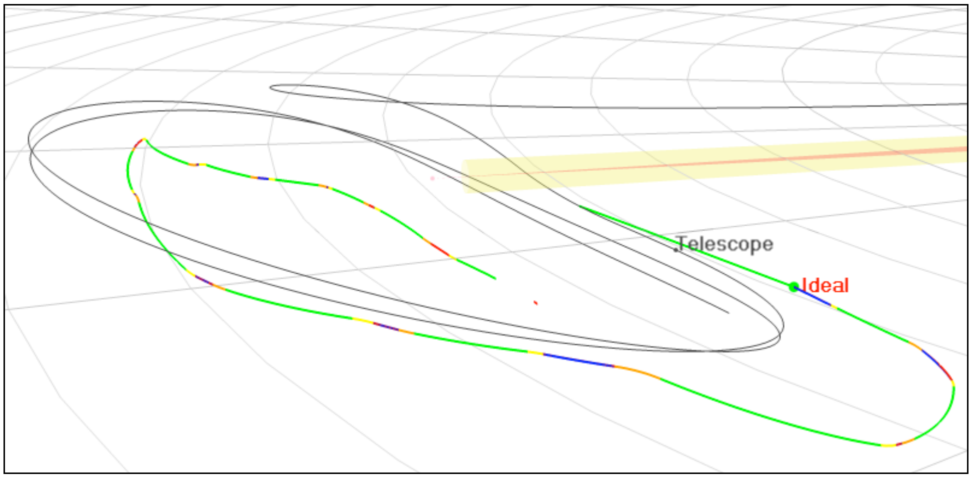


Figure 4: NWO Spacecraft Trajectories for 1 year using Sample Target List

The burn-coast-burn-observation sequence the starshade spacecraft executes is shown in Figure 5. At the end of Observation n-1, the starshade spacecraft uses its low-thrust SEP system to perform a days-long, low thrust maneuver, Maneuver arc 1, which gives the spacecraft the acceleration needed to reach the desired location at the desired time. A coast period follows as the starshade drifts towards the target location. The acceleration is counteracted with a retro-burn, called maneuver arc 2 in the figure, so that the starshade is in position at the beginning of the Observation n period.

Figure 5: Starshade Spacecraft Target Maneuver Scenario

During the science observation, the starshade does not follow the 'ideal' path (exactly 80,000 km from the telescope at all times) and traverses the Actual Path as shown, following its own LPO path, close enough to that of the telescope that it does not violate the formation flying constraints. This maneuver scenario meets requirements while providing for a realistic delta-v budget and amount of time between exoplanet observations.

Trajectory Determination

Accurate trajectory determination and prediction is needed for the NWO mission to succeed, although the accuracy requirements vary depending on the mission phase, with the most stringent during the exoplanet target alignment phase. To perform the occultation of the candidate star observation, the starshade must maneuver into a position ~80,000km from the telescope along the line of sight from the telescope to the star; ground-based navigation is sufficient to reach this position, after which the closed-loop onboard alignment control process takes over to maintain the alignment.

The NWO trajectory determination and alignment requirements are as follows:

- The telescope spacecraft trajectory determination requirement is 50 km (3-sigma), with a goal of 10 km.
- The starshade spacecraft accuracy requirements depend on whether it is what stage it is in the observation maneuver sequence.
    - During non-maneuver periods, the trajectory requirement is 800 km (3-sigma) with a goal of 50 km.
    - During the acquisition of target period, after the burn-coast-burn sequence described above but before the actual exoplanet observations can take place, the trajectory requirements are defined for each of the three alignment steps:
        - Coarse Alignment: 800km , 50km control box
        - Medium Alignment: 10m (TBD)
        - Fine Alignment: ± 1m in the plane perpendicular to line of sight, 80,000 km ±4000km along line of sight

These requirements can be met through a combination of Doppler and range measurements (ground station tracking) and inter-spacecraft range measurements, celestial navigation measurements from sensors onboard, and telemetry information about the dynamic disturbances (momentum management and delta-v maneuvers). Both ground-based orbit determination and onboard orbit determination is required for the starshade spacecraft while the telescope spacecraft requirements could be met using ground-based OD alone. The details are discussed in the Trajectory and Alignment appendix, G.

The telescope spacecraft orbit determination and prediction could be accomplished using a batch least squares estimator (ground only) or an orbit determination Kalman filter (onboard and ground), since the delta-h maneuvers are expected to be no more frequent than once every 2 weeks and the delta-v stationkeeping maneuvers once every 3 months. Inter-spacecraft range measurements and optical navigation information from the Wide Field Camera could be used in an onboard process as well, but is not required. Solar radiation pressure accelerates the telescope away from the Sun, so this must be solved for in the OD process.

Ground-based orbit determination and prediction methodology similar to the process described for the telescope above suffices for general orbit determination of the starshade spacecraft during the transfer trajectory. Once the starshade has begun its exo-planet observation campaign, onboard trajectory determination is required. The starshade spacecraft trajectory is perturbed by near-constant propulsive thrusting and significant solar radiation pressure. A realtime onboard OD filter is required to meet requirements during the exo-planet observation periods. Telemetry data related to spacecraft thrusting and inter-range measurements as well as inter-range measurements must be provided to the OD filter, which will solve for the spacecraft state and dynamic perturbations simultaneously. Realtime Astrometric Sensor optical navigation measurements could improve the orbit determination accuracy as well.

At least 1 hour per day per spacecraft of ground-based Doppler and range measurements from tracking stations with capabilities equal to the Deep Space Network (DSN) is needed to meet the general orbit determination requirements of each spacecraft. Both Northern and Southern hemisphere station 2-way Doppler and range measurements must be made for each spacecraft. Ground-based 2-way range data is required for short arc orbit determination of the telescope spacecraft. Delta-differential one-way range measurements (Delta-DOR) should also be baselined for the starshade spacecraft and possibly for the telescope; DDOR will improve the weakly determined relative position components that are nearly normal to the line-of-sight from the DSN stations to each spacecraft.

Relative Positioning of Starshade to Telescope Spacecraft

The uncertainties in relative positioning of the starshade to the telescope prior to the first target alignment procedure were characterized in analysis by KinetX, Inc. The analysis demonstrated the feasibility of using ground-based 2-way Doppler and range measurements augmented with optical navigation measurements to perform the initial rendezvous and the repositioning of the starshade for each new star target.

The study was limited to a particular DSN viewing geometry but illustrates some general aspects of the navigation performance for this type of rendezvous, especially when the DSN tracking data is augmented with optical tracking as shown below. Further studies should analyze the sensitivity of these results to variations in the Earth viewing relative to the alignment direction. Future studies should include the extent of the travel time between alignments including the acceleration and deceleration between alignments. One hour of DSN 2-way Doppler and range measurements from alternating Northern & Southern hemisphere tracking stations for each spacecraft.

The post-fit uncertainties were computed for each day on the approach, starting at the initial time and continuing up to the final alignment time. At each of these data “cutoff” times, all tracking data taken up to that point is processed and an orbit solution is generated. The solution uncertainties are then mapped to the time of alignment, and the results are shown in the figures below. The time value equal to zero in the Figures below corresponds to 1-MAY-2019, the time of alignment. The values shown at each time represent the trajectory target knowledge 1-sigma uncertainty given tracking data from epoch up to the data cut-off time. The relative position uncertainties on approach to alignment using DSN Doppler and ranging are shown in Figure 7 below.

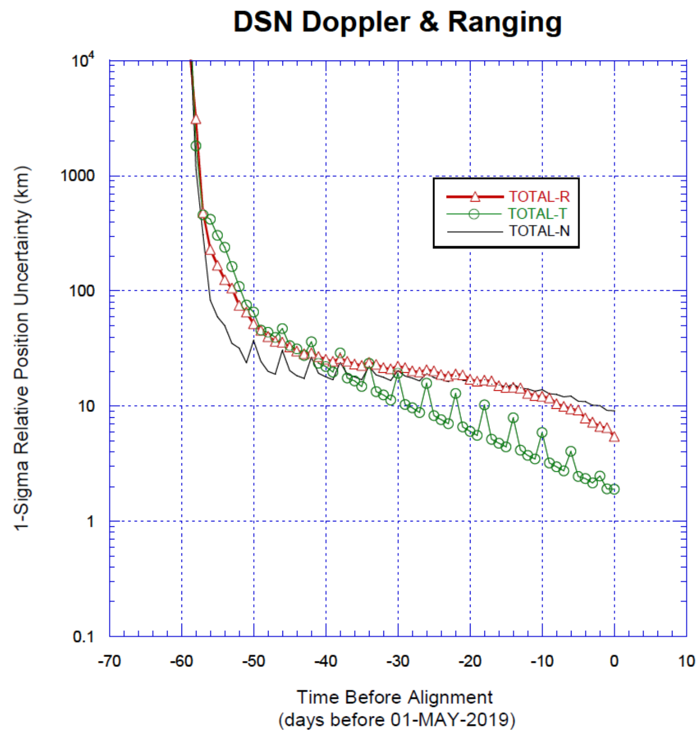


Figure 7: Relative Position Uncertainties (1 sigma) on Approach to Alignment Assuming DSN Doppler and Range Only Mapped to Alignment Point

DSN Doppler & Ranging

The position uncertainty is shown in terms Radial, Transverse and Normal components, where the Radial direction, ‘R’, is in the direction from the telescope to the star shade, the Transverse direction, ‘T’, is perpendicular to the Radial direction in the direction of the relative velocity, ‘V’, between telescope and star shade, and the Normal direction, ‘N’, completes the orthogonal basis vectors so that RxV=N. Note that the T and N directions are the two that must be precisely controlled to get the star shade into the ‘box’ for final control during the exo-planet observation.

Figure 8 illustrates the effect of adding optical navigation measurements to the DSN measurements, and Figure 9 shows the impact of restricting momentum dump perturbations the last 4 days before alignment.

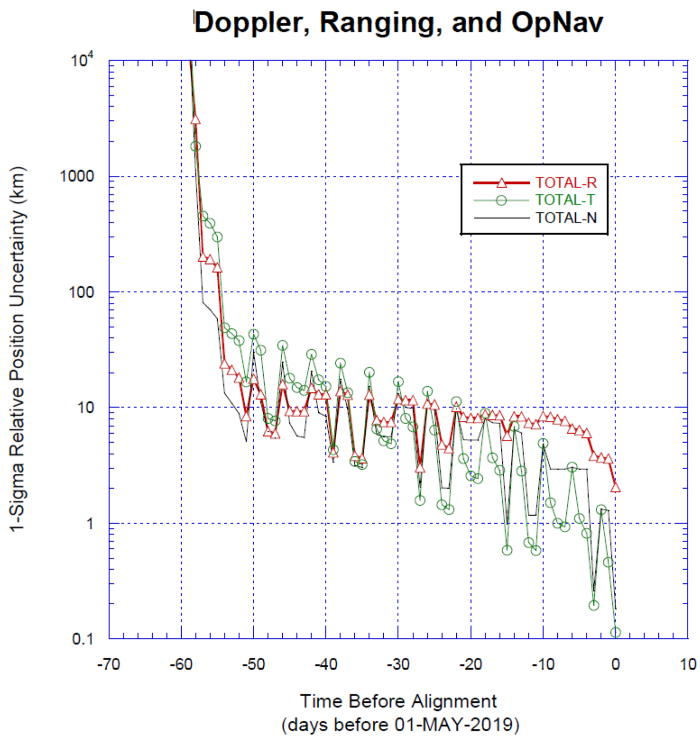


Figure 8. Effect of Adding Optical Navigation Measurements to DSN Data

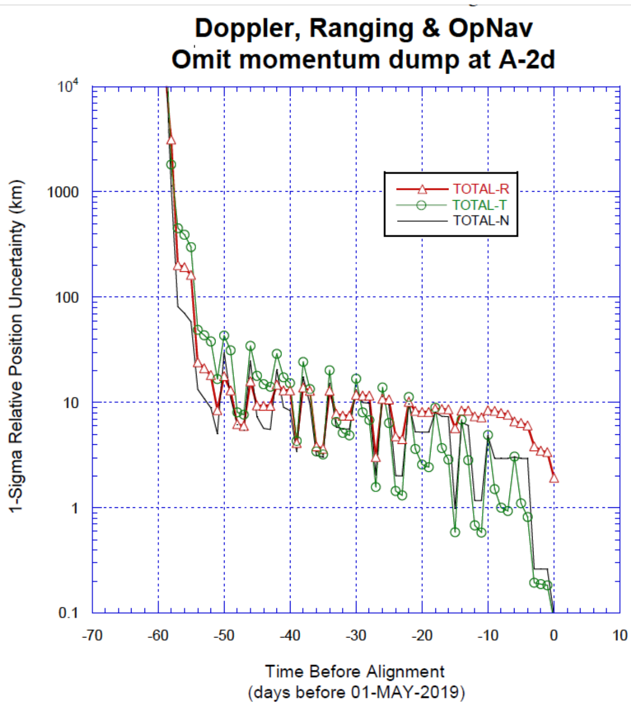


Figure 9. The Effect of Limiting Momentum Dumping on the Trajectory

References

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Folta, D. (NASA Goddard Space Flight Center) and Lowe, J. (Analytical Graphics, Inc.); “FORMATION FLYING OF A TELESCOPE/OCCULTER SYSTEM WITH LARGE SEPARATIONS IN AN L2 LIBRATION ORBIT”; IAC-08-C1.6.2, 2008.

Oleas et al, Northrop Grumman, Analysis/paper with picture of rendezvousing orbits

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