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DIFFERENTIAL DRAG DEMONSTRATION: A POST-MISSION EXPERIMENT
WITH THE EO-1 SPACECRAFT

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Differential drag is a technique for altering the semimajor axis, velocity, and along-track position of a spacecraft in low Earth orbit. It involves varying the spacecraft's cross-sectional area relative to its velocity direction by temporarily changing attitude and solar array angles, thus varying the amount of atmospheric drag on the spacecraft. The technique has recently been proposed and used by at least three satellite systems for initial separation of constellation spacecraft after launch, stationkeeping during the mission, and potentially for conjunction avoidance. Similarly, differential drag has been proposed as a control strategy for rendezvous, removing the need for active propulsion. In theory, some operational missions that lack propulsion capability could use this approach for conjunction avoidance, though options are typically constrained for spacecraft that are already in orbit.

Shortly before the spacecraft was decommissioned, an experiment was performed using NASA's EO-1 spacecraft in order to demonstrate differential drag on an operational spacecraft in orbit, and discover some of the effects differential drag might manifest. EO-1 was not designed to maintain off-nominal orientations for long periods, and as a result the team experienced unanticipated challenges during the experiment. This paper will discuss operations limitations identified before the experiment, as well as those discovered during the experiment. The effective displacement that resulted from increasing the drag area for 39 hours will be compared to predictions as well as the expected position if the spacecraft maintained nominal operations. A hypothetical scenario will also be examined, studying the relative risks of maintaining an operational spacecraft bus in order to maintain the near-maximum drag area orientation and hasten reentry.

1. Introduction

Differential drag is often considered a perturbation force to be compensated for in mission designs. For nearly three decades, though, it has been recognized as a potential method for propellant-free maneuvers in the lower altitude regions of Low Earth Orbit (LEO). The use as an intentional maneuvering technique was first reported in 1989 by C. L. Leonard[1]. In recent years, this potential has been recognized as particularly attractive for constellations of small satellites, both for initial constellation

formation and for formation-keeping. Numerous papers describe the theory behind differential drag maneuvers, and propose control algorithms for rendezvous and for maintenance of constellations. At least three constellations have successfully used differential drag to establish initial satellite separation into a constellation, and at least three have used the technique to maintain their constellations.

This work differs from previously reported efforts in four important ways. Most significantly, the EO-1 spacecraft was not designed to support a variety of attitudes needed to adjust its drag area, which presented some operations challenges. The orbit of EO-1, at a semimajor axis of about 7057 km, is also considerably higher than most missions that currently employ differential drag, resulting in reduced atmospheric density and smaller drag force. The EO-1 spacecraft was used to demonstrate a one-time, short-term application of differential drag, intended to simulate a collision avoidance maneuver by a spacecraft with no propulsion capability. Finally, this demonstration used a single spacecraft, not a constellation, displacing itself not relative to a target spacecraft but from its natural projected location.

2. Differential Drag Principles

The theory behind the force of differential drag as a perturbation is well understood and widely documented. In short, the technique involves taking advantage of the fact that spacecraft with different ballistic coefficients will experience different magnitude drag forces, resulting in slightly different trajectories. By intentionally altering the drag area, a spacecraft trajectory can be altered, closer to or further from a target spacecraft (or target location). Differential drag can be applied to a single spacecraft, or to multiple spacecraft flying in formation. A strong factor in the effectiveness of differential drag is the atmospheric drag in the satellite's orbit, largely driven by the orbit altitude and solar flux variations. While differential drag is often considered for constellations in altitudes of 500 km and below, it has been shown by both simulations and experience to be effective at up to 800 km[2].

At least four missions have employed differential drag, for commercial as well as scientific objectives. The first of these was the ORBCOMM[3] constellation, which launched its first communications satellites in 1995. ORBCOMM uses differential drag to perform the majority of the formation-keeping duties, greatly reducing the demand on limited thruster capacity. The ORBCOMM spacecraft continue to operate at a variety of altitudes, most above 700 km. The AeroCube-4[4] mission (launched in 2012) demonstrated differential drag to separate the three CubeSats by opening and closing 'wings' on the spacecraft to change their drag area by 35 percent. The technique was used to swap the positions of the spacecraft. Planet[5] provides ground imaging with a network of 3U CubeSats, and has relied on differential drag for both initial constellation separation and formation-keeping. Planet also reports that there may be potential to avoid conjunction, if necessary, using differential drag maneuvers. NASA's CYGNSS[6] mission (launched in 2016) used differential drag to separate the eight spacecraft into evenly distributed locations around the orbit plane, and to maintain that spacing. The CYGNSS constellation also has the capacity for conjunction avoidance.

Advantages of differential drag include the following:
- Mass savings over conventional propulsion
- No contamination from thruster plumes
- No shock generated by maneuvers
- Can be used as a backup to propulsion, or after fuel is exhausted
- Improved constellation management results in more efficient coverage, and fewer spacecraft needed[5]

Drawbacks of differential drag include:
- High dependence on orbit altitude
- Effectiveness varies based on solar flux
- Increased drag maneuvers result in greater altitude decay
- Conjunction avoidance by one constellation member means the entire constellation must be maneuvered and sacrifice altitude
- Can require the suspension of payload operations during the maneuver

3. EO-1 Mission

NASA's Earth Observing-1 (EO-1) mission was launched in November 2000, intended to demonstrate and validate a wide variety of new satellite technologies, including advanced instruments and a high degree of on-board autonomy. The spacecraft was designed for a one-year primary mission, but due to the high scientific value of results from the science payloads, the mission was ultimately extended for more than 16 years. At the conclusion of the mission, the spacecraft was used for yet another set of postmission testbed experiments in March 2017, including demonstrations of differential drag maneuvering.

The EO-1 observatory consists of a spacecraft bus and an instrument suite on the nadir face of the bus. The spacecraft bus is essentially a hexagonal right prism, nearly as tall as it is wide, with a deployed solar array on one side. The attitude during nominal science operations is shown in Figure 1. Attitude control is achieved using three momentum wheels, with star trackers for attitude determination. The spacecraft included a hydrazine monopropellant propulsion system, which was essentially depleted in 2011.

The nominal science orbit for EO-1, from launch until 2005, was 705 km circular Sun-synchronous. The orbit was then lowered by about 15 km, leaving the Earth science constellation. Following the exhaustion of fuel in 2011 EO-1's orbit began decaying, so that by the end of the mission (when the differential drag experiments were performed) the orbit was approximately 673 km x 686 km x 97.9° inclination.

Figures 2 through 4 show the EO-1 spacecraft maximum cross-sectional area and two orthogonal views. These represent the maximum and minimum possible drag areas, though operational considerations limit that somewhat; for example, the nadir direction needed to be maintained to preserve the instruments, so the orientation shown in Figure 3 could not face the velocity direction. It is also important to note that the solar array typically tracks the Sun, so the drag area is constantly changing during nominal operations. Table 1 shows the estimated effective drag area for nominal operations as averaged over the orbit, and the practical maximum and minimum drag areas for the experiments.
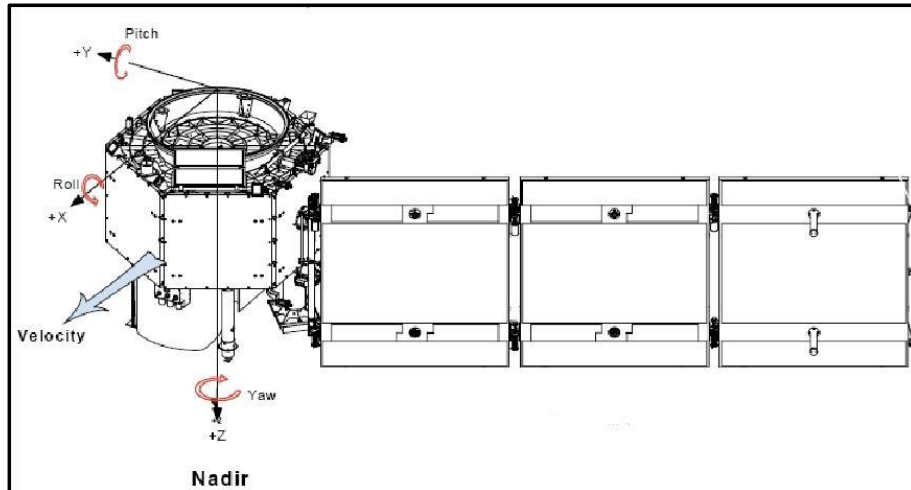
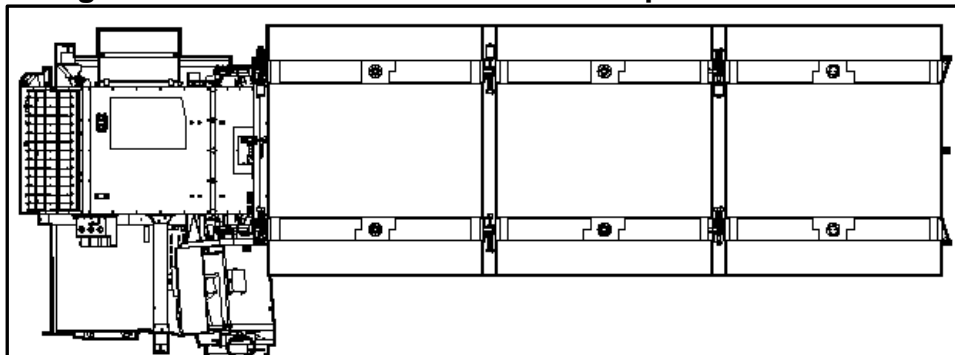**Figure 1. EO-1 in its nominal science operations attitude.**

Figure 1. View of Maximum Cross-sectional Area (A_{max}) of the EO-1 Spacecraft
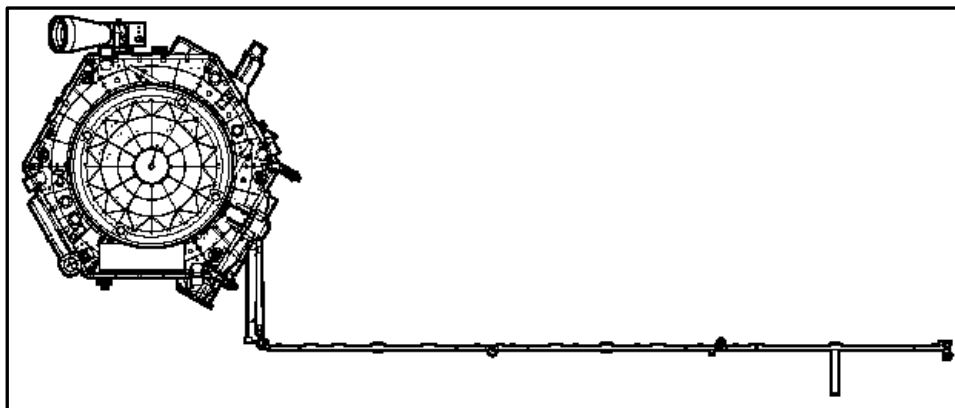

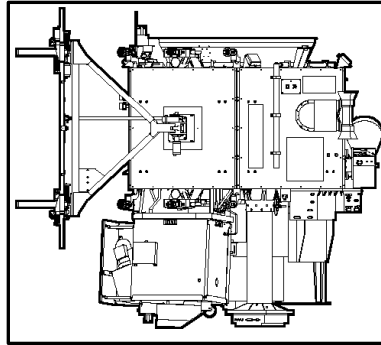**Figure 2. View of Cross-sectional Area (A_1) Orthogonal to A_{max}**

Figure 3. View of Cross-sectional Area (A$_2$) Orthogonal to A$_{max}$ and A$_1$

Table 1. Effective Drag Areas for Various Orientations

Orientation	Description	Effective Drag Area (m^2)	Percentage of Nominal Drag Area
Nominal Ops	Nominal science operations as shown in Figure 1 (solar array rotated 30° from the velocity vector)	5.37	100%
Minimum Drag 1	Solar array fixed as shown in Figure 1, but rotated to anti-ram direction (trailing the spacecraft)	2.86	53%
Minimum Drag 2	Solar array fixed as shown in Figure 1, but rotated to ram direction (leading the spacecraft)	2.86	53%
Maximum Drag	Solar array fixed as shown in Figure 1, and 15° to the velocity vector	8.04	150%
Orbit Decay	Tumbling following passivation	6.29	117%

4. Differential Drag Experiments

When the differential drag demonstration was first proposed as a part of the postmission experiments, the experienced Flight Operations Team engaged in discussions and evaluations of a variety of potential spacecraft configurations. Eight basic orientations were considered, and each was evaluated for expected power levels and thermal constraints, as well as attitude control subsystem capabilities. Of primary concern was to prevent spacecraft damage, and to regain control following the experiment, in order to ultimately comply with NASA policy to passivate the spacecraft as a part of disposal. On-board autonomy and safeguards would prevent serious damage, so long as the spacecraft remained powered. A key element of the experiment, then, was to identify the things to avoid in order for EO-1 to remain power positive. With the science mission concluded and the instruments powered down, only the spacecraft bus subsystems were drawing power. The EO-1 mission did not possess high-fidelity simulators, but the team of operators, some dating to before launch, felt confident in their appraisals.

The Minimum Drag 1 orientation was the first configuration to be tested. This involved parking the solar array parallel to the nadir-zenith line, and rotating the spacecraft so

that the array trailed behind the spacecraft (+Y becoming the velocity direction). The intent was to hold this orientation for a few hours as a test, then extend to a longer duration. The spacecraft remained in this orientation for only just over one hour before becoming power-starved and entering safehold mode. In safehold mode, the EO-1 spacecraft parks the solar array (as it already was parked), then allows the spacecraft attitude to vary as necessary to maintain the solar array pointing directly at the Sun, ensuring maximum power to the spacecraft survival systems. Unfortunately, no telemetry was available to record the spacecraft attitude during the safehold period, so it is impossible to estimate the drag area after the first hour of this experiment.

The second experiment was the Minimum Drag 2 orientation, in which the solar array was parked as before, but with the spacecraft rotated so that the array led the spacecraft (-Y becoming the velocity direction). This orientation was held for approximately twelve hours, until the star tracker overheated, causing the spacecraft to again enter safehold mode. As before, because the safehold mode drag area is unknown, the quantitative data is not useful. However, both experiments contributed to the operations lessons, as described below.

A third experiment was more successful in terms of stability and potential for generating quantitative data. The Maximum Drag orientation involved parking the solar array as before, then rotating the spacecraft so that the velocity vector was 15° off the +X axis, so that the solar array was nearly normal to the velocity vector. The team judged this configuration to be the most sustainable high-drag orientation possible for EO-1. The solar array was rapidly rotated 180° and the spacecraft was rotated 30° twice per orbit to keep the array facing the Sun, so the area remained the same before and after the brief transitions. The EO-1 spacecraft maintained this orientation for 39 hours, and appeared to be long-term stable.

5. Results

The EO-1 ephemeris was calculated and reported by the Flight Operations Team three times per week, based on two-way Doppler tracking data from three ground stations. The effective drag area (from the ballistic coefficient) was calculated from this definitive ephemeris data as a routine data product throughout the mission. This data continued to be available after science operations had ceased, throughout the postmission shutdown process.

Differential drag experiments were performed between day-of-year 72 and 76 of 2017, during relatively low solar activity (f10.7 ≈ 69 sfu). Ephemeris data was studied before and after the experiments as a control representing the nominal science operations orientation. For the maximum drag experiment timeline, the actual ephemeris data was compared to the propagated nominal orbit using Goddard's General Mission Analysis Tool GMAT[7]. The maximum drag experiment was started at midnight GMT on day 074 and continued for 39 hours total.

As previously described, the minimum drag orientations cause the spacecraft to enter safehold mode, resulting in a continuously varying and unreported attitude, preventing an estimate of the actual drag area during that period. The Flight Operations Team reported a 13% overall increase in the effective drag area during and after the

minimum drag area tests, comparable to the 17% increased drag expected during random tumbling. For the period including the maximum drag test (including some time in the nominal attitude), the effective drag area increased by 36% relative to the nominal case. This can be compared to the ideal 50% increase in the estimated drag area based on spacecraft geometry.

Equation 1[9] was used to calculate the change in semimajor axis during nominal operations and again for the time between the start of the maneuver and the end of the maneuver.

$$\text{Equation 1:} \qquad \Delta a_{rev} = -2\pi \left(\frac{C_D A}{m}\right) a^2 \rho_P e^{-c}[I_0 + 2eI_1]$$

The coefficient of drag was $C_D = 0.151704$.   The semimajor axis was $a = 7060.5565\ km$. Average atmospheric density during the 39-hour timespan was $\rho_P = 7.966\text{E} - 6\frac{kg}{km^3}$.   The largest observed atmospheric density at perigee was $\rho_P = 1.376 - 5\frac{kg}{km^3}$. The eccentricity was $e = 0.0017$. The density scale height was $c = 0.1209$. The zeroth order Modified Bessel Function was $I_0 = 1.0037$ and the first order was $I_1 = 0.0605$. Under these conditions, for a 39-hour timespan, the semimajor axis should theoretically be reduced by 0.135 meters in the Nominal Ops orientation and by 0.202 meters in the High-drag orientation. Reducing the semimajor axis will also cause the spacecraft to speed up due to conservation of angular momentum. This small increase in velocity is what would cause the in-track displacement and be used to avoid collision.

Analysis of the definitive ephemeris during the maximum drag test was challenging due to the very loose tolerances on the spacecraft tracking during operations. When the flight dynamics team did the orbit determination, they used the RIC report to compare the Radial, In-Track, and Cross-Track position with tolerances as follows:

Radial: (+/-) 0.15 km
Cross-Track: (+/-) 0.15 km
In-Track: (+/-) 0.5 km

The data showed an in-track position change of 0.154 km (relative to a simulation with no drag maneuver) during the 39-hour experiment, but that is within the accepted position error tolerances so it cannot be considered a usable observation. We cannot say for certain whether the drag maneuver caused any changes in the semimajor axis, velocity, or along-track position, or whether changes even happened.

6. Operations Lessons

One of the main objectives of these experiments was to identify the logistical implications of implementing differential drag for a spacecraft not designed to perform this technique. One potential application for differential drag might be to provide non-maneuverable spacecraft with an option for conjunction avoidance, so identifying challenges and best practices ahead of time is valuable.

Not surprisingly, the team concluded that implementing differential drag for such maneuvers would be far easier and more reliable if tighter-tolerance tracking

requirements and a maneuver capability were introduced during the design of the spacecraft hardware and operations scenarios. For example, had the thermal impacts of holding in Minimum Drag 2 orientation been recognized early, perhaps some accommodations could have been made to prevent the spacecraft from entering safehold mode. Or, had the position ephemeris been required to have tolerances of (+/-) 0.02 km as is used with the Aqua and Aura spacecraft[10] (which are in a similar orbit to EO-1), then the results might have shown the maneuver to be effective. EO-1 receives the same fidelity tracking data as Aqua and Aura from the ground stations in the form of Two-way Doppler, but about half as often. Adapting an existing operational mission to use differential drag maneuvering carries a number of constraints, and requires considerable evaluation and simulation to identify stable orientations. Once a stable orientation is determined, it should be tested well ahead of it being needed, both to confirm the stability and to measure the actual effectiveness of increased or decreased drag. Performing such tests during the mission, however, comes at the cost of operations time.

Especially when using differential drag for an unusual maneuver (as opposed to routine constellation maintenance), early planning is important to identify the necessary commands and communication strategies. Conjunction warnings only allow a few days to evaluate the risk, decide on a strategy, plan a maneuver, and execute it. A differential drag maneuver itself can take days to produce significant spacecraft orbit displacement, so it is important to have such contingency plans ready ahead of time.

This experiment was enabled by a management and operations team who were willing to consider the use of the spacecraft as a testbed. During the postmission period, unconventional operational modes can sometimes be studied and attempted, which might not be allowed during nominal operations. The planning, operations, and results of this experiment provided a wide range of educational opportunities, demonstrating the value of allowing such postmission testbed experiments.

7. Conjunction Avoidance Potential

A number of factors determine whether differential drag can be used effectively for conjunction avoidance maneuvering. Goddard mission operations experience shows that such a maneuver generally requires a displacement of about 20 to 120 meters to be effective. This displacement distance is based on a number of factors, including the uncertainties in orbit determinations for the two objects, drag variations during the propagation period, and the solar activity (larger maneuvers are needed near solar maximum). Some missions could inherently be candidates for differential drag displacement of these magnitudes, and others will not.

Using a change in the drag on the spacecraft for maneuvering implies that there is appreciable drag during nominal operations. While the ORBCOMM constellation employs differential drag effectively to maintain the constellation spacing at 780 km and above, the displacement necessary for conjunction avoidance must be accomplished within no more than 48 hours, preferably sooner. The higher drag needed to induce such a rapid maneuver effectively limits the candidate orbit altitude

to approximately 700 km and below. Differential drag maneuvers below 600 km altitude would be more practical.

The higher degree of anisotropy in a spacecraft cross-sectional area, the greater potential there will be for effective differential drag maneuvering. Large deployed solar array wings can generally allow the drag area to be varied significantly. Bear in mind that a decrease in the drag area relative to nominal operations may in fact be more effective than an increase. A collision can be avoided by sufficient displacement in any direction. Effective differential drag maneuvers for collision avoidance require that the drag area can be varied considerably, probably at least 30% for most candidate orbits.

As observed for the EO-1 spacecraft, the design of the spacecraft hardware (or remaining capability late in the mission) may not support differential drag maneuvers of more than a few hours. Battery capacity, for example, limits the duration that a spacecraft can maintain an attitude with the solar arrays parked for increased or decreased drag. Attitude control components (such as reaction wheels) need to have sufficient control authority to attain the desired spacecraft attitude, and then maintain that attitude against perturbing forces including drag. Thermal excursions can become a problem when a spacecraft is placed into an unusual attitude for an extended time, so if possible simulations should be used to examine thermal effects on key hardware components. Some spacecraft components (such as sensitive science instruments) may also place restrictions on the available spacecraft attitude choices in order to prevent damage from sunlight. The uniqueness of each spacecraft and mission design may have stronger bearing on the potential for differential drag maneuvers than the orbit or drag area. One potential option may be the intentional commanding of safehold mode, which is designed to be safely maintained by the spacecraft, and may offer a significant change in the effective drag profile. For EO-1, the effective drag on the spacecraft increased by approximately 15 % due to time spent in safehold mode.

A further factor in the effectiveness of differential drag for conjunction avoidance is timely decision making. Initial conjunction warnings often predict close approaches as much as seven days before the time of closest approach, but can be shorter due to a number of factors. Decisions to perform an avoidance maneuver are typically made only after additional refinements to the tracking data, and risk assessment analyses. All of this takes time, which can reduce the duration of any differential drag maneuvers, and therefore their effectiveness. Early preparation can help to mitigate the impact of the time inherent in the decision process.

Simulation and testing can be used to prepare for differential drag maneuvers before they might be needed. High fidelity simulations can be used to examine the long-term stability of a spacecraft orientation in terms of attitude control authority, thermal limits, and power status. On-orbit tests can be used to verify the stability of the orientation, and also to measure its effectiveness for displacing the spacecraft. Performing these tests early in the mission can contribute crucial information for the avoidance maneuver decision-making process.

8. Theoretical Alternative Disposal

As a hypothetical scenario, disposal of the spacecraft by maintaining maximum drag will be studied to identify potential benefits and risks. EO-1 included sufficient on-board autonomy that it likely could continue to maintain a commanded orientation without further ground contact, but there are other factors to consider. Note that the EO-1spacecraft was passivated (all systems disabled to the extent possible) at the conclusion of the mission, and it is believed to have begun slowly tumbling during the orbit decay process, so this scenario can not be enacted at this stage.

The asymmetrical nature of the EO-1 spacecraft should cause it to tumble due to drag and other perturbations, soon after the attitude control was disabled. The spacecraft was disabled on March 30, 2017, with a projected orbital decay period of 38.3 years, assuming a tumbling spacecraft. NASA policy is to passivate a spacecraft as completely as possible for those missions using uncontrolled (not targeted) reentry for disposal. The EO-1 spacecraft was passivated per this policy.

As shown in Table 1, the drag area for a random tumbling spacecraft has been estimated as 6.29 m^2, about 17% more than the drag experienced during nominal operations. If the spacecraft could have maintained maximum drag orientation throughout the orbital decay period, that drag area would be estimated as just over 8 m^2, approximately 28% greater than for the tumbling case. The higher drag area would result in a projected orbital decay period of 29.0 years, 9.3 years sooner than the passivated tumbling scenario. Further, the risk of large object collision during the orbit decay period (estimated using DAS 2.1.1[8]) is reduced from 0.00083 to 0.00073, a 12 percent decrease. Considering only this information, method of disposal might appear advantageous, but there are other factors to consider.

It is far from assured that the EO-1 spacecraft could have maintained a maximum drag orientation throughout orbital decay. The spacecraft itself had already been active for over 16 years – having been designed for only a one-year primary mission. It would be impossible to predict the remaining life of the momentum wheels, not to mention the attitude control electronics and other avionics needed to command the wheels autonomously, but a total lifetime of over 46 years is probably unreasonable. In addition, a demonstration of 39 hours of seemingly stable performance in the maximum drag orientation is insufficient to conclude that the spacecraft would truly remain long-term stable throughout seasonal changes. If the spacecraft were to fail to maintain the maximum drag orientation, though, it would likely begin tumbling, which would simply result in the nominal orbit decay from the point of failure.

A maximum drag disposal for EO-1 would also violate NASA policy to passivate a spacecraft to the extent possible at the end of the mission. This policy is consistent with international guidelines, and it is based largely on preventing the potential for unanticipated responses on the spacecraft, which could possibly generate orbital debris. In fact, un-passivated spacecraft and launch vehicle stages are known to have generated a significant portion of the debris currently in the LEO region. Using a maximum drag disposal scenario for EO-1 would have placed the spacecraft into a condition it was neither designed nor tested to accommodate long-term. Preventing potential unexpected and undesirable consequences is perhaps the best reason not

to implement an autonomous maximum drag orbital decay strategy after decommissioning.

9. Conclusions

The adaptation of differential drag for non-propulsive maneuvers of spacecraft not designed for that purpose has been described. A recent demonstration of this technique using the EO-1 spacecraft has not shown that sufficient displacement could be generated to avoid a conjunction, due to loose tolerances on tracking data. Observations and lessons from the spacecraft operations perspective have also been described, including the value of early mission-specific planning and testing. The factors that determine the suitability of this technique for existing mission hardware have also been discussed. Finally, a hypothetical scenario for maintaining high drag to accelerate orbit decay was explored, including the potential benefits and risks.

Acknowledgements

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