Appendix B
# EO-1 Waiver

## Standard TA Waiver Request Form (100407INTERIM with mods)

<table>
<thead>
<tr>
<th>Organization Requesting Waiver:</th>
<th>Date of Request:</th>
<th>System Waiver #:</th>
<th>Title: EO-1 Orbital Lifetime</th>
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<tr>
<td>Science Mission Directorate</td>
<td>Oct 12, 2007</td>
<td>OD-07-05</td>
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<tr>
<th>Initiator Name/phone/e-mail/Organization:</th>
<th>Waiver effects:</th>
<th>Duration of Waiver:</th>
<th>Waiver Risk Scope:</th>
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<tbody>
<tr>
<td>Cheryl Yuhas 202/358-0758 <a href="mailto:Cheryl.L.Yuhas@nasa.gov">Cheryl.L.Yuhas@nasa.gov</a></td>
<td></td>
<td>until atmosphere reentry</td>
<td>Worldwide</td>
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<table>
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<tr>
<th>Requirement needing Waiver:</th>
<th>Waiver Risk Scope:</th>
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<tr>
<td>Document: NPR 8715.6</td>
<td>Worldwide</td>
</tr>
<tr>
<td>Paragraph: 3.3.2.3</td>
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<tr>
<td>System Requirement ID #: 56876</td>
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<tr>
<th>Additional Documentation Affected:</th>
<th>Risk Affected by Request:</th>
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<tr>
<td>New Millennium Program (NMP) Earth Observing – 1 (EO-1) Orbital Debris Assessment (November 1999)</td>
<td>♦ None</td>
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<tr>
<th>Parentage of Requirement:</th>
<th>Lead TA &amp; Role:</th>
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<tr>
<td>NASA requirement established to assure compliance with National Space Policy (Section 11)</td>
<td>SMA Lead</td>
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<td>CE Mandatory</td>
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<td>CHMO N/A</td>
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<td></td>
<td>Other {none}</td>
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## Text of Requirement to be Waived:

3.3.2.1 Maneuverable spacecraft that are terminating their operational phases at altitudes of less than 2000 km above the Earth shall be maneuvered to reduce their orbital lifetime, commensurate with 25-year low-Earth orbit lifetime limitations, or relocated, when feasible, if analysis shows the probability of collision with large objects exceeds criteria for objects in these highly utilized orbit regions (Requirement 56876).

## Summary of Waiver Requested:

Allow the EO-1 spacecraft to decommission at an orbit of 705 km apogee, 685 km perigee. In this orbit, EO-1’s orbital lifetime is estimated to be 32 years, which exceeds the policy requirement of 25 years. Spacecraft will be passivated at decommissioning.

## Alternate Requirement to be Imposed:

The EO-1 shall decommission at an orbit not to exceed 705 km apogee, 685 km perigee, commensurate with a 32-year low-Earth orbit lifetime. An End-of-Mission Plan, including passivation plans, will be submitted 15 November 2007.
Reason/Justification for request:

Per the National Space Policy of August 2006 paragraph 11, SMD confirms that the need for this waiver is consistent with mission requirements and cost effectiveness, in the operation of the EO-1 spacecraft.

EO-1 is currently producing good science supporting NASA’s Earth Science Objectives and the national Earth Observing system. In addition to use by NASA-funded researchers, EO-1 data continues to be requested by numerous U.S. agencies and universities through the U.S. Geological Survey (USGS) land remote sensing archive at the Center for Earth Resources Observations and Science (EROS). EO-1 is also employed by the international Committee on Earth Observation Satellites (CEOS) for calibration/validation intercomparison studies and is a registered component within the Global Earth Observation System of Systems (GEOSS) Initial Operational Capability.

The spacecraft is in a 705 km x 685 km orbit at a 98-degree inclination. The Mean Local Time (MLT) of the descending node has drifted below 10:00 and is continuing to decrease. Project scientists indicate that an MLT value of 10:00 is the minimum operating value for the HyperSpectral instrument, since the HyperSpectral imaging signal-to-noise ratio (SNR)—and hence the quality of the science collected—rapidly degrades as MLT dips below 10:00. In addition, project scientists indicate that further lowering of the EO-1 orbit will cause ground track velocities to be high enough to cause gaps in imagery due to undersampling and variable pixel sizes, i.e. additional lowering of the orbit will make the science data collected unusable.

Preserving science quality requires both MLT to be maintained above 10:00 and the altitude to be maintained at its current value. To maintain an MLT above 10:00, the EO-1 project proposes to use the remaining ~7kg of fuel to perform inclination maneuvers for the remaining life of the mission (estimated to be approximately 4 years). These maneuvers will maintain MLT without lowering altitude. Science data quality is preserved with regards to the abovementioned concerns. At the end of four years, the projected orbit has an apogee of 705 km and a perigee of 685 km.

If the waiver in question is granted, EO-1 will passivate and decommission the satellite when useful science operations have ceased. Passivation & decommissioning plans include:

- All remaining hydrazine will be purged by utilizing orbit-lowering burns with increasingly long burns to evacuate propellant out of the thrusters into the vacuum of space.
- To minimize re-entry time, the spacecraft will be placed in a sun-pointing safehold attitude with the solar array parked so as to increase orbital drag. The reaction wheels will be used to maintain that re-entry attitude. The reaction wheels have internal over-speed protection to reduce the possibility of compromising the housings.
- The Command and Data Handling (C&DH) Mongoose will have all Failure Detection and Correction (FDCs) and Real Time Sequences (RTSs) zeroed out so there will be no possibility of recovery from safehold.
- There is no way to disconnect the battery or vent the remaining GN2 pressurant in the fuel tank, but the remaining GN2 will be approximately 1/16th the tank burst pressure > 680 psi). Heaters will remain ON to minimize charge to the battery. Instruments will be OFF. S-Band transmitter can be left either on or can be commanded OFF. NASA may make this decision in the future prior to excessing the Mission Operations Center equipment at GSFC.
- When EO-1 finally re-enters the atmosphere, it has a smaller than 1 in 10,000 possibility of collision with anything on the Earth’s surface.

An EO-1 End of Mission Plan with full details of this passivation and decommissioning procedure will be delivered 15 November 2007.

Summary of Additional Information Supporting the Waiver Request Attached:

Attachment A. Excerpts on EO-1 from the 2007 Earth Science Senior Review report.
Attachment C. Memo from R. DeHart & B. Sahin “Analysis of EO-1 Reentry Flight Profile Once at
Attachment E. E-mail from Orbital Debris Program Office.

**Change in Risk if Waiver is approved:** (Include stated requirement risk and risk due to Waiver)

The EO-1 initial decay orbit will not meet the Requirement 56876 in NPR 8715.6, which will extend the orbital lifetime by approximately 7 years beyond the policy limit, increasing the opportunity for collisions, potentially resulting in generation of new orbital debris. During this extended orbital lifetime, the EO-1 will pose a risk to Public Assets (i.e. operational satellites), but not a public safety risk.

**Summary of Risk Mitigation to be added/modified:**
Nominal monitoring of passivated NASA satellites will be sufficient unless a problem is detected.

**Summary of Risk Quantification Analyses and Mitigation Plans attached:**
N Johnson e-mail dated 10/3/07

<table>
<thead>
<tr>
<th>Required Signatures (per NPR 7120.5C/D Paragraph 3.1 &amp; NPR 8715.3 paragraph 1.13)</th>
<th>Signature</th>
<th>Date</th>
<th>Concur/Approve</th>
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<td>OCE TA Concurrence:</td>
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<td>12/20/07</td>
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<tr>
<td>NASA Lead TA:</td>
<td>Chief, SMA</td>
<td>12/21/07</td>
<td>Accept &amp; Grant</td>
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</table>

**Dispositioning TA Comments:** None

**ATTACHMENTS to EO-1-ODA-1:**
A. Excerpt on EO-1 from the 2007 Earth Science Senior Review Report
C. Memo from R. DeHart & B. Sahin “Analysis of EO-1 Reentry Flight Profile Once at Conforming Orbit” dated September 24, 2007
D. Memo from R. DeHart & B. Sahin “Mean Local Time (MLT) Control Options Summary” dated October 2, 2007
E. E-mail from Orbital Debris Program Office, October 3, 2007.
Attachment A: Excerpts from the 2007 Senior Review

Senior Review Summary Report:
(4) EO-1: The Committee finds EO-1 to be unique among current NASA missions. Originally designed as a technology demonstration, the mission continues to serve this purpose by way of a flexible and largely autonomous spacecraft, a unique hyperspectral imager, and an innovative data collection approach. The Committee also finds this asset to be underutilized by the NASA science community due to weak financial and programmatic support leading to insufficient data availability. Increased NASA programmatic support could transition the EO-1 mission from a small technology demonstration to a broad science and applications test bed. This would allow for

an expansive use of the EO-1 ALI and Hyperion data across science disciplines, and at the same time, advance the methods for autonomous (cost-effective) spacecraft, instrument and tasking operations already initiated by the PI. The Committee finds the core mission merits funding through FY2009, with potential extension through FY2011, but with increased funding from NASA Headquarters to facilitate an increased use of EO-1 data throughout the Earth science community.

Senior Review Detailed Evaluation:
EO-1

Instrument(s): ALI and Hyperion
Research Activities: Technology demonstration for highly automated data collection, Sensor webs for volcanic activities, Ecosystem characterization
Data Product Names: Multispectral and hyperspectral images
Science Strengths/Weaknesses: Strength is agility / flexibility to collect data in response to events such as hurricanes, volcanic eruptions, floods, forest fires, etc.
Relevance to NASA Science Goals: HIGH
Maturity of Data Products: HIGH

General Comments
EO-1 is the first and only Earth Science New Millennium Program (NMP) mission to make it into orbit. As a technology demonstration, it has successfully pioneered a number of new techniques (e.g., formation flying, shared launch with SAC-C, automated spacecraft tasking, onboard processing, and spectroscopy). Launched in November 2000 with a nominal expected lifetime of one year, and a second year for data analysis, the prime mission ended in 2002. This mission has thus been in extended mode since January 2003. Currently, the satellite acquires approximately 100 scenes total per week from the ALI and Hyperion instruments. “Collects” are scheduled based on a variety of purposes (events such as storms or volcanic eruptions, requests from NASA HQ, DoD, and “paying customers,” on-orbit calibration, and “filler” scenes collected for historical value).

EO-1 began as a NMP demonstration of flight technology, but has recently morphed into a facility instrument that provides a unique demonstration two satellite capabilities: (1) high-resolution (30 m) hyperspectral (10 nm) remote sensing at prescribed look angles; and (2) a rapid-response high resolution imager that can retrieve scene data within a few hours to one day. These satellite capabilities are unique in the civilian sector and provide data that are
relevant to NASA’s mission. This is the first time it has been considered by a Senior Review, whereas earlier efforts to justify continued mission operations have been based on a variety of criteria. The mission operation, data acquisition and archiving were transferred to the USGS EROS Data Center (EDC) after the prime mission with the intent to support mission operations by selling data. The cost of a tasking request and scene delivery was initially about $5K but is now reduced to $750 for tasking and $500 or less per image for distribution for acquisitions requested by the general public, and scenes in the archive can be ordered for the cost of reproducing data. There are efforts underway by the GSFC management team to facilitate free and open access to data by NASA-sponsored investigators. This is a critically important step since the previously stated costs for EO-1 data have likely precluded their widespread use by the scientific community.

Detailed Comments

(1) With the possible exception of data collected over coral reefs, atolls, and islands (see below), there has been no effort made to collect long-term systematic data records. The collection of scenes is ad hoc. One (possible) exception is the collection of coral reef, atoll and island scenes in support of the ESD mid-decadal study, an effort that was undertaken in the wake of the Landsat-7 anomaly. This collection focused on a time frame of 2004-2006, and will be repeated again in 2009-2011 if the mission is extended.

There are numerous projects that utilize EO-1 data to address science goals consistent with NASA’s Science Strategic Plan, but these are not explicitly included as part of the continued or enhanced mission. These could have been included as ‘in kind.’ It would be a stronger proposal if they had identified a couple of key facilitating tasks directly funded as part of the project that ensure some of the key developments continue (e.g., sensor web and highly automated collection).

(2) The proposal makes no distinction between “basic continuation” and “enhanced science.” The ad hoc nature of data collection allows for the use of EO-1 data collection in response to natural and anthropogenic hazards/disasters, and the development of new technologies (e.g., sensor webs that alert observing systems of volcanic activity) allow experimental use of the sensors. This flexibility (agility) has merit because use of EO-1 to collect ‘event/rapid response’ data or experiment with new techniques does not interrupt data streams from the systematic global missions.

(3) EO-1 was initially flying in formation with Landsat 7, Terra, and SAC-C as part of the morning constellation. The redundancy of collecting visible/NIR data for the same scene with different spatial and spectral resolution was deliberate, and has led to improved algorithms for future mission (e.g., LDCM, HyspIRI). This purpose does not justify continued operation of the mission because the algorithm development efforts can be carried out with data in hand (over 30,000 scenes). A complementary application of EO-1 data is for cross-calibration of other visible/NIR sensors. This purpose could justify continued operation, but the proposal lacks detail about the calibration / characterization of the ALI and Hyperion sensors. Use of one or both of these instruments as a “transfer radiometer” to cross-calibrate other sensors requires that their own calibration be well characterized. ASTER on Terra lists an enhanced mission goal of expanding the volcano sensor web initiated by EO-1 to alert ASTER to collect data.

(4) There is no E/PO plan in the proposal, but in many respects, the ability to collect images in response to disasters serves an E/PO purpose. These “secondary criteria” are actually the primary reasons for continuing the mission. That is, the mission is continuing to be used for technology development (e.g., sensor webs, Open Geospatial Consortium demo, ESTO AIST funded projects, Nabster, etc.). The cost is very low. The proposal is only to continue mission
operations at a minimum level to schedule, collect and distribute data to serve science and technology development efforts funded by other means.

(5) The flight demonstration of the hyperspectral images HYPERION is complete, and now HYPERION is being used to support specific, individual field investigations or data gathering (e.g., coral reefs) and to develop new satellite missions. The ability to gather HYPERION data at different look angles provides an observational simulation system that can test the necessary spectral/spatial needs for new instruments. Such data cannot be acquired from aircraft instruments. The spacecraft has been re-programmed to act as an autonomous scheduling and data acquisition platform with a response time to high priorities within one orbit. The scheduling algorithm merges with Air Force weather data to determine if the target is cloud-free for that orbital pass. It works with a 'web' of other sensors (in situ, satellite) that creates autonomously a 'request' and 'location' and 'time' for the EO-1 acquisition. Such capability is expected for national technical means but unheard of in the civilian sector. The commercial very-high-resolution satellites QuickBird, Ikonos) can be targeted, but the response time for data acquisition and distribution is generally far too slow (10 days) for observing transient science or responding to geohazards.

(6) The proposal is to continue the mission throughout the four year proposal window, or as long as the satellite and sensors continue to operate. Continuation of the mission and the many 'in kind' uses of the data has largely depended on the continued lead evangelism of one or two individuals and the contributed time of others who built the hardware and have a personal interest in its continuation. It appears to be operating outside of the realm of the other earth science missions at the GSFC. It would be worthwhile to develop a strategy for succession of this 'management team' in the event of personnel changes. A problem with the effective utilization of the EO-1 satellite lies in the very limited use of this facility by NASA to define future missions. EO-1 is being used as a gap-filler for some projects (e.g., coral reefs, other field studies), but there is no clear plan for proposals to use EO-1 as an observing simulator. There also appear to be a large set of "in-kind" users for individual science projects. The 'sensor web' project is being highlighted for individual geo-hazards and possibly outreach, but the capability of rapid acquisition of transient geophysical events has potential application beyond volcanic plumes (e.g., landslides, major air pollution events, dangerous chemical releases, etc). Use of the autonomous schedule/acquisition for volcanic plumes is included in Terra's enhanced mission. The Committee observes that by improving the organizational structure via HQ support and some additional project level support to the EO-1 team could significantly enhance the value of EO-1 to Earth science. The project needs to develop a plan for how the data will be used (e.g., for simulating future missions, for demonstrating sensor web technology, and for cross-calibration of orbiting sensors). It could be valuable as a facility, but currently is it "below the radar" and too dependent on the energy of an individual investigator.
To: S. Frye, S. Hunter, N. Lenora, L. Ong, S. Shulman  
From: R. DeHart, B. Sahin  
Date: September 6, 2007  
Re: Analysis of EO-1 Flight Profile Using Inclination Burns

INTRODUCTION

This document is a description of the projected flight profile for EO-1. For the past year, EO-1 has been executing orbit-lowering burns in order to reduce the rate of decrease in MLT. As of the date of this publication, EO-1 MLT is nearly 10:00 and is falling. With just over seven kilograms of propellant remaining, a decision will be made as to how to best utilize the remaining fuel while maintaining the flight profile for the rest of the mission.

The Landsat Data Continuity Mission (LCDM) has a scheduled launch date of no earlier than July 2011. In order to assist with LCDM baselining efforts, it would be desirable for the EO-1 flight profile to situate the spacecraft in a position to collect useful science data in the abovementioned timeframe. Thus, any fuel usage strategy would ideally:

1. Consume fuel at a pace that allows operations for at least four years
2. Maintain stable orbit altitudes for at least the next four years
3. Maintain EO-1 MLT values of approximately 10:00

In order to determine if inclination burns can be used to turn around EO-1 MLT values and meet the three demands listed above, the EO-1 Flight Operations Team (FOT) has conducted studies to project the effects of inclination burns on the EO-1 flight profile. This study includes examining what impact such burns will have on the EO-1 reentry timeline. The results of those studies are contained herein.

METHODOLOGY

The current EO-1 state has been used as a starting point for propagations, using FreeFlyer 4.8 as the propagation tool. In order to first stabilize MLT, two pairs of inclination burns are conducted. From this point onward, a targeting algorithm is used to initiate inclination burns if the MLT drops below 10:00. The EO-1 orbit was propagated until fuel was exhausted. The assumptions used in this portion of the study are listed below:

- Runge Kutta 8/9 Propagation
- Schatten Predicted Mean Nominal Solar Cycle model
- 21x21 JGM2 Earth Potential model
- Sun and moon perturbation effects included
- EO-1 dry mass of 548.2 kg
• EO-1 area of 6.03 m\(^2\)

• Propagation step size of 60 s

• Drag coefficient of 2.292456

• Solar radiation coefficient of 1.5

After fuel was exhausted, a reentry propagation was conducted, using Bulirsch Stoer VOP propagation. This propagation uses larger step sizes and is more efficient in terms of execution time required. A list of the assumptions used in this portion of the EO-1 propagation is listed below:

• Bulirsch Stoer VOP Propagation

• Schatten Predicted Mean Nominal Solar Cycle model

• 21x21 JGM2 Earth Potential model

• Sun and moon perturbation effects included

• EO-1 dry mass of 548.2 kg

• EO-1 area of 6.03 m\(^2\)

• Propagation step size of 300 s

• Drag coefficient of 2.2

• Solar radiation coefficient of 1.5

Note that the drag coefficient of 2.2 in the long-term reentry propagation assumes the spacecraft maintains attitude control. If the solar panel is instead allowed to drift into a position providing the minimum resistance, a lower effective value should instead be used.

Lastly, data for the Schatten Predicted Mean Nominal Solar Cycle model is only available to 2030. Any propagation past this point will have to be conducted in a manner that still includes the effects of the solar cycle. In this study, if a propagation ends in 2029 with EO-1 still in orbit, a separate run is executed to cover the time period after 2029. The state at 2029 is manually adjusted to show a date 2007 (to maintain the same relative position inside of the solar cycle). This state is then fed as input to the separate propagation.

RESULTS

The use of inclination burns to maintain MLT allows EO-1 to operate with fuel for approximately 4.4 years. This translates to the beginning of 2012. The resulting flight profile is shown in Figures 1 – 5.
Figure 1. Apogee and Perigee for EO-1 During Inclination Burn MLT Control

Figure 2. Semi-Major Axis for EO-1 During Inclination Burn MLT Control
Figure 3. Inclination for EO-1 During Inclination Burn MLT Control

Figure 4. Mean Local Time for EO-1 During Inclination Burn MLT Control
As shown in Figure 4, the inclination burn algorithm was able to maintain an MLT of approximately 10:00 for 4.4 years. Variations in MLT can also be observed in Figure 4. The discrete steps in remaining fuel shown in Figure 5 indicate that often three burns are required to return MLT to values above 10. This is caused by overshooting MLT on the previous set of burns. More active maintenance of MLT, performed by the FOT, during the inclination burns will most likely lead to more efficient use of fuel. In order to save computational time, the targeting algorithm used in these executions did not attempt to optimize fuel usage; rather the algorithm simply called for inclination burns if MLT decreased below 10. During this period of inclination burns, the FOT could conduct studies to optimize fuel usage before each burn. This may lead to a slightly longer life than 4.4 years.

After this period of inclination burns, a separate reentry propagation was executed. The results showed EO-1 to still be in orbit as of 2029. Hence, multiple runs were necessary, using the technique described in the Methodology section. The results of the first propagation, which spans the time from 2012 to 2029, are shown in Figures 6 – 9.
Figure 6. Apogee and Perigee for EO-1 During Beginning of Reentry

Figure 7. Semi-Major Axis for EO-1 During Beginning of Reentry
Figure 8. Inclination for EO-1 During Beginning of Reentry

Figure 9. Mean Local Time for EO-1 During Beginning of Reentry
Figure 7 shows the semi-major axis of the orbit to measure approximately 7045 km in 2029. This differs significantly from runs executed by FOT in 2002. Corresponding runs from that analysis showed EO-1 to have a semi-major axis of approximately 7000 km in that timeframe (with a reentry in approximately 2036). Before proceeding further with the current analysis, the above propagation was repeated, but using the Schatten Predicted Mean Nominal Solar Cycle data available in 2002. The resulting output agreed closely with that achieved in 2002. Thus, the higher-than-expected orbit shown in Figures 6 and 7 appear to be due to using solar data predictions that contain less activity than the predictions in 2002.

Since the propagation shown in Figures 6 – 9 take the EO-1 orbit out to 2029, a separate propagation was conducted to model the orbit in years after 2029, using the technique detailed in the Methodology section. The results, corresponding to years 2029 – 2055, are provided in Figures 10 – 13.

![FreeFlyer Plot Window](image)

**Figure 10. Apogee and Perigee for EO-1 During 2029 – 2055**
Figure 11. Semi-Major Axis for EO-1 During 2029 – 2055

Figure 12. Inclination for EO-1 During 2029 – 2055
The output of this propagation was examined to ensure that the technique described earlier did not cause the orbit to be discontinuous. Comparison of Figures 6 – 9 and 10 – 13 indicate that the continuity of the orbit was largely maintained. The one noticeable effect of this method is a break in the high-frequency oscillation of the orbit inclination. The inclination illustrated in Figure 8 exhibits a large-scale, low-frequency oscillation, in conjunction with a higher-frequency oscillation. The amplitude of this high-frequency oscillation grows over time. Inspection of Figure 12 shows the higher-frequency oscillation restarting at low amplitude and again growing with time. While not ideal, this inconsistency was accepted because of the need to model solar activity cycling. In addition, the effect of this inconsistency on the long-term trend of the orbit is minor.

Figure 11 indicates that EO-1 is projected to still be in orbit in the year 2055. Recall that solar cycle prediction data is only currently available until 2030. In order to project past 2055, the same “rollback” procedure was utilized as for the period 2029 – 2055. Namely, the solar activity during the period in question is assumed to be the same as that predicted for 2007 – 2029. While projections so far out may be tenuous, they are conducted here for the sake of thoroughness. The results are provided in Figures 14 –17.
Figure 14. Apogee and Perigee for EO-1 Past 2055

Figure 15. Semi-Major Axis for EO-1 Past 2055
Figure 16. Inclination for EO-1 Past 2055

Figure 17. Mean Local Time for EO-1 Past 2055
Solar cycle predictions become unavailable for this propagation after approximately day 7000. This is exhibited by the lack of changes in the slope of the semi-major axis curve that appears in Figure 15. The propagation past this point (which is the year 2074) does not contain adequate solar data and should be ignored.

CONCLUSIONS

The analysis conducted in this study indicates that EO-1 has sufficient fuel to conduct inclination burns until the beginning of 2012. These burns would maintain MLT to values very close to 10.0, mostly ranging between 9.998 and 10.002. The resulting flight profile causes EO-1 to remain in orbit for many years. While propagations of similar flight profiles performed using 2002 solar activity projections had EO-1 reentering in approximately 2036, propagations performed with current solar predictions do not show EO-1 reentering for many decades. The unavailability of Schatten Predicted Mean Nominal Solar Cycle data past 2030 makes projections past this point somewhat tenuous. However, general trends can be discerned from this analysis. Namely, using current projections, if EO-1 utilizes inclination burns for MLT control, the spacecraft will likely not reenter for many decades, perhaps past the year 2074. The other observation that can be drawn from this study is that the magnitude of projected solar activity has a very large impact on predicted reentry time. In fact, if current estimates were revised to those levels predicted in 2002, EO-1 would be projected to reenter in approximately 2036.
To: S. Frye, S. Hunter, N. Lenora, L. Ong, S. Shulman, J. Young

From: R. DeHart, B. Sahin

Date: September 24, 2007

Re: Analysis of EO-1 Reentry Flight Profile Once at Conforming Orbit

INTRODUCTION

This document is a description of the projected reentry flight profile for EO-1. For the past year, EO-1 has been executing orbit-lowering burns in order to reduce the rate of decrease in MLT. As of the date of this publication, EO-1 MLT is below 10:00 and is continuing to fall. With just over seven kilograms of propellant remaining, studies and negotiations are underway as to how to best utilize the remaining fuel for the rest of the mission.

Recent analysis by DeHart and Sahin (“Analysis of EO-1 Flight Profile Using Inclination Burns”, dated September 6, 2007) suggests that the use of inclination burns for the next four years may cause EO-1 to require many decades to reenter. In that study, it was found that recent revisions to the solar flux predictions in the Schatten Predicted Mean Nominal Solar Cycle model had a large effect on the reentry timeline. More specifically, the reductions in solar flux predictions caused the reentry timeline to lengthen by many years. Propagations with similar initial conditions but different solar predictions exhibited vastly different results; in fact, using solar predictions published in 2002 caused EO-1 to reenter in approximately 2036, while using predictions published in 2007 caused reentry to occur sometime after 2074.

Perturbations of nearly any parameter in a long-term propagation can have a large impact. In part to address the inherent uncertainty involved with such propagations, NASA guidelines utilize a simplified parameterization where the mass and area of the satellite are utilized to determine the prescribed end-of-mission orbit. In the case of EO-1, the mass and area provide an orbit of 700 km at apogee, 600 km at perigee. This orbit, in theory, would cause EO-1 to reenter in a manner that conforms to the NASA guideline of 25 years.

The surprisingly long reentry times obtained in the abovementioned study raises many additional questions. Many of these questions center on how propagations using the latest Schatten solar predictions would compare to the reentry timelines obtained using the NASA mass/area parameterization. Two of these questions are addressed in this document. First, using propagations with the latest solar predictions, in how many years would EO-1 reenter if the spacecraft was at the conforming orbit? Second, does EO-1 have any excess fuel that is not needed to get to the conforming orbit, fuel that could be used for other activities, such as inclination burns?

METHODOLOGY

The EO-1 state as of September 19, 2007 was used as a starting point for propagations, utilizing FreeFlyer 4.8 as the propagation tool. In order to drop the EO-1 to the conforming orbit of 700-km apogee/600-km perigee, weekly orbit-lowering burns, which each drop the semi-major axis by 1 km, were conducted. The EO-1 orbit was propagated until the desired orbit was achieved. The assumptions used in this portion of the study are listed below:
- Runge Kutta 8/9 Propagation
- Schatten Predicted Mean Nominal Solar Cycle model
- 21x21 JGM2 Earth Potential model
- Sun and moon perturbation effects included
- EO-1 dry mass of 548.2 kg
- EO-1 area of 6.03 m$^2$
- Propagation step size of 60 s
- Drag coefficient of 1.918947
- Solar radiation coefficient of 1.5

Once in the desired orbit, a reentry propagation was conducted, using Bulirsch Stoer VOP propagation. This propagation uses larger step sizes and is more efficient in terms of execution time required. A list of the assumptions used in this portion of the EO-1 propagation is listed below:

- Bulirsch Stoer VOP Propagation
- Schatten Predicted Mean Nominal Solar Cycle model
- 21x21 JGM2 Earth Potential model
- Sun and moon perturbation effects included
- EO-1 dry mass of 548.2 kg
- EO-1 area of 6.03 m$^2$
- Propagation step size of 300 s
- Drag coefficient of 2.2
- Solar radiation coefficient of 1.5
- Any fuel left from above propagation remains unused

Note that the drag coefficient of 2.2 in the long-term reentry propagation assumes the spacecraft maintains attitude control. If the solar panel is instead allowed to drift into a position providing the minimum resistance, a lower effective value should instead be used.

Secondly, if any fuel remains after obtaining the desired orbit, this fuel will not be used. Since it is currently unclear as to how this fuel, if any, may be used, this study does not make any assumption as to how it may be used. In any case, investigation of flight operations records indicates that most likely very little fuel will remain.
Lastly, data for the Schatten Predicted Mean Nominal Solar Cycle model is only available to 2030. Any propagation past this point needs to be conducted in a manner that still includes the effects of the solar cycle. In this study, if a propagation ends in 2029 with EO-1 still in orbit, a separate run is executed to cover the time period after 2029. The state at 2029 is manually adjusted to show a date 2007 (to maintain the same relative position inside of the solar cycle). This state is then fed as input to the separate propagation.

Before proceeding to the results of this analysis, one point needs mentioning regarding the burn schedule used in this study. In practice the orbit-lowering burns would not be done on a weekly basis, since EO-1 is still actively collecting useful science data. However, the restricted nature of the solar data drove this investigation to insert EO-1 into the prescribed orbit as quickly as possible. In this manner, the reentry propagation will have as many years as possible with actual (as opposed to “rolled-back”) solar prediction data. On the other hand, it is desirable to mimic the orbit-lowering burns that would actually be implemented by the FOT. Hence, instead of using a few very long orbit-lowering burns, this study utilizes the same 1-km orbit-lowering burns that the FOT has been conducting. So to balance the desire to mimic FOT operations, yet to quickly enter the desired orbit, weekly 1-km orbit lowering burns were used.

RESULTS

The EO-1 spacecraft has sufficient fuel to use orbit-lowering burns to obtain the conforming orbit. The desired orbit is obtained in approximately one year. Recall that this schedule is not what would be operationally performed; rather, this quick lowering of the orbit was performed simply to maximize the number of years in the reentry propagation that will have actual solar data. The resulting flight profile is shown in Figures 1 – 5.
Figure 1. Apogee and Perigee for EO-1 During Orbit Lowering

FreeFlyer Plot Window
9/20/07

Figure 2. Semi-Major Axis for EO-1 During Orbit Lowering
Figure 3. Inclination for EO-1 During Orbit Lowering
Figure 4. Mean Local Time for EO-1 During Orbit Lowering

Figure 5. Fuel Remaining for EO-1 During Orbit Lowering
As shown in Figure 5, EO-1 ends this procedure with very little fuel remaining (0.308 kg). Most of the fuel margin that once existed for EO-1 was used in its last inclination burn.

After this period of orbit-lowering burns, a separate reentry propagation was executed. The results showed EO-1 to still be in orbit as of 2029. Hence, multiple runs were necessary, using the technique described in the Methodology section. The results of the first propagation, which spans the time from 2008 to 2029, are shown in Figures 6 – 9.

Figure 6. Apogee and Perigee for EO-1 During Reentry Until 2029
Figure 7. Semi-Major Axis for EO-1 During Reentry Until 2029

Figure 8. Inclination for EO-1 During Reentry Until 2029
Figure 7 shows the semi-major axis of the orbit to measure approximately 6967 km in 2029. This differs significantly from runs executed by FOT in 2002. A run from that analysis that roughly corresponds to the above scenario showed EO-1 reentering in approximately 2023. DeHart and Sahin first discussed this difference in the September 6, 2007 document “Analysis of EO-1 Flight Profile Using Inclination Burns.” It is due to the downward revisions in the solar predictions since 2002. In fact, it is this large impact that the downward revisions have that caused speculation as to whether propagations would show EO-1 reentering in 25 years even if the spacecraft was in a conforming orbit.

Since the propagation shown in Figures 6 – 9 take the EO-1 orbit out to 2029, a separate propagation was conducted to model the orbit in years after 2029, using the technique detailed in the Methodology section. The results, corresponding to years 2029 – 2050, are provided in Figures 10 – 13.
Figure 10. Apogee and Perigee for EO-1 During 2029 – 2050

Figure 11. Semi-Major Axis for EO-1 During 2029 – 2050
Figure 12. Inclination for EO-1 During 2029 – 2050
The output of this propagation was examined to ensure that the technique described earlier did not cause the orbit to be discontinuous. Comparison of Figures 6 – 9 and 10 – 13 indicate that the continuity of the orbit was largely maintained. The one noticeable effect of this method is a break in the high-frequency oscillation of the orbit inclination. The inclination illustrated in Figure 8 exhibits a large-scale, low-frequency oscillation, in conjunction with a higher-frequency oscillation. The amplitude of this high-frequency oscillation grows over time. Inspection of Figure 12 shows the higher-frequency oscillation restarting at low amplitude and again growing with time. While not ideal, this inconsistency was accepted because of the need to model solar activity cycling. In addition, the effect of this inconsistency on the long-term trend of the orbit is minor.

Figure 11 indicates that EO-1 is projected to finally reenter in the year 2050. Recall that the reentry propagation started in 2008. Hence, even though NASA procedures and guidelines suggest that EO-1 would reenter within 25 years if placed in a 700-km apogee/600-km perigee orbit, the above analysis suggests that the spacecraft would not reenter until 42 years have elapsed.

**CONCLUSIONS**

The analysis conducted in this study indicates that EO-1 has sufficient fuel to conduct orbit-lowering burns in order to place the spacecraft in an orbit that conforms to NASA guidelines. These burns would leave the spacecraft with 0.308 kg of fuel. Such a small amount of fuel is
probably not sufficient to conduct an inclination burn that would have any appreciable impact on the EO-1 orbit. Once in the conforming orbit, the propagations conducted in this analysis indicate that EO-1 would require 42 years to reenter, not the 25 years specified in NASA guidelines. These findings cast the results of the inclination burns analysis conducted by DeHart and Sahin in a new light.
To: S. Frye, S. Hunter, N. Lenora, D. Mandl, L. Ong, S. Shulman, J. Young

From: R. DeHart, B. Sahin

Date: October 2, 2007

Re: Mean Local Time (MLT) Control Options Summary

**ASSUMPTIONS**

This document is a summary of the main options available to both stabilize and maintain the EO-1 MLT. The spacecraft MLT is currently 9.9940 and falling, which is below the desired minimum value of 10. Any fuel used in maneuvers to stabilize MLT is fuel that will not be available later in the mission. Hence, any choices made about stabilizing MLT can directly impact the mission’s ability to meet NASA reentry guidelines.

The results presented in this document are primarily compiled from earlier analysis performed and reported by R. DeHart and B. Sahin in July – September 2007. As necessary, some results have been updated to reflect current conditions. Also, current data suggests 7.10 kg of fuel is available; these analyses assume this full amount is indeed available and no dramatic change in efficiency occurs.

**RESULTS**

Two types of MLT stabilization burns were considered. The burns required to stabilize MLT are described below. A matrix of the results and the follow-on MLT maintenance options is supplied in Table 1.

- Inclination burns to stabilize MLT: Four 900-s burns (pair on Oct. 9, pair on Oct. 11)
- Orbit-lowering burns to stabilize MLT: Four 2-km orbit-lowering burns (Oct. 9, Oct. 11, Oct. 16, Oct. 18) and one 1-km orbit-lowering burn (Oct. 23)

<p>| Table 1. Matrix of Options for Stabilization and Maintenance of EO-1 MLT |
|---------------------------------|----------------|----------------|----------------|
| Type of MLT Stabilization      | Option 1 | Option 2 | Option 3 | Option 4 |
| Inclination                     | Inclination | Inclination | Orbit-Lowering | Orbit-Lowering |
| Fuel Left After Stabilization   | 5.82 kg | 5.82 kg | 5.82 kg | 5.82 kg |
| Time Required for Stabilization | 1 week | 1 week | 2.5 weeks | 2.5 weeks |</p>
<table>
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<th>Type of MLT Maintenance</th>
<th>Orbit-Lowering</th>
<th>Inclination</th>
<th>Orbit-Lowering</th>
<th>Inclination</th>
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<td>Years MLT Maintained at 10</td>
<td>4.4 years</td>
<td>4.4 years</td>
<td>4.4 years</td>
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<tr>
<td>Approximate Apogee/Perigee at end of Maintenance</td>
<td>700 km / 615 km</td>
<td>705 km / 685 km</td>
<td>700 km / 600 km</td>
<td>705 km / 670 km</td>
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<tr>
<td>Meet NASA Guidelines for Initial Orbit Decay?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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</table>
John,

Over the years we have worked closely with the EO-1 project office. They have historically been very conscientious about complying with OD mitigation guidelines.

First, attached are the original EO-1 orbital debris assessment report (dated Dec 1999, but not submitted until early 2000) and our evaluation. Note that the last reentry risk assessment indicated that the spacecraft would be compliant with the 1 in 10,000 human casualty risk.

In late 2004, the EO-1 project office began looking at the consequences of further extensions of the mission (originally only scheduled for 1 year, i.e., ending in late 2001). Attached is a letter to Bryan O'Connor in November 2004 which sums up their plans at that time.

The fourth attachment is a history of the orbit of EO-1 (Satellite Number 26619) from launch in November 2000 through September of this year. You can see the series of orbit-lowering maneuvers since 2005.

Re the emails from EO-1 below, the most important issue is selecting the best solar prediction model to use for the next few decades. For various reasons, considerable disagreement currently exists in the international community on the character of solar activity for the next solar cycle. Some experts predict markedly lower than normal levels, while others envision average or even higher than normal levels. The degree of uncertainty of future solar activity is the greatest in recent memory.

We fundamentally disagree with a philosophy of selecting an older solar prediction model simply because it was used previously. Current evaluations should be based upon the best current models. On the other hand, the new Schatten model used by the EO-1 project is likely to underestimate, perhaps significantly, solar activity over the next cycle. Hence, the orbital lifetime predictions for EO-1 now reported by GSFC are likely pessimistic. From its current orbit and using an average solar activity model, we estimate a natural reentry in 2043. Assuming that the mission continues for four more years (see below), reentry would occur about 32 years after end of mission.

The 2 October 2007 memo from DeHart and Sahin describes four options which can stabilize the Mean Local Time (MLT). Maneuvers which only change inclination will have no significant effect on future orbital lifetime. To the greatest extent possible, while maintaining the necessary MLT, the EO-1 project should continue to employ orbit-lowering maneuvers, which might well bring the postmission orbital lifetime within the 25 year guideline.

If you have any questions about the above or the attachments, please do not hesitate to call.

Nick