DESIGN AND EVALUATION OF AN ACTIVE SPACE DEBRIS REMOVAL MISSION USING CHEMICAL PROPULSION AND ELECTRODYNAMIC TETHERS

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Introduction

- Space Debris: Critical Level LEO
- Kessler Effect
- Idea: Integrate de-orbiting system with an upper stage
- Each upper stage will de-orbit itself and space debris
- We can use upper stage subsystems during the mission, reducing mission costs.
Introduction: Flight Phases

- Launch and separation of payloads
- Maneuver to approach space debris
- Grab debris and control attitude
- Decrease inclination (chemical propulsion)
- Reduce altitude using EDT
Target Debris Identification

- Low earth orbit.
- Selected body: Kosmos 3M

Target Debris

- Kosmos 3M
- Soyuz
- Tsyklon-3
- Zenit
- Dnepr
- Thor Burner 2A
- Scout
- Other

157
27
10
8
11
19
14
33
Target Debris Identification

**SL-8 R/B**

- **Catalog ID:** 32053
- **International Designator:** 2007-038R
- **Country/Organization:** Russia/USSR
- **Perigee:** 596.00 km
- **Apeage:** 968.00 km
- **Inclination:** 83.00 deg
- **Launch Date:** 2007-9-11
- **Size (From Radar Cross Section):** 2.743748 m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Motion (deg/s)</td>
<td>0.0573292</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.002639</td>
</tr>
<tr>
<td>Inclination (deg)</td>
<td>82.976</td>
</tr>
<tr>
<td>Argument of Perigee (deg)</td>
<td>151.655</td>
</tr>
<tr>
<td>RAAN (deg)</td>
<td>233.421</td>
</tr>
<tr>
<td>Mean Anomaly (deg)</td>
<td>208.605</td>
</tr>
</tbody>
</table>
Launch Vehicle and Launch Site

- Analyzed all launch vehicles with
  - Upper stage restartability
  - Large payload mass for SSO
  - High propellant capacity
- Chosen Launch Vehicles:
  - Soyuz 2 with Fregat upper stage
  - Proton-M with Breeze-M upper stage
- Chosen Launch site:
  - Plesetsk (Russian Federation - 62°57′35″N, 40°41′2″E)
Mission Simulation in STK

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Velocity Increment (km/s)</th>
<th>Provided by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch to Park Orbit</td>
<td>-</td>
<td>Launch Vehicle</td>
</tr>
<tr>
<td>Altitude increase</td>
<td>0.105</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Hohman transfer</td>
<td>0.056</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Combined change</td>
<td>0.849</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 1 (83 to 74 deg)</td>
<td>1.71</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 2 (74 to 66 deg)</td>
<td>1.101</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 3 (66 to 53 deg)</td>
<td>1.809</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 4 (53 to 43 deg)</td>
<td>1.402</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 5 (43 to 29 deg)</td>
<td>1.576</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Inclination change 6 (29 to 18 deg)</td>
<td>2.808</td>
<td>Upperstage</td>
</tr>
<tr>
<td>Altitude Decrease (900 to 500 km)</td>
<td>Depends</td>
<td>EDT</td>
</tr>
</tbody>
</table>

ALTITUDE INCREASE 0.105
HOHMAN TRANSFER 0.056
COMBINED CHANGE 0.849
INCLINATION CHANGE 1 (83 to 74 deg) 1.71
INCLINATION CHANGE 2 (74 to 66 deg) 1.101
INCLINATION CHANGE 3 (66 to 53 deg) 1.809
INCLINATION CHANGE 4 (53 to 43 deg) 1.402
INCLINATION CHANGE 5 (43 to 29 deg) 1.576
INCLINATION CHANGE 6 (29 to 18 deg) 2.808
ALTITUDE DECREASE (900 to 500 km) Depends
EDT Model

- EDT mass 80 kg

\[
T(mN) = 0.0077 \times i^2 - 0.8542 \times i^2 - 21.315 \times i + 3391.5 \quad (i < 90^\circ)
\]

\[
T(mN) = -0.0001 \times i^4 + 0.0604 \times i^3 - 9.5709 \times i^2 + 646 \times i - 15987 \quad (i > 90^\circ)
\]
# Mass and Altitude Properties

<table>
<thead>
<tr>
<th></th>
<th>Soyuz upper stage (Fregat)</th>
<th>Proton upper stage (Breeze-M)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary payload mass (ton)</strong></td>
<td>1-3</td>
<td>4-5</td>
</tr>
<tr>
<td><strong>Vacuum specific impulse (s)</strong></td>
<td>327</td>
<td>325.5</td>
</tr>
<tr>
<td><strong>Propellant mass (ton)</strong></td>
<td>5.35</td>
<td>19.8</td>
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<tr>
<td><strong>Structural mass (ton)</strong></td>
<td>1</td>
<td>2.37</td>
</tr>
<tr>
<td><strong>EDT mass (kg)</strong></td>
<td>80</td>
<td></td>
</tr>
<tr>
<td><strong>Debris altitude (km)</strong></td>
<td>900</td>
<td></td>
</tr>
<tr>
<td><strong>Debris inclination (deg)</strong></td>
<td>83</td>
<td></td>
</tr>
<tr>
<td><strong>Kosmos 3M mass (kg)</strong></td>
<td>1435</td>
<td></td>
</tr>
<tr>
<td><strong>Target orbit (km)</strong></td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>
Results: Propellant use

(a) Propellant used versus inclination at which EDT is turned on for the Soyuz upper stage

(b) Propellant used versus inclination at which EDT is turned on for the Proton upper stage
Results: Residual Propellant

(c) Residual propellant versus inclination at which EDT is turned on for the Soyuz upper stage

(d) Residual propellant versus inclination at which EDT is turned on for the Proton upper stage
Results: De-orbiting Time

(e) Time to de-orbit versus inclination at which EDT is turned on for the Soyuz upper stage

(f) Time to de-orbit versus inclination at which EDT is turned on for the Proton upper stage
Conclusions

- Modified Soyuz or Proton upper stage equipped with a tether system, can deliver a primary payload to a 900 km polar orbit and connect to a Kosmos 3M 2nd stage to de-orbit it.

- It is clear that a hybrid solution using a chemical-EDT system is the best choice for this particular mission because of the short quantity of propellant left from previous stages of the mission.
Future Work

- Further simulation to refine the preliminary result
- Modelling the close approach, grabbing and stabilization of the space debris
- Simulating the EDT system using MATLAB
Acknowledgement

1. Analytical Graphics, Inc. (AGI)

2. Secure World Foundation
Thank you!
Space Safety and Sustainability Group

Sustaining space activities for future generations

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