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Debris Collision Avoidance by Means of Attitude Control - In-Flight Demonstration with TET-1

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Abstract

Collision avoidance is more and more of importance due to the growing amount of space debris posing a threat not only on satellites in orbit but also on upcoming missions. To avoid a collision between space debris and functioning satellites or even between two functioning satellites collision avoidance manoeuvres can be induced if one of the satellites has a functioning propulsion system. An alternative method of collision avoidance operations is presented in this study. By changing the satellites attitude, it is possible to obtain an increase or decrease in the semi-major axis in relation to its nominal orbital decay. The change in the semi major axis together with the time until closest approach provokes a change in the relative geometry of the satellite orbit resulting in a decreasing collision risk. This method enables collision avoidance manoeuvres for satellites in Low Earth Orbits in case of functioning attitude control systems and drag susceptible satellite geometries. Additionally the probability of a collision can be reduced by changing the satellite attitude so that the minimum effective area is perpendicular to the relative velocity vector at the time of closest approach. Both methods can be applied to satellites without propulsion, which otherwise would be defenceless. A test run for verification of collision avoidance by means of drag-minimization was performed in June 2018 with the Technology Experiment Carrier (TET-1) satellite of the FireBIRD constellation. The experiment planning and results are presented along with representative examples for collision avoidance scenarios.

Keywords: Collision avoidance, Attitude control, Satellite operations

Nomenclature

A_{0i}	Cross-sectional area of respective body axis, $i \in$ {x,y,z}
A_{eff}	Total effective area
$A_{\mathrm{eff,i}}$	Effective area of respective body axis, $i \in$ {x,y,z}
ΔE	Energy loss due to atmospheric drag
Δv	Delta velocity
θ_i	Angle between flight direction and respective body axis, $i \in$ {x,y,z}
φ_i	Bias angles, $i \in$ {roll, pitch, yaw}

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control Subsystem
BIROS	Bi-spectral InfraRed Optical System
COLA	Collision Avoidance
DLR	German Aerospace Centre
EPM	Earth Pointing Mode
EPM*	Modified Earth Pointing Mode
GSOC	German Space Operations Centre
LEO	Low Earth Orbit
OOV	On-orbit Verification of new techniques and technologies
PoC	Probability of Collision
SMA	Semi Major Axis
SPFM	Sun Pointing Fix Mode
TCA	Time of Closest Approach
TET-1	Technology Experiment Carrier 1
UTC	Coordinated Universal Time

1. Introduction

This study presents orbital decay through attitude control as an alternative method for collision avoidance (COLA) of small satellites in Low Earth Orbit (LEO). In the first sections preliminary considerations and analysis results are presented, followed by an evaluation of the in-flight experiment and its results. In the end, examples for collision avoidance scenarios are laid out and evaluated in conjunction with the in-flight experiment results.

1.1. Motivation

In lower altitudes the atmosphere has significant impact on the orbital decay of space borne objects, such as TET-1. The friction of the space craft with the atmosphere results in slightly descending trajectories. For example, the international space station ISS, orbiting Earth at an altitude of about 400 km, descents due to the atmosphere about 2 km per month. This effect can be utilised for non-thrust collision avoidance manoeuvres of small, strongly asymmetrical satellites without functioning propulsion systems.

Because of its asymmetrical shape, TET-1 was chosen for an in-flight demonstration of collision avoidance by means of attitude control. This experiment consisted of a 12 hour period in a customized flight mode with minimum drag. It took place on 11th June 2018, initiated and monitored by the German Space Operations Centre (GSOC) of the German Aerospace Centre (DLR) in Oberpfaffenhofen.

1.2. Mission TET-1

The Technology Experiment Carrier TET-1, launched on 22nd July 2012, is part of the FireBird (Fire Bispectral InfraRed Detector) constellation. Originally it was flown to qualify new technological solutions for their application in space projects in course of the "On-orbit Verification of new techniques and technologies" (OOV) program. Since 2016 it forms the FireBird mission together with the identically constructed BIROS (Bi-spectral InfraRed Optical System) satellite, launched on 22nd June 2016. The goal of the FireBird mission is to monitor and detect high-temperature events from space.

The satellite bus of TET-1 together with the payload has a mass of 120 kg at dimensions of 670 x 580 x 880 mm in flight configuration. TET-1 orbits Earth at about 430 km in LEO with an orbital period of 98 minutes and 15 orbits a day.

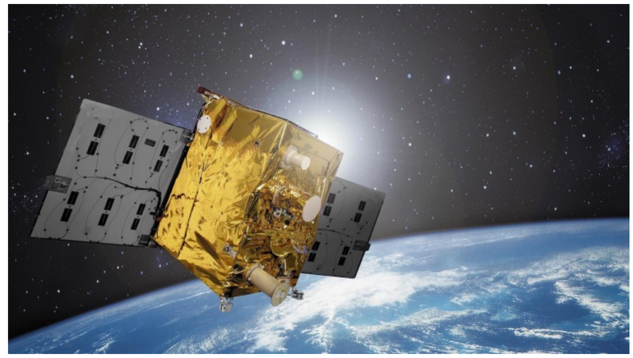

Figure 1. Technology Experiment Carrier TET-1 fully assembled (satellite bus and payload) [8]

2. Preliminary Considerations and Analysis

In low altitudes of 200 km to 800 km the atmospheric drag is the dominant perturbation force. The atmospheric drag scales with the effective area of the space craft facing flight direction. A change in attitude leads to a minimized or maximized decay depending on the body dimensions.

Assuming constant density and velocity, the time integrated area is a measure for the energy loss due to atmospheric drag, see (1).

$$\Delta E \propto \int A_{\mathrm{eff}}\,\mathrm{d}t \qquad (1)$$

The total effective area A_{eff} which is facing flight direction is calculated by summing the partial area contributions with respect to the body axes, see (2).

$$A_{\mathrm{eff}} = A_{\mathrm{eff,x}} + A_{\mathrm{eff,y}} + A_{\mathrm{eff,z}} \qquad (2)$$

For TET-1 the partial areas are computed using the cross-sectional areas of each body axis in relation with the angle between the respective body axis and the flight direction $\theta_i, i \in \{\mathrm{x,y,z}\}$. Thus, the partial effective area of the z-axis is calculated as

$$A_{\mathrm{eff,z}} = A_{0\mathrm{z}} \cos\theta_{\mathrm{z}}. \qquad (3)$$

The remaining body, x- and y-axis proportion, has to be scaled by $\sin\theta_{\mathrm{z}}$. If the angle between the flight direction and the negative z-axis is zero, the solar panels occult the remaining body. Otherwise if the angle is ±90 degrees, the solar panels do not play a role and the remaining body has to be fully taken into account. In between, the effective area is ramped up using $\sin\theta_{\mathrm{z}}$

$$\begin{aligned} A_{\mathrm{eff,x}} &= A_{0\mathrm{x}} \cos\theta_{\mathrm{x}} \sin\theta_z, \\ A_{\mathrm{eff,y}} &= A_{0\mathrm{y}} \cos\theta_{\mathrm{y}} \sin\theta_z. \end{aligned} \qquad (4)$$

With the dimensions and the attitude of TET-1, its energy loss due to atmospheric drag can be calculated from its effective area facing flight direction.

2.1. TET-1 Dimensions and Attitude

TET-1 comprises different flight modes with different attitudes. In this study the Earth Pointing Mode (EPM) and the Sun Pointing Fix Mode (SPFM) are of interest.

In case of SPFM the –z-axis is pointing towards the Sun and the projection of the Earth rotation axis on the spacecraft x-y-plane has only a positive x component (y=0). In EPM, the nadir Pointing mode, the z-axis is pointing towards the Earth and the y-axis is perpendicular to the orbital plane. The SPFM is the nominal flight mode and the EPM is used for observations. [1],[2]

With the body axes in Figure 2 the cross-sectional areas of each body axis of TET-1 are calculated from its body dimensions in Figure 3 andFigure 4

$$\begin{aligned} A_{0\mathrm{x}} &= 0.88 \cdot 0.67 = 0.5896\ \mathrm{m}^2, \\ A_{0\mathrm{y}} &= 0.67 \cdot 0.58 = 0.3886\ \mathrm{m}^2, \\ A_{0\mathrm{z}} &= 2 \cdot (0.48 \cdot 0.67) + (0.88 \cdot 0.58) = 1.1536\ \mathrm{m}^2. \end{aligned} \tag{5}$$

According to (5), the minimal cross-sectional area is given by $A_{0\mathrm{y}}$ and the maximum cross-sectional area by $A_{0\mathrm{z}}$. Therefore, the atmospheric drag is maximized when the z-axis and minimized when the y-axis of TET-1 is facing in flight direction.

2.2. Analysis of TET's Orbital Decay

In Table 1 the decrease in the semi major axis (SMA) and the integrated area of one nominal day (5th April 2018) is displayed. A nominal day consists of 24 hours in an alternating sequence of short EPM and longer SPFM periods. Hence, a nominal day can be denoted as a day with mean effective area and mean orbital decay. With the ratios $A_{\mathrm{eff,Mean}}/A_{\mathrm{eff,min}} = 2.44$ and $A_{\mathrm{eff,Mean}}/A_{\mathrm{eff,max}} = 0.88$ the possible minimum and maximum decrease in the semi major axis is estimated for 24 hours of minimized or maximized drag.

Table 1. Effective area of TET-1, decrease in semi-major axis and equivalent Δv to counteract the orbital decay of one nominal day together with estimated minimum and maximum (5th April 2018)

	Effective area [m²d]	Decrease in SMA [m]		Equivalent Δv [cm/s]	
		per day	per orbit	per day	per orbit
Min.	33563.33	5.81	0.396	0.326	0.022
Mean	81989.92	14.21	0.967	0.798	0.054
Max.	99636.28	17.25	1.175	0.971	0.066

From the relations in Table 1 a minimization of the orbital decay seems to be more promising than maximizing the drag, as it shows the largest differences towards the nominal day. Thus, an in-flight experiment where the effective area of TET-1 is minimized was recommended.

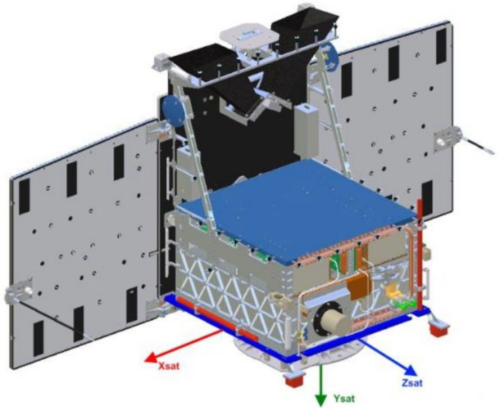

Figure 2. TET-1 body axis [6]

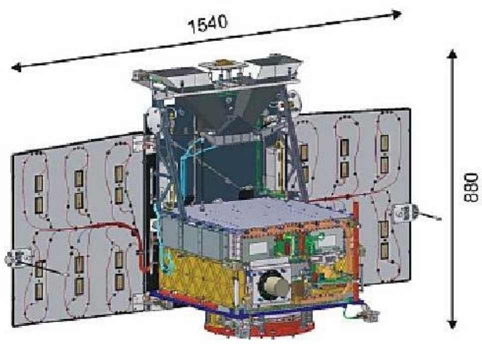

Figure 3. Dimensions of TET-1 satellite bus in flight configuration (in [mm]) [5]

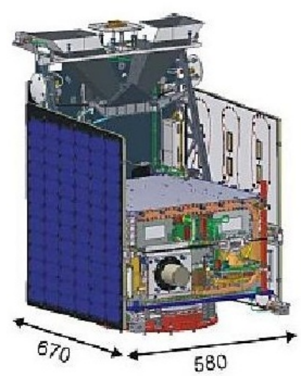

Figure 4. Dimensions of TET-1 satellite bus in launch configuration (in [mm]) [5]

3. In-Flight Experiment

As mentioned in paragraph 2.1, the atmospheric drag is minimized when the y-axis is facing in flight direction. Therefore, to achieve an attitude with minimal orbital decay TET-1 needs to be commanded into a modified Earth pointing mode (EPM*).

A single orbit pre-experiment was executed to ensure that the desired attitude was achieved with the chosen bias angles. This test orbit was completed on 23rd May 2018 from 13:12 till 14:42 UTC (DOY18143). After evaluation, the experiment itself took place on 11th June 2018 from 8:40 UTC till 20:40UTC (DOY18162). Due to restrictions concerning the power and thermal conditions of TET-1 the EPM* attitude was kept for no more than 12 hours.

3.1. Spacecraft Operations and System Constraints

For the in-flight experiment, TET-1 is commanded into a modified EPM. In the modified Earth pointing mode, bias angles of $(\varphi_{\mathrm{roll}}, \varphi_{\mathrm{pitch}}, \varphi_{\mathrm{yaw}}) = (-90°, 0°, -90°)$ are applied to the nominal EPM. This results in an attitude where the +y-axis is facing in flight direction and the +x-axis is pointing nadir. This mode is further referred to as EPM*.

An estimation of the battery behaviour suggests that the spacecraft can be operated in this specific attitude mode for collision avoidance for 14 orbits, roughly 21 hours. This is valid if initiated under the same conditions as the tests, with the battery fully charged and at a certain temperature.

No noteworthy restrictions for a valid GPS solution resulted from this attitude. However, a possible constraint arises from the fact that the EPM* is not suitable for downlink. Therefore, passes have to be configured in low rate and datatakes planned accordingly.

4. Experiment Results

The in-flight experiment was validated by a single orbit pre-test in EPM*. The results of the single orbit as well as the in-flight experiment are presented in the following sections.

4.1. Single orbit pre-experiment

The pre-experiment was executed for one single orbit. In Figure 5 the evolution of the velocity components is displayed, showing that the +y-axis faces in flight direction ($v_{\mathrm{y}} = 1$) from 13:12 till 14:42 UTC and that the desired attitude was reached with the commanded bias angles.

From operations point of view, conditions proved safe and effective with regard to power, thermal and attitude aspects. The solar panels were hit by the sun at an angle of 48.7 degrees.

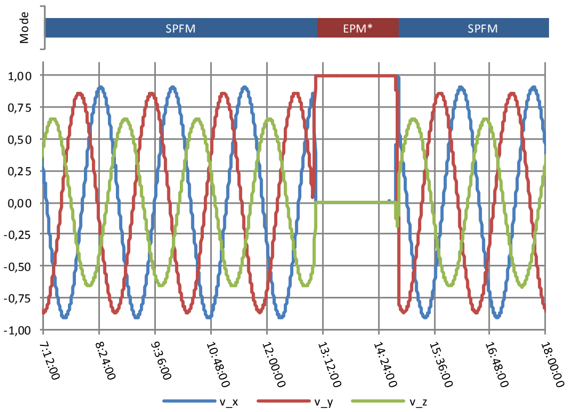

Figure 5. Evolution of the velocity components during the single orbit pre-experiment on 23rd May 2018

4.2. In-Flight Experiment

In Figure 6 the evolution of the velocity components on 11th June is shown. The y component of the velocity vector is the main velocity component, whereas the x and z components are zero for the time of the experiment, meaning that the y-axis is facing in flight direction, as intended.

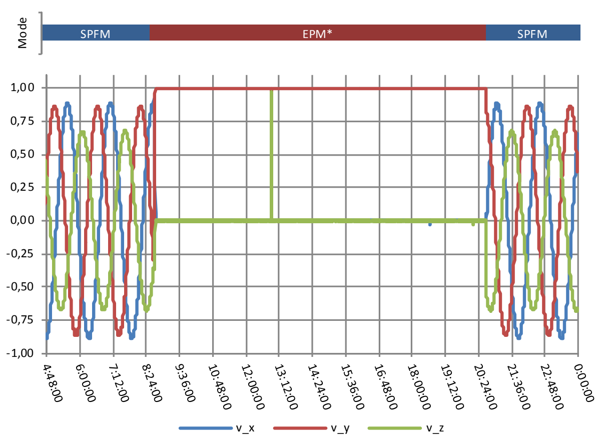

Figure 6. Evolution of the velocity components during the 12 hour in-flight experiment on 11th June 2018

In order to evaluate the impact on the orbital elements, in particular the SMA, the on-board GPS navigation solution was processed within a batch least square orbit determination process.

Taking 24 hours before and after the experiment into account, the decrease in the mean SMA is getting slightly weaker during the 12 hours in EPM*, see Figure **7**. The periods observed are 24 hours before and after the in-flight experiment as well as the experiment period itself, see Table 2. Numerically spoken, the decrease in semi-major axis declined from about 11.5m in 24 hours to 3.8m during the 12 hour minimized drag experiment, see Table 3.

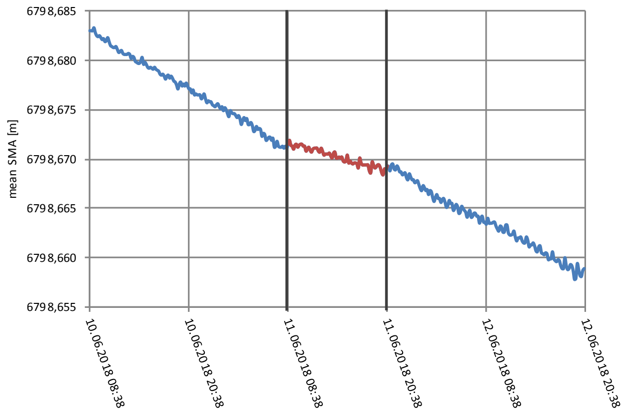

Figure 7: Evolution of the mean semi-major axis from 24 hours before to 24 hours after the in-flight experiment (10th till 12th June 2018)

Table 2. Evaluated time periods

previous	10-06-2018 8:40	11-06-2018 8:40
experiment	11-06-2018 8:40	11-06-2018 20:40
subsequent	11-06-2018 20:40	12-06-2018 20:40

Table 3. Effective area and decrease in semi-major axis of the 12 hour in-flight experiment and 24 hours previous and subsequent

	Effective area [m^2d]	Decrease in SMA [m]	
		per period	per orbit
24h previous	83507.552	11.389	0.775
12h experiment	17022.027	3.832	0.522
24h subsequent	83790.373	11.690	0.779

Extrapolated to 24 hours with minimized drag, the decrease in the semi-major axis can be reduced by 7.66m, if the EPM* was retained for 24 hours. Compared to the 24 hours previous the decrease is reduced by 32.74%. Additionally a decrease in the effective area is observable. A reduction by 59.3% compared to 24 hours in nominal flight mode can be achieved.

Table 4. Effective area and decrease in semi-major axis of considered days in comparison for time periods of 24 hours (0:00 till 23:59 UTC) each

	Effective area [m^2d]	Decrease in SMA [m]	Decrease in SMA per orbit [m]
05-04-2018	81989.921	15.419	1.028
23-05-2018	79573.931	15.841	1.056
10-06-2018	87507.522	13.004	0.867
11-06-2018	58895.627	8.442	0.563
12-06-2018	83790.373	13.565	0.904

In Table 4 the decrease in the semi-major axis and the effective area of several different days is compared. It strikes that the least decrease in SMA happened on 11th June, the day of the in-flight experiment. Also, the single orbit test on 23rd May had no influence on the decrease in SMA.

Summing up, the in-flight experiment shows that a SMA change of 0.25m per orbit can be achieved by minimizing the effective area of TET-1.

5. Collision Avoidance

After successful in-flight experiment, the idea is to utilize orbital decay as an alternative method for collision avoidance manoeuvres. Normally thrust manoeuvres are commanded, starting half an orbit in advance of the probable collision. However, collision avoidance by orbital decay must be precisely evaluated and planned, needing larger lead time ahead of the collision.

5.1. Requirements and Constraints for Collision Avoidance of TET-1

From the in-flight experiment it is derived that at maximum a change in SMA of 0.25m per orbit can be achieved, when minimizing the drag, which results in approx. 3.8m decay for 24 hours in EPM*. Due to power and thermal constraints a maximum of 14 orbits (21 hours) in EPM* are possible. If a larger amount of decay is needed a rest period of 3 to 4 orbits (4.5 to 6 hours) in-between two periods of EPM* is needed.

5.2. Exemplary Scenarios

Based on past conjunction events of BIROS, which is identically constructed as TET-1 and flying in the same altitude, two conjunction scenarios with a COSMOS 2251 debris and ZY-3 were analysed as shown in Table 5 and Table 6. For both cases, the orbits of the secondary objects were almost circular, and the relative velocity at the time of closest approach (TCA) was 14.9 km/s. The object radius used for the collision probability calculation was 0.75m for BIROS, and the default value of 2.0m for each secondary object due to its unknown dimension.

The differential drag during the attitude change was simulated as continuous low thrust, for which the thrust magnitude F was calculated as follows.

$$F = m\,\Delta a_D, \tag{6}$$

with the delta acceleration Δa_D

$$\Delta a_D = -\frac{1}{2}\rho\frac{C_D\,\Delta A}{m}v^2, \tag{7}$$

and atmospheric pressure ρ

$$\rho = \frac{\Delta a_{\mathrm{orb}}}{-2\pi\frac{C_D\Delta A}{m}a^2}, \tag{8}$$

where a is the current SMA, v the orbital velocity, ΔA the difference between nominal and minimum cross-sectional area and Δa_{orb} the change in SMA per orbit.

According to (6),(7),(8) and a change in SMA of $\Delta a_{orb} = 0.25$ m, a thrust magnitude of $\mathrm{F} = 2.829 \cdot 10^{-6}$ N in along-track direction represents the effects of the orbital decay caused by the attitude change.

The start epoch of the attitude change was set to1.5 and 2.0 days prior to TCA. Earlier manoeuvre planning increases uncertainties of the conjunction prediction [3,4], while later planning reduces the drag change effect. Duration of the attitude change was simulated for 12 and 24 hours according to the TET-1 constraints as mentioned in 5.1.

Table 5. Original conjunction scenarios

TCA [UTC]	PoC	Min. dist [m]	dR [m]	dT [m]	dN [m]
Scenario 1: 2018/01/29 17:50:34.463	7.75e-5	536	-49	105	523
Scenario 2: 2018/01/29 17:50:34.508	2.15e-4	402	-5	79	394

Table 6. Estimated object area and orbit uncertainties (at TCA-2 days) used for each scenario

Object	Object name	Area [m^2]	σ_R [m]	σ_T [m]	σ_N [m]
Primary	BIROS		8	737	10
Scenario 1: Secondary	COSMOS 2251 deb	0.01	73	3198	71
Scenario 2: Secondary	ZY-3	5.27	21	1126	4

Table 7. Conjunction parameters after attitude change

Begin of att.change [d]	Duration [hr]	PoC	Min. dist [m]	dR [m]	dT [m]	dN [m]
Scenario 1						
TCA-2.0	24	4.89e-5	703	-56	137	688
	12	5.89e-5	634	-52	124	619
TCA-1.5	24	5.57e-5	648	-55	127	633
	12	6.30e-5	606	-52	118	592
Scenario 2						
TCA-2.0	24	6.74e-5	569	-12	112	558
	12	1.13e-4	499	-8	98	490
TCA-1.5	24	1.05e-4	513	-11	101	503
	12	1.38e-4	499	-8	92	462

5.3. *Evaluation of Usability*

In the following the usability of collision avoidance by orbital decay and minimized effective area based on the exemplary scenarios is analysed. Two approaches are evaluated. First utilizing orbital decay as a collision avoidance manoeuvre and second minimizing the effective area facing towards the collision direction.

5.3.1. *Collision Avoidance by Orbital Decay*

Conjunction parameters after applying the simulated attitude change are summarized in Table 7. For scenario 1, the collision probability was reduced by max 37%, which is only a slight improvement in mitigating the conjunction risk. For scenario 2, the probability was reduced by max. 69%. Taking into account the avoidance manoeuvre threshold of PoC=1.0e-4 [4], the achieved probability of 6.74e-5 improved the initial critical situation.

In conclusion, in the operational collision avoidance, the usability of the attitude change strategy should be carefully analysed for each critical situation, considering the conjunction geometry, orbital accuracies, and also the applicable manoeuvre schedule of the satellite.

5.3.2. *Minimum Cross-Sectional Area Facing Collision Direction*

Another method to minimize the probability of a collision is to adjust the attitude of the spacecraft so that the integral of the position probability density is minimized. In the current collision avoidance operation, however, the collision probability is computed assuming that the object is a sphere with the diameter of its maximum dimension. The effect of this method shall be evaluated by taking into account the object shape and its orientation in the collision probability computation.

6. Conclusion

The 12 hour in-flight experiment indicated the expected minimized decay. With an attitude of minimized drag a decrease in the SMA of 0.253m per orbit can be achieved for TET-1 compared to a nominal day. Moreover, collision avoidance manoeuvres by orbital decay can be an alternative to thrust manoeuvres in certain circumstances. Those circumstances need to be carefully evaluated and the COLA manoeuvre by orbital decay needs to be planned according to the satellite operations and system constraints.

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