V1.0
2019

PREPARED FOR TELESAT IN SUPPORT OF THE LEO 1 SATELLITE

ANALYSIS BY NXTRAC

11 APRIL 2019

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Revision History

Revision	Description of Revisions	Release Date
1.0	Initial Release --- Initial ODAR Report Format per NASA NASA-STD 8719.14 Revision A with Change 1 dated 8 Nov 2011	10/02/2018
1.1	Updates to incorporate analysis results	3/08/2019

NXTRAC Mission Analysts

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ODAR Analysis Tools

NASA Debris Assessment Software (DAS) v2.1.1

NASA General Mission Analysis Tool (GMAT) R2018a

Introduction

This document provides a detailed orbital debris assessment report (ODAR) for the operations and disposal of the Telesat LEO 1 satellite. This ODAR provides an overview of current and planned LEO 1 operations and demonstrates compliance with all US Government orbit lifetime and orbital debris mitigation regulations.

Figure 1: Telesat LEO 1

Telesat's LEO 1 satellite was launched on 12 Jan 2018, as NORAD catalog identifier 43113, and is depicted in Figure 1.

As of this report, the LEO 1 satellite has maneuvered to its final mission orbit; a 1000 km altitude circular orbit inclined at 99.5 degrees. Telesat's LEO 1 satellite has a planned 3-year mission lifetime at which point the health of the satellite may be assessed for mission extension activities. If a viable mission extension is not possible, a sequence of planned disposal maneuvers will be performed over 3 to 6 months to allow atmospheric drag to ultimately remove the vehicle from orbit.

For this analysis, a 165.5 kg small satellite with an initial area to mass ratio of 0.00513 m^2/kg, was placed in a 1000 km altitude 99.5 degree inclined orbit for three years. Over the three year operational period the orbit evolves to 975 x 1025 km and will then be maneuvered to a final elliptical disposal orbit of 425 x 975 km. Its final mass at end of life is expected to be 127.9 kg with a corresponding increased area to mass ratio of 0.006646 m^2/kg. From this final orbit and configuration, the decay and collision potential for LEO 1 were assessed with the precision NASA GMAT trajectory engine and the standard NASA DAS 2.1.1 toolset.

Analysis of the LEO 1 mission operations and deorbit plan meets or exceeds all disposal and flight safety requirements with a decay timeline less than the 25 year maximum and a minimal collision probability (9e-5).

Summarized List of Compliance Status to Orbital Debris Requirements

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4.3-1, Mission-Related Debris Passing Through LEO:	**COMPLIANT**
4.3-2, Mission-Related Debris Passing Near GEO	**COMPLIANT**
4.4-3, Limiting the long-term risk to other space systems from planned breakups:	**COMPLIANT**
4.5-1, Probability of Collision with Large Objects:	**COMPLIANT**
4.5-2, Probability of Damage from Small Objects:	**COMPLIANT**
4.6-1, Disposal for space structures passing through LEO:	**COMPLIANT**
4.6-2, Disposal for space structures passing through GEO:	**N/A**
4.6-3, Disposal for space structures between LEO and GEO:	**N/A**
4.7-1, Casualty Risk for Reentry Debris	**COMPLIANT**
4.8-1, Collision Hazards of Space Tethers	**N/A**

1.0 Program Management & Mission Overview

Program / Project Manager: Christian Vince
Mission Description: LEO 1 was launched into lower orbit on January 12, 2018 and maneuvered into its final orbit of 1000 km altitude circular orbit inclined at 99.5 degrees over a period of several weeks. The satellite has a planned 3-year mission lifetime, during which it will be used for testing and demonstration. At the end of mission life, a sequence of maneuvers will be performed over 3 to 6 months to allow atmospheric draft to ultimately remove the vehicle from orbit through reentry.
Foreign Government Involvement: Canada
Project Milestones: Final mission orbit achieved – disposal operations begins NET 5 April 2021
Launch Date: 12 Jan 2018
Launch Vehicle: LEO 1 PSLV
Launch Site: LEO 1 India
Launch Vehicle Operator: LEO 1 India
Mission Duration: 3 YEARS
Mission Start: 5 April 2018
Launch / Deployment Profile: Launch Checkout Raise – 2 months Operations Post-mission Disposal: Maneuver to 425 x 975 km orbit, then NATURAL ORBITAL DECAY
Selection of Orbit: Operations 1000 x 1000 km 99.5 degree, disposal 425 x 975 km
Potential Physical Interference with other Orbiting Object: 9e-5

2.0 Spacecraft Description

Physical Description:

PARAMETER	VALUE
Total Mass at Launch	165.5 kg
Dry Mass at Launch	127.9 kg
Form Factor	Small Satellite
Center of Mass	0.28 x 0.28 x 0.55 m
Envelope (stowed)	0.642 x 0.642 x 1.003 m
Envelope (deployed)	0.642 x 0.642 x 1.003 m
Propulsion Systems	Hydrazine
Fluid Systems	NONE
AOCS	3-axis controlled ADCS unit consisting of sun-vector sensors, earth-horizon sensors, magnetometer, magnetorquers, and reaction wheels
Range Safety / Pyrotechnic Devices	NONE
Electrical Generation	SOLAR POWER
Electrical Storage	LITHIUM ION BATTERY
Radioactive Materials	NONE

1. Can spacecraft propellant and pressurant tanks be emptied at end of mission?

   YES

2. Can the spacecraft battery be disconnected from the charging circuit at end of mission?

   YES

3. If the answer to either of questions 1 and/or 2 is negative, what alternatives are available (bus modification or different bus) and at what additional, if any, cost?

   N/A

4. Have all mission-related debris generation been eliminated to the greatest extent possible?

   YES

5. For spacecraft operating in low Earth orbit (less than 2000 km), will the spacecraft reenter the atmosphere within 25 years after end of mission (and no more than 30 years after launch) or will the spacecraft be moved to a disposal orbit above 2000 km?
   YES - LEO 1 will reenter the atmosphere within 25 years after end of mission

6. For spacecraft operating in GEO, will the spacecraft be moved to a compliant disposal orbit, i.e., one which will remain at least 200 km (~125 mi) above/below GEO for at least 100 years?
   N/A

7. Will all launch vehicle orbital stages and mission-related debris be left in low Earth orbits with orbital lifetimes of less than 25 years or left in compliant disposal orbits above 2,000 km (~1,240 mi)?
   N/A

8. If an uncontrolled atmospheric reentry is anticipated after EOM, does the spacecraft bus or the payload contain any objects which might survive reentry, e.g., tanks, structural components, or other items made of high melting temperature materials such as titanium, beryllium, or stainless steel?
   YES - but the small titanium tank poses less than 1:71200 hazard to human life

9. If a disposal maneuver is planned for a mission not utilizing a controlled reentry, will the spacecraft propulsion system have a designed reliability of at least 0.9 at EOM?
   YES

10. Does the spacecraft have any critical components, other than sensors and solar cells, which are exposed to the environment without MMOD protection?
    NO

3.0 Assessment of Debris During Normal Operations

Description:

LEO 1 has been designed so that during its normal operation it will release no debris. The materials on the outside are tolerant of radiation and thermal cycling/mechanical fatigue to ensure no release of extraneous material. All critical components (e.g., computers and control devices) are built within the structure and shielded from external influences to ensure the spacecraft remains in full control from the ground.

Objects larger than 1mm expected to be released during orbit:	**NONE**
Rationale for release of each object:	**N/A**
Time of release of each object:	**N/A**
Release velocity of each object:	**N/A**
Expected orbital parameters of each object:	**N/A**
Calculated orbital lifetime of each object:	**N/A**

Assessment of spacecraft compliance with Requirements 4.3-1 & 4.3-2:	
4.3-1, Mission-Related Debris Passing Through LEO:	**COMPLIANT**
4.3-2, Mission-Related Debris Passing Near GEO:	**COMPLIANT**

4.0 Assessment of Spacecraft Intentional Breakups and Potential for Explosions

Description:

LEO 1 has been designed with redundancy considerations so that individual unit faults will not cause the loss of control of the spacecraft.

Telesat has also taken specific precautions to pre-empt accidental explosions in orbit. All pressure vessels (pressurized propellant tanks, heat pipes, Lithium ion batteries etc.) on board have the appropriate structural margins to failure as per the MIL-Spec requirements used in the industry. All batteries and fuel tanks are monitored for pressure or temperature variations. The batteries are operated utilizing a redundant automatic recharging scheme. Doing so ensures that charging terminates normally without building up additional heat and pressure. Alarms in the Satellite Control Centre will inform controllers of any anomalous variations. Additionally, long-term trending analysis will be performed to monitor for any unexpected trends. On board fault protection will ensure the isolation of any affected units and their replacement with the back-up hardware/systems. As this process would occur within the spacecraft, it would also afford protection from command link failures (on the ground).

Potential causes for spacecraft breakup:

There are only two plausible causes for breakup of the satellites:

- Failure of batteries
- Mechanical failure of the reaction wheels

Summary of failure modes and effects analysis of all credible failure modes which may lead to an accidental explosion:

The battery pack complies with all controls / process requirements identified in NASA JSC-20793 Section 5.4.3 to mitigate the chance of any accidental venting / explosion caused from overcharging, over-discharging, internal shorts, and external shorts.

The reaction wheels are contained within a sealed compartment to preclude release of debris from operating at a high angular rate or part failure. Additional risk mitigation strategies include limiting the maximum rate the wheels operate.

Detailed Plan for any designed spacecraft breakup, including explosions and intentional collisions:

There is no planned breakup of the satellite on-orbit.

List of components passivated at EOM:

At the end of mission, the wheels will be despun and the batteries will be set to only discharge.

Rationale for all items required to be passivated that cannot be due to design: N/A

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4:	
4.4-1, Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon	**COMPLIANT**
4.4-2, Design for passivation after completion of mission operations while in orbit about Earth or the Moon	**COMPLIANT**
4.4-3, Limiting the long-term risk to other space systems from planned breakups: There are no planned breakups of any of the satellite.	**COMPLIANT**
4.4-4, Limiting the short-term risk to other space systems from planned breakups: There are no planned breakups of any of the satellites.	**COMPLIANT**

5.0 Assessment of Spacecraft Potential for On-Orbit Collisions

Description:

Telesat has been operating geostationary satellites for many years and performs station-keeping from the Telesat Satellite Control Centre in Ottawa, Ontario, Canada.

Telesat also has experience in operating a non-geostationary LEO satellite. Specifically, since 2007 Telesat has been operating Radarsat-2 for MacDonald, Dettwiler and Associates Ltd. (MDA). Radarsat-2 is a LEO non-geostationary satellite at an altitude of 798 km.

In order to protect against collision with other orbiting objects, Telesat shares daily ephemeris data with the Canadian Space Agency (CSA), the Combined Space Operations Center (CSpOC) (formerly the Joint Space Operations Center (JSpOC)), and the Space Data Center (SDC). These daily ephemeris updates have been tagged with both the CSpOC and the SDC as available to all operators for their space situational analysis. The CSpOC and the CSA provide notifications to Telesat for any object they see approaching a Telesat satellite including LEO 1, together with assessments of whether avoidance maneuvers are required, and Telesat maneuvers its satellites accordingly.

For the LEO satellite Radarsat-2, Telesat works with the Canadian Space Agency to use Probability of Collision (PoC) analysis to determine the need for collision avoidance maneuvers. This system of highly effective PoC analysis is in use for LEO 1 operations and will be maintained for the entire mission and disposal phases. The PoC analysis provides a greater than 3 day notice of requirement of action for coordination of planned avoidance maneuvers, based on the normal accuracy of the CSpOC observations of the objects in the space catalog.

Telesat has and will continue to coordinate with other non-geostationary satellite networks, such as it has with Iridium, to minimize the risk of collision between LEO 1 and any other NGSO satellite.

To further limit the potential for collision, Telesat monitors new satellite launches to ensure that future satellites do not present a danger to LEO 1.

LEO 1 has a propulsion system to maintain its orbit. The propulsion system on the satellite also enables it to make necessary maneuvers to avoid collision with any approaching object. Avoidance of other space objects will be achieved by the satellite firing its thrusters to adjust its position within its control box in order to avoid the other object. Coordination with other operators will aid this process.

Probability for Collision with Objects >10cm: 9e-5

Assessment of spacecraft compliance with Requirement 4.5-1 and 4.5-2:	
4.5-1, Probability of Collision with Large Objects:	COMPLIANT
4.5-2, Probability of Damage from Small Objects:	COMPLIANT

6.0 Assessment of Spacecraft Post-Mission Disposal Plans and Procedures

Description:

Telesat has been operating GSO satellites for more than 40 years during which multiple generations of its satellites have been retired and duly disposed of in the appropriate (graveyard) orbit to avoid adding debris to the GSO orbit. Telesat takes LEO orbital debris mitigation very seriously, as it plans to be a major operator of satellites in LEO orbits. Debris control and mitigation are stated requirements for Telesat spacecraft design specifications. Telesat has always met the requirements of the regulatory bodies and intends to continue to fully meet debris mitigation requirements.

At the end of life, LEO 1 will be de-orbited by re-entering the satellite into the Earth's atmosphere and burning.

The de-orbiting has two phases. The first phase consists of the satellite being moved from its operational orbit to a planned lower orbit, the "Decaying Lower Orbit". The second phase, the passive disposal phase, the satellite will be passivated and will burn up in the Earth's atmosphere.

First Phase De-Orbit: Decaying Lower Orbit

In the first phase, the satellite will be moved from its operational orbit to a planned lower orbit, the "Decaying Lower Orbit".
The Decaying Lower Orbit for LEO 1 is a highly elliptical orbit of approximately 975 x 425 km. This orbit minimizes the time in the disposal orbit and the debris generation potential, for the fuel onboard. If more propellant is on board than is conservatively estimated, then the perigee will be lowered to its maximum extent to further decrease the duration of the passive disposal.

The propellant needed to achieve the minimum de-orbit altitude is based on the change in velocity (delta-V) required. Telesat will carefully track propellant usage over the life of the LEO 1 satellite to ensure the satellite de-orbit is planned at a time that ensures this reserve of fuel is available, along with additional fuel margin to allow for uncertainties in propellant accounting, orbital determination and maneuver execution. Propellant tracking is accomplished using a bookkeeping method in accordance with industry standard. Using this method, the ground control station tracks the number of jet seconds utilized for station keeping, momentum control and other attitude control events. The amount of fuel used is determined from the number of jet seconds. This process, which is calibrated using data collected from thruster tests conducted on the ground, has been found to be accurate to within a few months of life on the satellite. In addition to bookkeeping updated based on orbital performance, Telesat will use in orbit thermal testing analysis and trending, as a cross check. Telesat is familiar with and has experience with all of the above cited methods.

Second Phase De-Orbit: Passive Disposal

In the second phase, the passive disposal phase, all stored energy sources onboard the satellite will be removed by venting the remaining propellant and any remaining pressurant. All propulsion lines and latch valves will be vented and left open. All battery chargers will be turned off and batteries will be left in a permanent discharge state. All momentum storage devices will be switched off. These steps will ensure that no buildup of energy can occur and eliminate the risk of explosion after the satellite has stopped operating.

Once the satellite is moved to this lower orbit, and passivated to a safe state, it will be left in the Decaying Lower Orbit which, within 25 years, will result in the re-entry of the satellite into the Earth's atmosphere and burning of the satellite.

Calculated for LEO 1, using the Decaying Lower Orbit of approximately 975 x 425 km, to deorbit its satellites, the NASA DAS program for the probability of collision with an object of greater than 10 cm, with a mission duration of about 3 years plus approximately a 15 year passive disposal, the collision risk, is 0.00008.

At the time of entry into disposal phase, Telesat will custom design disposal orbit parameters that minimize probability of collision with the International Space Station (ISS), other operational satellites and constellations. To pre-predict the required parameters in advance is challenging, but Telesat is experienced in eccentricity and inclination collocation and probability of collision avoidance strategies. At this eccentricity, even a passive disposal strategy, with properly chosen argument of perigee and orbital parameters, will create significant separation.

Following its maneuver to a lower perigee of 425 km, the satellite's orbit will naturally decay until it reenters the atmosphere. Determining orbital decay timelines is challenging due to the complex interplay of the satellite's initial orbital parameters (e.g. altitude, eccentricity and inclination), spacecraft mass, area, attitude profile (e.g. nadir facing, tumbling, gravity gradient) and atmospheric density as a function of solar and geomagnetic activity. Predicting the environment decades in the future results in a wide range of decay timelines depending on the level of activity assumed. To account for this atmospheric variability, 5000 Monte Carlo trials were performed to quantify the decay timeline distribution for LEO 1 as depicted in Figure 2. The simulation varied solar activity and atmospheric density per the DAS 2.1.1 current solar flux table. The 95th percentile for the decay timeline distribution is 8.25 years with 20 years representing the 99.9th percentile as shown in Figure 3 and 10 sigma from the mean. In Figure 4, a detailed 6.7 year (1 sigma) decay profile is depicted for the LEO 1 satellite. As can be seen in Figure 2, the LEO 1 satellite will deorbit well within 25 years once achieving its final 425 by 975 km disposal orbit.

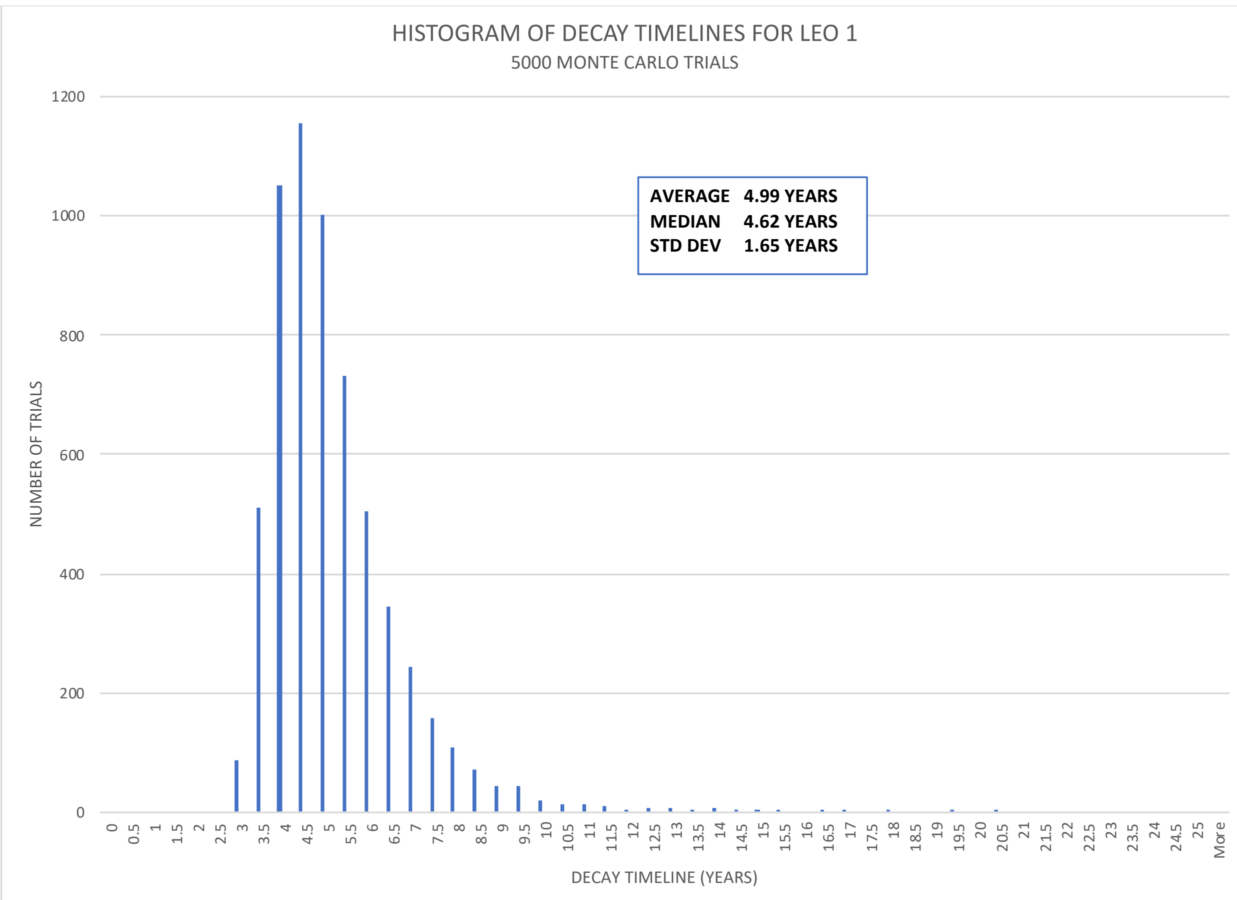

Figure 2: Histogram of Monte Carlo Trials for LEO 1 Decay Timeline (5000 trials)

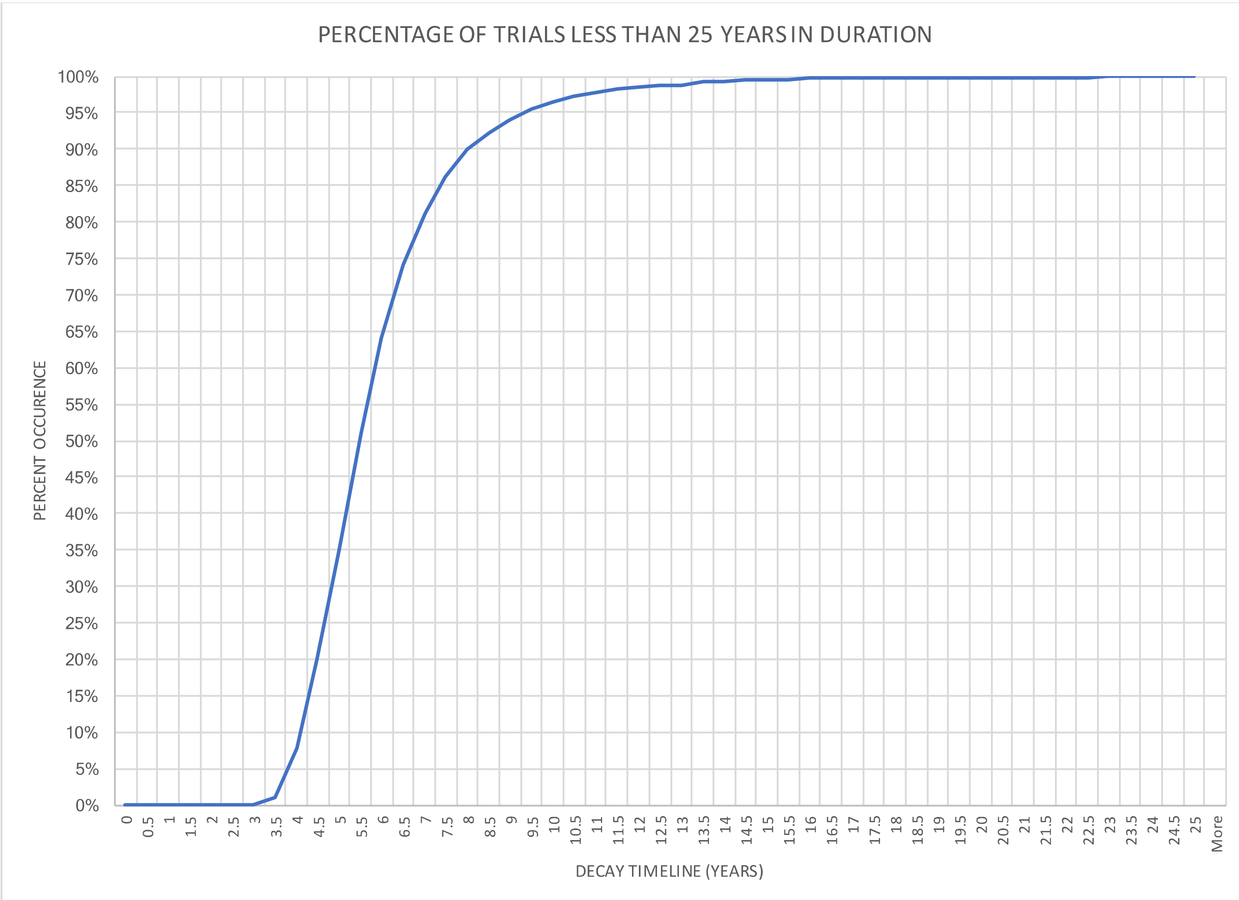

Figure 3: Monte Carlo Trials of Decay Timeline by Percentile (5000 trials)

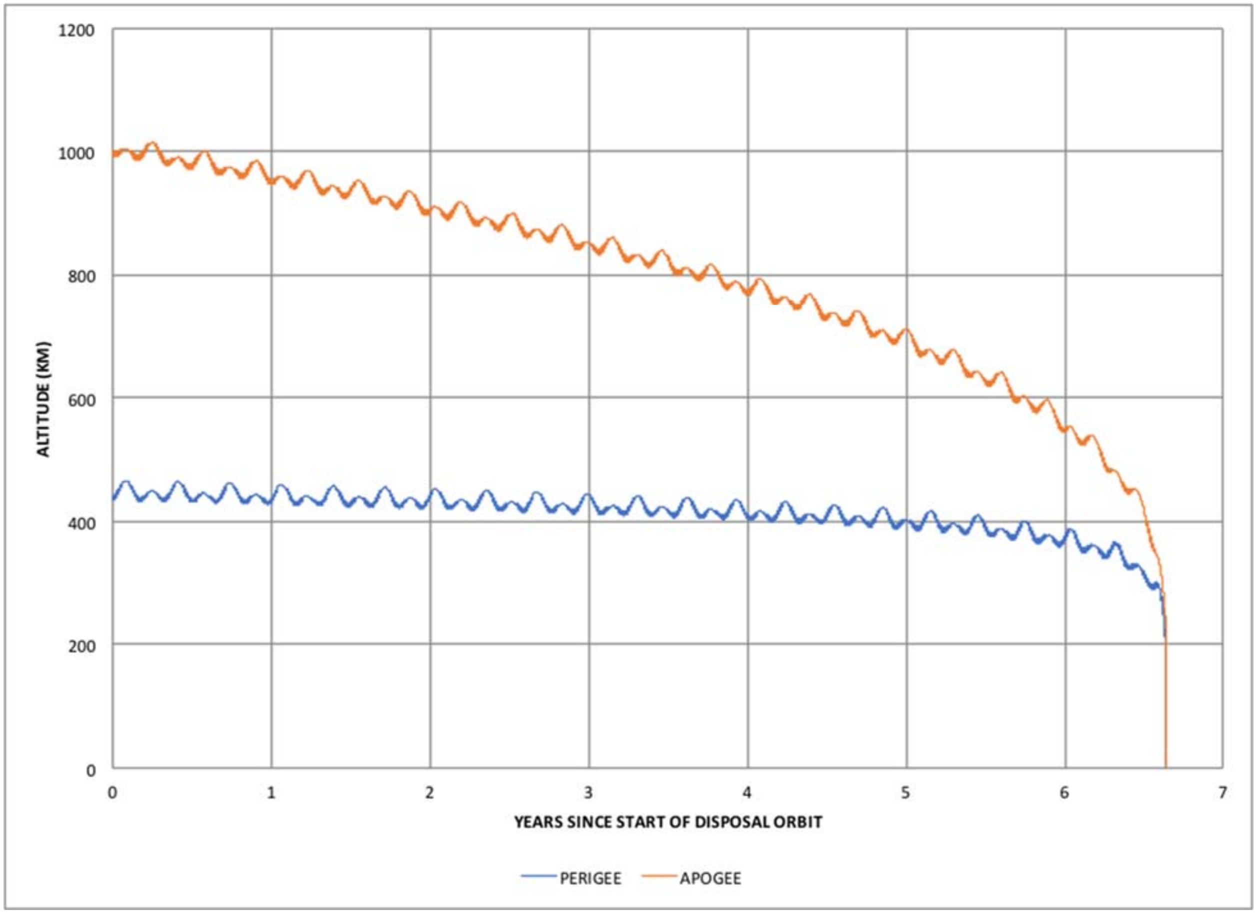

Figure 4: Nominal Orbital Decay Profile for Telesat LEO 1 Satellite

Identification of Systems Required for Postmission Disposal:
GNC, Communications and Propulsion

Plan for Spacecraft Maneuvers required for Post-Mission Disposal:
Lower perigee from 975 x 425km over 3 - 6 months with coordination with CSpOC and other mission management entities. Nominally 100 km per month with a minimum change in perigee altitude of 50 km and a maximum change in perigee altitude of 200 km.

Calculation of final Area-to-Mass Ratio if Atmospheric Reentry Not Selected: N/A

Assessment of Spacecraft Compliance with Requirements 4.6-1 through 4.6-4:	
4.6-1, Disposal for space structures passing through LEO All of the satellites will reenter the atmosphere within 25 years of mission completion and 30 years of launch.	**COMPLIANT**
4.6-2, Disposal for space structures passing through GEO:	**N/A**
4.6-3, Disposal for space structures between LEO and GEO:	**N/A**
4.6-4, Reliability of postmission disposal operations:	**N/A**

7.0 Assessment of Spacecraft Reentry Hazards

Description:

LEO 1 has been designed to ensure the probability of survival of spacecraft components through the re-entry into the Earth's atmosphere is extremely limited. The design is consistent with requirement 4.7.-1 of NASA-STD 8719.14- Process for Limiting Orbit Debris and has been assessed using NASA DAS (Debris Assessment Software) to ensure that the human casualty risk resulting from the de-orbiting of the satellites is less than 1 in 10,000, in accordance with the applicable guidelines.

Detailed description of spacecraft components by size, mass, material, shape, and original location on the space vehicle:

Subsystem	Materials	Quantity	Mass (g)	Size (mm)
Propulsion	Titanium Fuel Tank	1	5640	506

Summary of objects expected to survive an uncontrolled reentry (using DAS 2.1.1 software):
None

Calculation of probability of human casualty for expected reentry year and inclination:
1:71200

Assessment of spacecraft compliance with Requirement 4.7-1:	
4.7-1, Casualty Risk from Reentry Debris:	**COMPLIANT**

7.1 Assessment of Spacecraft Hazardous Materials

Summary of Hazardous Materials Contained on Spacecraft:
None

8.0 Assessment for Tether Missions

Type of tether:
N/A

Description of tether system:
N/A

Determination of minimum size of object that will cause the tether to be severed:
N/A

Tether mission plan, including duration and postmission disposal:
N/A

Probability of tether colliding with large space objects:
N/A

Probability of tether being severed during mission or after postmission disposal:
N/A

Maximum orbital lifetime of a severed tether fragment:
N/A

Assessment of compliance with Requirement 4.8-1:	
4.8-1, Collision Hazards of Space Tethers:	**N/A**

Appendix A: DAS 2.1.1 Screenshots

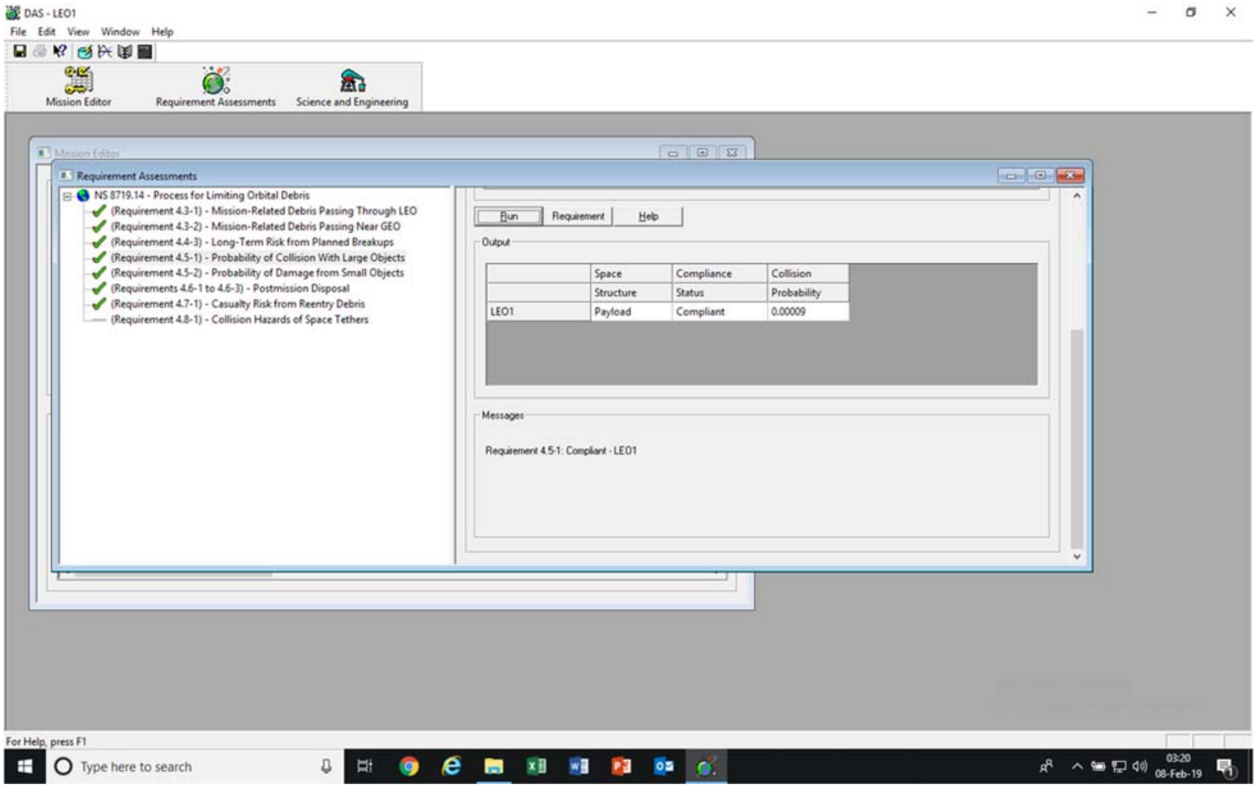

Figure 5: DAS 2.1.1 Compliance Checklist

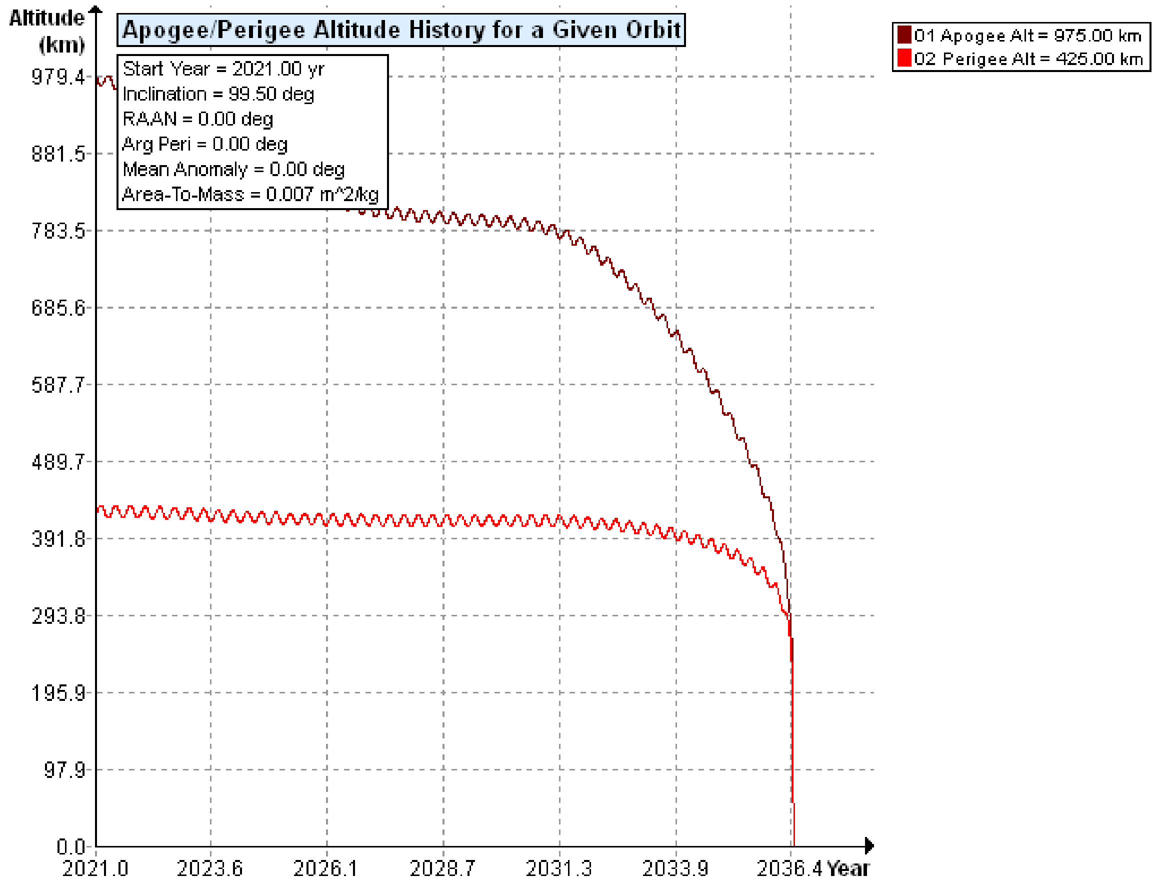

Figure 6: DAS 2.1.1 Conservative Decay Profile