Appendix 1

Final Orbital Debris Assessment Report for

ORBITAL-REFLECTOR

December 12, 2018

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DAS Version 2.1.1

ORBITAL-REFLECTOR Updated Orbital Debris Assessment Report (ODAR)

December 12, 2018

The following ODAR revises and supplements the prior ODAR submissions included as part of Global Western's application for special temporary authority granted by the Commission on September 20, 2018 ("STA Application").[1] The ORBITAL-REFLECTOR is compliant with the orbital debris requirements contained in NASA-STD-8719.14A: Process for Limiting Orbital Debris, as shown in this report using NASA's Debris Assessment Software (DAS) Version 2.1.1, for all operational geometries and configurations and will not become a source of orbital debris if deployed at an operational altitude of 575 km.

1. Program Management and Mission Overview

As explained in the STA Application, the ORBITAL REFLECTOR was created by artist Trevor Paglen, working in collaboration with the Nevada Museum of Art and aerospace engineers at Global Western. The ORBITAL-REFLECTOR is an artwork constructed out of lightweight, highly reflective material similar to Mylar that will be launched into low earth orbit (LEO) to make an artistic statement while encouraging dialogue related to the integrated fields of science, engineering, politics, and space exploration.

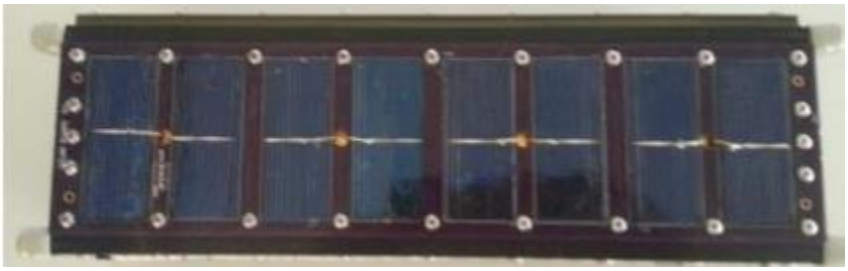
The ORBITAL-REFLECTOR is schedule to launch on a Falcon-9 with SSO-A out of Vandenberg Air Force Base on December 1, 2018 to a 575 km, 97.4 degree orbit. While in-orbit, it will be a visible sculpture, observable from Earth with the naked eye and trackable via connected devices.

2. ORBITAL-REFLECTOR Satellite Description

The ORBITAL-REFLECTOR Satellite is a 3U Cubesat with a mass of 3.3 kg, and dimensions of 10 cm x 10 cm x 34 cm in its stowed configuration. The original mission plan was for a timer to initiate inflation of a 100' long, 5.2' max diameter double-tapered spar shaped balloon approximately 10 hours after ejection from the launch vehicle. That timer has been disconnected from the balloon, and now inflation can only be initiated via radio command. When the balloon is inflated the configuration is defined to be "deployed."

The Spacecraft also includes a low power radio telemetry and command system that is being tested for exposure to LEO conditions in order to achieve NASA's highest Test Readiness Level. The radio system only responds to ground-to-space interrogations; it does not beacon unless commanded.

The stowed configuration of the 3U ORBITAL-REFLECTOR satellite measures 10 cm x 10 cm x 34 cm, and is shown in Figure 1. It is important to note that this configuration is only valid if the balloon is not inflated.



[1] *See* ODAR submissions included with OET File No. 0619-EX-ST-2018 (filed Apr. 4, 2018 and Aug. 28, 2018).

Figure 1. Stowed Configuration of the 3U ORBITAL-REFLECTOR Satellite

As previously mentioned, the deployed configuration of the 3U ORBITAL-REFLECTOR satellite measures 10 cm x 10 cm x 34 cm (cubesat structure) with a 100' long, 5.2' max diameter double-tapered spar shaped balloon aligned with velocity vector coming out of the 10 cm x 34 cm face. The deployed cubesat structure is shown in Figure 2. The balloon inflation occurs when a nichrome-energized Spectra string cutter releases both the door and the gas (two 25 gram CO2 cartridges that are DOT rated for air and surface transport, and are hermetically sealed). The balloon is made from 0.35 mil polymer and is opaqued with TiO_2 powder, which is evenly dispersed inside the balloon. The balloon (deployed in vacuum) is designed to not over-inflate and rupture. Additionally, the 3U cubesat will not experience deleterious deformation in the extremely unlikely event of unscheduled gas dispensing. A flight-identical Qualification unit has successfully undergone GEVS compliant 14.1 g's RMS random vibration testing.

There are two small lithium rechargeable batteries and two solar panels on-board, as well as a small patch antenna incorporated into each end of the satellite to give full-spherical RF coverage.

There is no propulsion system, no attitude control systems, no radioactive materials, and no pyrotechnic devices on-board. There are also no planned releases of spacecraft debris.

There are two electrical systems. The primary system is a countdown timer, which has been disabled. The second electrical system (with radio) includes solar panels and charge regulator feeding a Tenergy 30000-1 800mA*hr 3.7 Volt cell.

For the deployed configuration, both random tumbling and fixed orientation were assessed, along with a scenario that represents the satellite as a 100 ft. (30.48 m) radius sphere.

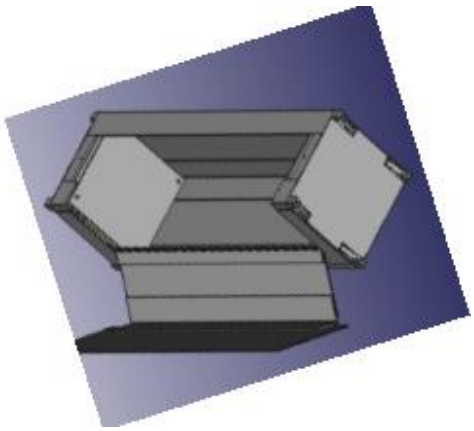


Figure 2. Deployed ORBITAL-REFLECTOR Cubesat structure (inflated balloon not pictured here)

3. Orbital Lifetime

A summary of the four configurations analyzed is presented in Table 1.

Table 1. Summary of Orbital Lifetime Results

Configuration	Orientation	Cross Sectional Area (m^2)	Area-to-Mass Ratio (m^2/kg)	Orbital Lifetime

Stowed	Random Tumbling	0.039	0.0118	7.086 years
Deployed	Fixed Orientation	1.977	0.5991	1.922 years
Deployed	Random Tumbling	19.021	5.7639	82.125 days (0.225 years)
Deployed	Conservative- if one assumes the cross section is an area of radius = 100 ft.	2918.635	884.4349	0 days (immediately re-enters)

Detailed Orbital Lifetime Analysis of Configurations

Stowed Configuration: Figure 3 shows the inputs and outputs of the Orbital Lifetime/Dwell Time for the stowed configuration.

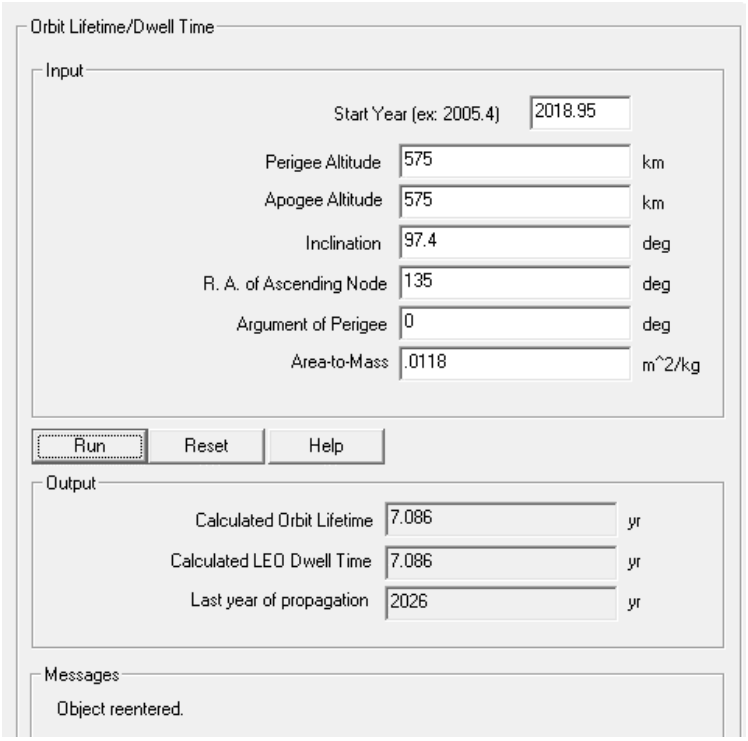


Figure 3. Orbital Lifetime/Dwell Time of Stowed Configuration

Figure 4 provides a graph of the ORBITAL-REFLECTOR Altitude History, which shows that the majority of the 7.086 year orbit lifetime occurs at an altitude greater than 350 km. In other words, it takes approximately 7 years to reach 350 km, and less than 2 months is spent below 350 km.

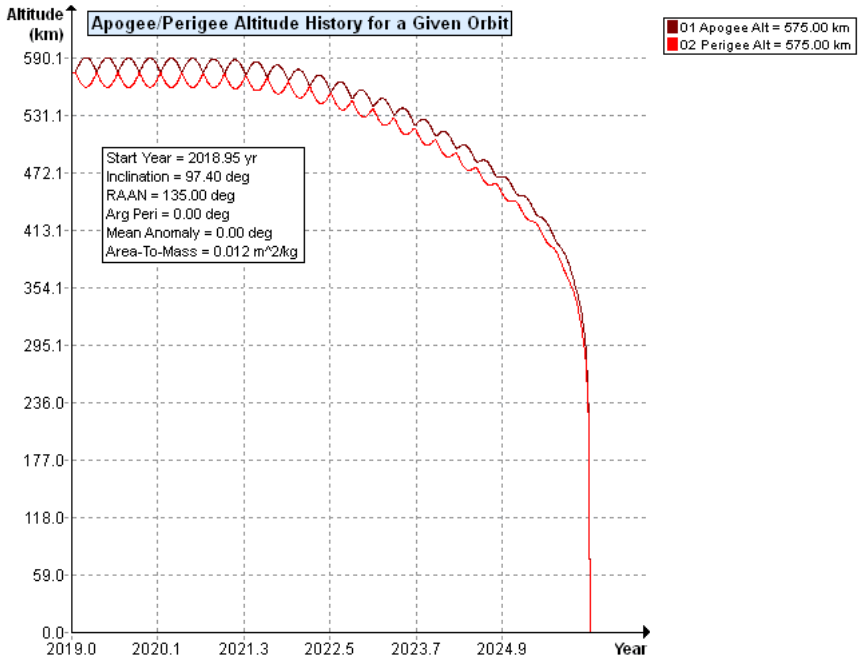
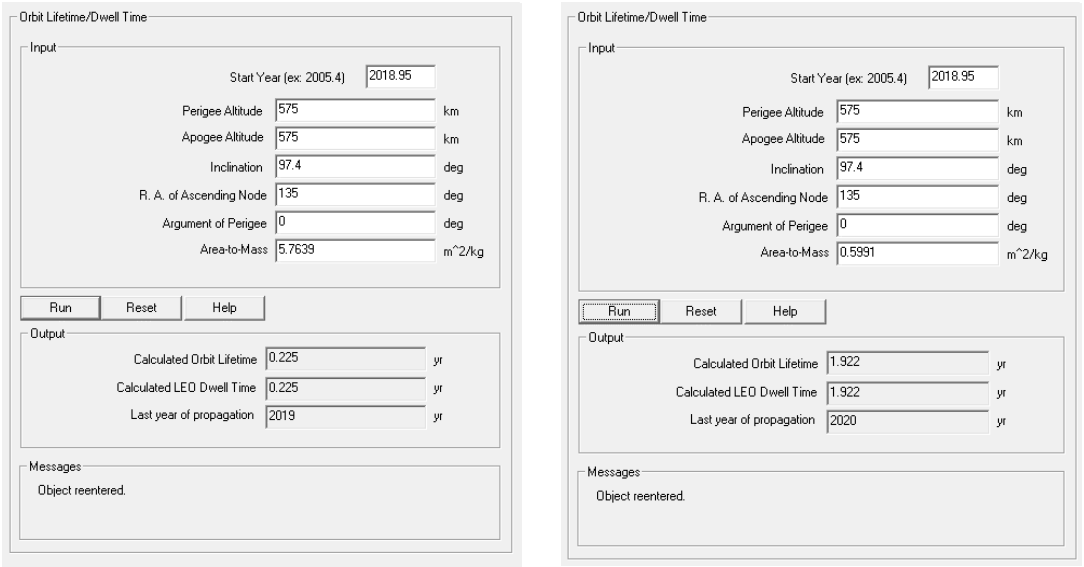


Figure 4. Altitude History for ORBITAL-REFLECTOR in Stowed Configuration

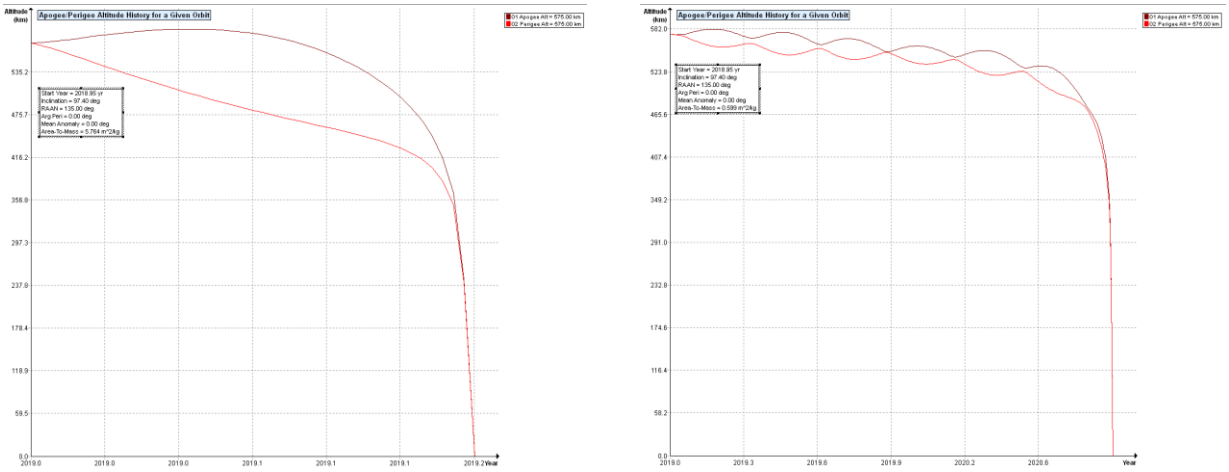
Deployed Configurations (Random Tumbling and Fixed Orientation): The deployed geometry has a cross sectional area of 19.021 m^2 for random tumbling and 1.977 m^2 for fixed orientation. Like in the stowed configuration, a mass of 3.3 kg was assumed, generating an area-to-mass ratio of 5.7639 m^2/kg for random tumbling and 0.5991 m^2/kg for fixed orientation. These two area-to-mass ratios return a calculated orbital lifetime of 0.225 years (82.125 days) for random tumbling and 1.922 years for fixed orientation.



(a) (b)

Figure 5(a,b). Orbital Lifetime/Dwell Time of Deployed Configuration assuming (a) Random Tumbling and (b) Fixed Orientation

The orbital trajectories for the (a) Random Tumbling and (b) Fixed Orientation are provided in Figure 6 below. It is important to note that the x-axis (time) is not on the same scale for the two figures. In Figure 6(a), the ORBITAL-REFLECTOR satellite randomly tumbles and re-enters after 82.125 days. In Figure 6(b), the ORBITAL-REFLECTOR is in a fixed orientation with the balloon facing the velocity vector. In this configuration, the satellite re-enters after 1.922 years. For a random tumbling configuration, the apogee of the orbit does not increase signifcantly beyone 575 km. For a fixed orientation, the apogee increases slightly above 575 km to 595 km.



(a) (b)

Figure 6(a,b). Orbital Trajectory of Deployed Configuration assuming (a) Random Tumbling and (b) Fixed Orientation

Deployed Configurations (100 ft. radius sphere):

The last configuration models the spacecraft as a 100 ft. radius sphere. In this scenario, the cross-sectional area is computed to be 2918.6 m^2 and the area-to-mass ratio is 884.43 m^2/kg. Figure 7 shows the inputs and outputs of the Orbital Life computation.

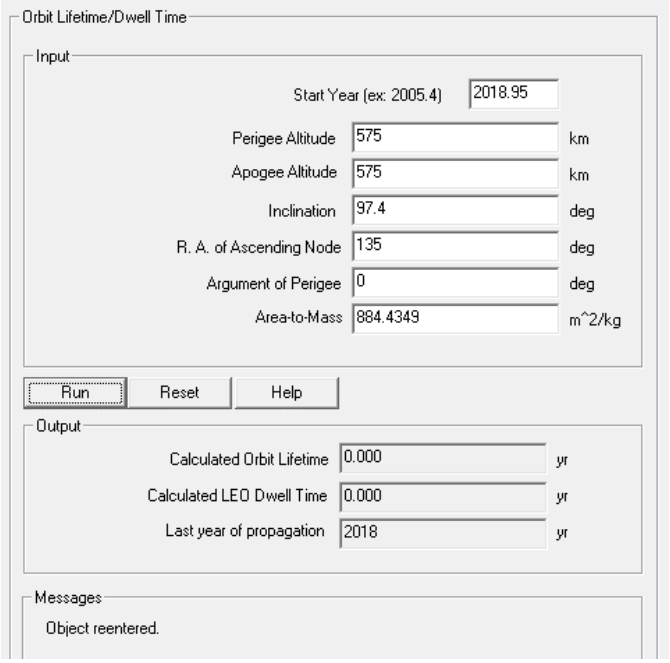


Figure 7. Orbital Lifetime/Dwell Time of Deployed Configuration assuming the spacecraft is a 100 ft. radius sphere

For this configuration, the orbital lifetime is 0.000 years, meaning that the spacecraft immediately re-enters. Due to the relatively fast nature of re-entry a plot of orbital trajectory is not provided.

4. Orbital Debris Requirements Assessment

The Orbital Debris Requirements were analyzed for each of the four scenarios presented in Table 1. However, the mission lifetime was extended for the conservative deployed configuration in order to more accurately account for the complex geometry of the spacecraft. Table 2 summarizes the configurations and mission lifetimes modelled. **All requirements are met for each of the four configurations.**

Table 2. Summary of Scenarios Modelled

Configuration	Orientation	Area-to-Mass Ratio (m^2/kg)	Orbital Lifetime	Mission Duration Assumed in Modelling
Stowed	Random Tumbling	0.0118	7.086 years	7.086 years
Deployed	Fixed Orientation	0.5991	1.922 years	1.922 years
Deployed	Random Tumbling	5.7639	82.125 days (0.225 years)	0.225 years
Deployed	Conservative - assumes the cross section is a circle of radius = 100 ft.	884.4349	0 days	0.65 years

Requirements 4.3-1a, 4.3-1b, 4.3-2 – Compliant (No planned debris released)

The assessment of spacecraft debris requires the identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material. No releases are planned on the ORBITAL REFLECTOR, therefore this section is Compliant or Not Applicable

Requirements provided for reference:

(Requirement 4.3-1a & 4.3-1b) - Debris passing through LEO: For missions leaving debris in orbits passing through LEO, released debris with diameters of 1 mm or larger shall satisfy both Requirement 4.3-1a and Requirement 4.3-1b:

> *a. All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release.*
>
> *b. The total object-time product shall be no larger than 100 object-years per mission. The object-time product is the sum of all debris of the total time spent below 2000 km altitude during the orbital lifetime of each object*

(Requirement 4.3-2) - Debris passing near GEO: For missions leaving debris in orbits with the potential of traversing the GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km.

Requirement 4.4-3 - Compliant (No planned breakups)

A detailed explanation of the unlikelihood of any on-board explosion due to Lithium-ion batteries was presented in our previous ODAR. Since there are no planned breakups, ORBITAL-REFLECTOR is compliant to Requirement 4.4-3.

Requirement provided for reference:

(Requirement 4.4-3) - Limiting the long-term risk to other space systems from planned breakups: Planned explosions or intentional collisions shall:

> *a) Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years. For example, if the debris fragments greater than 10 cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.*
>
> *b) Not generate debris larger than 1 mm that shall remain in Earth orbit longer than one year.*

Requirement 4.5-1 and 4.5-2 – Compliant (Meet probability of collision with large objects and probability of damage from small satellites)

As previously mentioned, in order to account for the complex geometry of the ORBITAL-REFLECTOR, an extended mission lifetime of 0.65 years was modelled for the three "deployed" configurations. The inputs and outputs are provided in the next four figures for Requirement 4.5-1, and show that all of the configurations are compliant. Compliance with Requirement 4.5-2 was also achieved.

Requirements provided for reference:

(Requirement 4.5-1) - Limiting debris generated by collisions with large objects when operating in Earth orbit. For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001.

(Requirement 4.5-2) - Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit: For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable post-mission disposal requirements is less than 0.01.

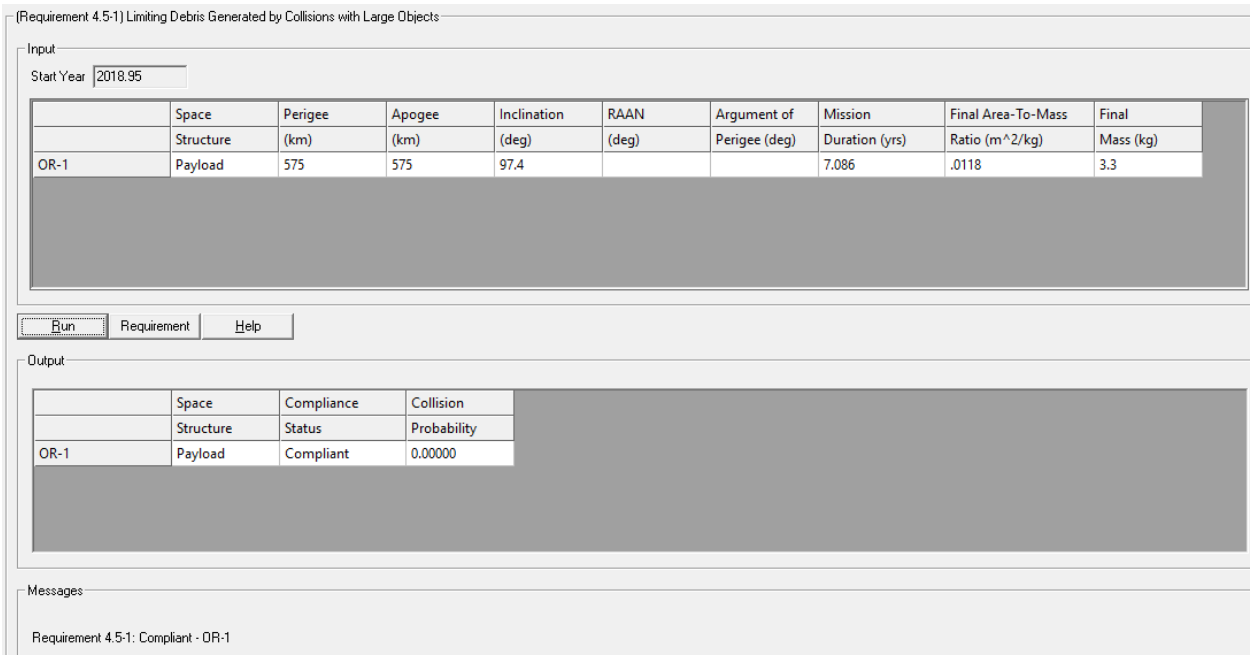


Figure 8. Compliance with 4.5-1 for the Stowed Configuration

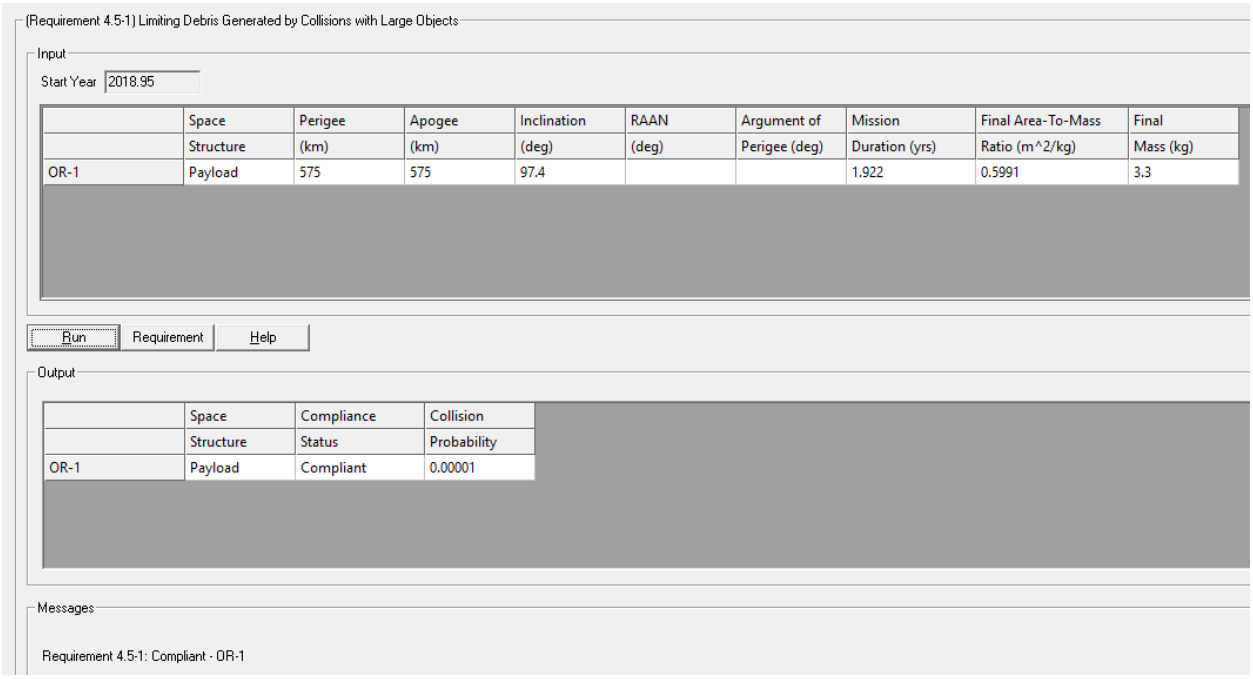


Figure 9. Compliance with 4.5-1 for the Fixed Orientation Deployed Configuration

(Requirement 4.5-1) Limiting Debris Generated by Collisions with Large Objects

Input

Start Year 2018.95

	Space Structure	Perigee (km)	Apogee (km)	Inclination (deg)	RAAN (deg)	Argument of Perigee (deg)	Mission Duration (yrs)	Final Area-To-Mass Ratio (m^2/kg)	Final Mass (kg)
OR-1	Payload	575	575	97.4			0.225	5.7639	3.3

Run | Requirement | Help

Output

	Space Structure	Compliance Status	Collision Probability
OR-1	Payload	Compliant	0.00002

Messages

Requirement 4.5-1: Compliant - OR-1

Figure 10. Compliance with 4.5-1 for the Random Tumbling Deployed Configuration

(Requirement 4.5-1) Limiting Debris Generated by Collisions with Large Objects

Input

Start Year 2018.95

	Space Structure	Perigee (km)	Apogee (km)	Inclination (deg)	RAAN (deg)	Argument of Perigee (deg)	Mission Duration (yrs)	Final Area-To-Mass Ratio (m^2/kg)	Final Mass (kg)
OR-1	Payload	575	575	97.4			0.65	884.4349	3.3

Run | Requirement | Help

Output

	Space Structure	Compliance Status	Collision Probability
OR-1	Payload	Compliant	0.00007

Messages

Requirement 4.5-1: Compliant - OR-1

Figure 11. Compliance with 4.5-1 for the Conservative 100 ft. Radius Sphere Configuration

Requirement 4.6-1 to 4.6-3 – Compliant (Passive Post-mission Disposal within 25 years)

ORBITAL-REFLECTOR is compliant with Req. 4.6-1 for all four configurations because disposal of the entire spacecraft will occur via atmospheric reentry within 25 years. Requirement 4.6-2 and 4.6-3 are not applicable as they pertain to spacecraft in GEO, and between LEO and GEO, respectively.

Requirements provided for reference:

(Requirement 4.6-1) - Disposal for space structures passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods:

a. Atmospheric reentry option:

(1) Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or

(2) Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

(Requirement 4.6-2) - Disposal for space structures near GEO: A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum altitude of GEO + 200 km (35,986 km) for a period of at least 100 years after disposal.

(Requirement 4.6-3) - Disposal for space structures between LEO and GEO:

a) A spacecraft or orbital stage may be left in any orbit between 2000 km above the Earth's surface and 500 km below GEO.

b) A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,100 km and 20,200 km.

Requirement 4.7-1

Figure 12 lists component data input into the DAS to determine the risk of human casualty. The CO_2 gas was not included in the component data, but the gas containers were included.

Component Data

	Name	Quantity	Material Type	Object Shape	Thermal Mass	Diameter/Width	Length	Height
					(kg)	(m)	(m)	(m)
1	OR-1	1	Aluminum 6061-T6	Box	3.3	0.1	0.34	0.1
2	Door/Hatch	1	Aluminum 6061-T6	Flat Plate	0.1	0.1	0.3	
3	SC rails	4	Aluminum 6061-T6	Box	0.1	0.02	0.32	0.02
4	Rectangular Pl	1	Aluminum 6061-T6	Box	0.4	0.08	0.31	0.01
5	Solar Panels	3	Fiberglass	Flat Plate	0.15	0.08	0.32	
6	Circuit Board	4	Fiberglass	Box	0.01	0.1	0.1	0.01
7	Balloon Memb...	1	Polyimide	Cylinder	1.2	2	30	
8	Balloon Basepl	1	Aluminum 6061-T6	Flat Plate	0.2	0.08	0.28	
9	Gas Cylinders	2	Steel A-286	Cylinder	0.055	0.03	0.221	
10	Short Screws	100	Steel AISI 304	Cylinder	0.0005	0.003	0.01	
11	Batteries	2	Zinc	Cylinder	0.005	0.009	0.06	
12	Springs	2	Steel A-286	Cylinder	0.02	0.015	0.29	
13	Long_screws	130	Stainless Steel 17-4 ph	Cylinder	0.0011	0.003	0.02	

Figure 12. Component Data Input for Requirement 4.7-1 Compliance

Figure 13 shows the output of the DAS, and that ORBITAL-REFLECTOR is compliant with Requirement 4.7-1 (there is a total zero casualty area, and a casualty risk of 1:100000000).

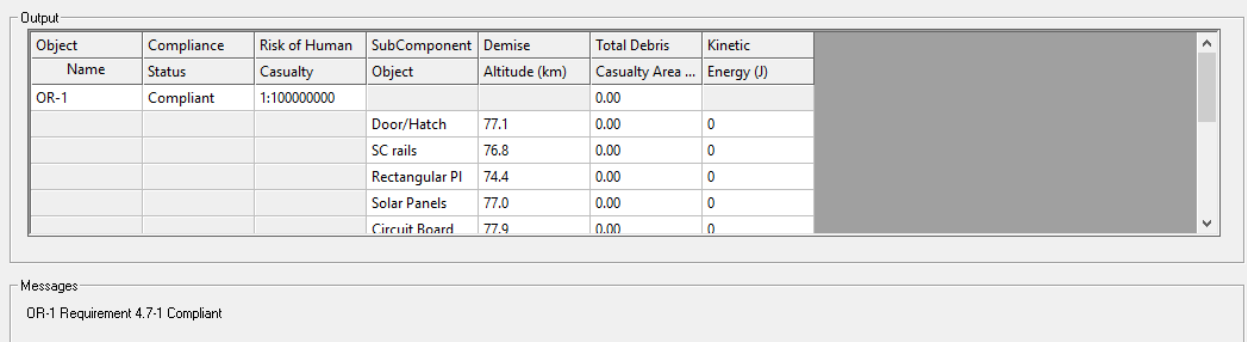


Figure 13. Output of DAS showing Req. 4.7-1 Compliance

Requirement provided for reference:

(Requirement 4.7-1) - Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 Joules:

a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000).

b) For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 Joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica.

c) For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000).

Requirement 4.8-1 – Compliant (no tether on-board)

While there are no tethers on-board the ORBITAL-REFLECTOR, the overall geometry of the ORBITAL-REFLECTOR could be viewed as resembling a tether, in that it is long and narrow. Therefore, the spacecraft was entered in to the DAS to assess for Req. 4.8-1 compliance.

DAS defines a tether system as being made of two end objects connected by a momentum tether or an electromagnetic (EM) tether. One of the end objects is the ORBITAL-REFLECTOR spacecraft (2.05 kg, which is the mass without the mass of the gas and balloon membrane), and the other end object is a nearly massless and nearly zero-area object. A momentum tether was selected to represent the ORBITAL-REFLECTOR. The cross-sectional area of the ORBITAL-REFLECTOR in the stowed configuration was used as the input to the end-point. The dimension of the tether is 1.585 m (5.2 ft.) in diameter and 30.48 m (100 ft.) in length, and the mass of the tether is 1.25 kg (1.2 kg for the balloon membrane, and .05 kg for the CO_2 gas). This is conservative since it assumes a constant diameter of 5.2 ft. where in actuality the balloon is tapered on each end. In this section of the software, the DAS checks for compliance with Req. 4.5-1, 4.5-2, and 4.6. Figure 14 shows that based off these inputs, the ORBITAL-REFLECTOR complies with Req. 4.8-1.

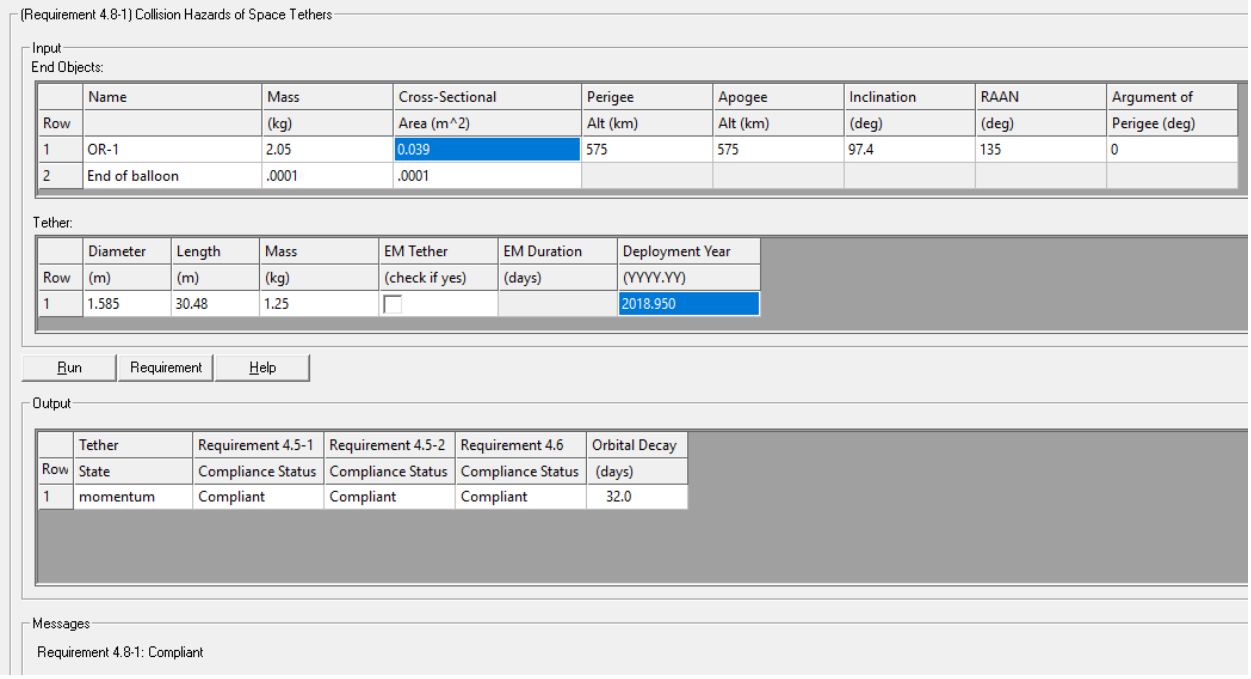


Figure 14: Requirement 4.8-1 Compliance

Requirement provided for reference:
(Requirement 4.8-1) - Mitigate the collision hazards of space tethers in Earth or Lunar orbits: Intact tether systems in Earth and lunar orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions (Requirements 4.5-1 and 4.5-2) and the requirements governing post-mission disposal (Requirements 4.6-1 through 4.6-4) to the limits specified in those paragraphs. Due to the potential of tether systems being severed by orbital debris or meteoroids, all possible remnants of a severed tether system shall be compliant with the requirements for the collision, debris, and disposal of space structures.

Summary

This report contains detailed analysis of the ORBITAL-REFLECTOR debris environment. Four different geometries were modelled: stowed, deployed (fixed orientation), deployed (random tumbling), and modelled as a 30.48 m radius sphere. For all configurations modelled, the ORBITAL-REFLECTOR is compliant with all of the Orbital Debris Requirements contained within NASA-STD-8719.14A: Process for Limiting Orbital Debris, as assessed using NASA's Debris Assessment Software (DAS) Version 2.1.1. Furthermore, the system was modelled as a 100 ft. x 5.2 ft diameter tether for Requirement 4.8-1, and complied with NASA's Orbital Debris Requirements contained in the DAS.

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