8/20/2018

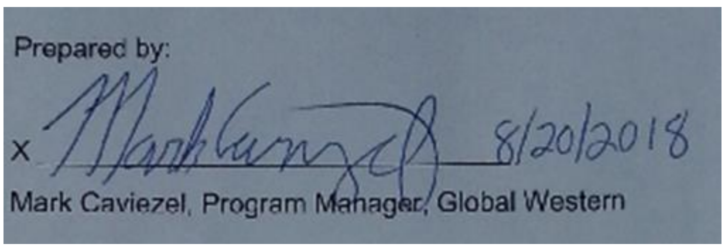
Orbital Debris Assessment for

ORBITAL REFLECTOR

on the

SSO-A mission

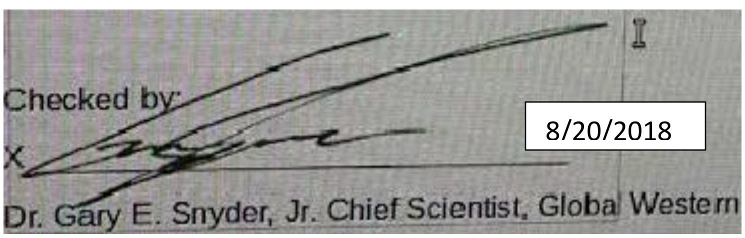
Per NASA-STD 8719.14A



Prepared by:

x 8/20/2018

Mark Caviezel, Program Manager, Global Western



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Dr. Gary E. Snyder, Jr. Chief Scientist, Global Western

REFERENCES:

A. *NASA Procedural Requirements for Limiting Orbital Debris Generation,* NPR 8715.6A, Feb 2008

B. *Process for Limited Orbital Debris,* NASA-STD-8719.14A 25 May 2012

C. *Battery Life Plan, Orbital Reflector,* Dr. Gary E. Snyder, Jr. May 2018

D. McKissock, Barbara, Patricia Loyselle, and Elisa Vogel. *Guidelines on Lithium-Ion Battery Use is Space Applications.* Tech # RP-08-75 NASA Glenn Research Center Cleveland, OH

E. *UL Standards for Safety for Lithium Batteries* UL 1642 UL Standard 4th Ed. Northbrook, IL, Underwriters Laboratories 2007

F. *Specification Approval Sheet Lithium-Ion Rechargeable Battery 30000-1* Tenergy Corporation

G. *Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads and Ground Support Systems Requirements,* AFSCM 91-710 V3.

H. *Interface Control Document, Orbital Reflector on SSO-A,* Spaceflight Industries

I. *UL Standard for Safety for Household and Commercial Batteries, UL 2054* UL Standard, 2nd edition, Northbook, IL Underwriters Laboratories, 2005

J. *Common Risk Criteria Standards for National Test Ranges,* Standard 321-10 December 2010

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the ORBITAL REFLECTOR mission launching in conjunction with the SSO-A launch.

The Following table summarized the compliance status of the ORBITAL REFLECTOR SATELLITE flown on SSO-A. ORBITAL REFLECTOR is fully compliant with all applicable requirements.

TABLE 1: Orbital Debris Requirements Compliance Matrix

Requirement	Compliance Assesment	Comments
4.3-1	Compliant	LEO Debris- none planned
4.3-2	Compliant / (Not Applicable)	GEO Debris- none planned
4.1-1	Compliant	On board Energy Source (batteries) is incapable of debris-producing failure
4.4-3	Compliant	No planned breakups
4.4-4	Compliant	No planned breakups
4.5-1	Compliant	Probability of collision with large objects
4.5-2	Compliant	Probability of damage from small objects
4.6-(1-3)	Compliant	Postmission Disposal- passive. Worst case 140 days
4.7-1	Compliant	No credible Human Casualty Risk
4.8-1	Compliant	No tether on this mission

Section 1 Program management and mission overview.
OR Sat Mission Narrative:

Created by artist Trevor Paglen working in collaboration with the Nevada Museum of Art and aerospace engineers, the Orbital Reflector is a satellite artwork to be launched into low-earth orbit in fall-2018. Paglen's work will make an artistic statement while encouraging dialogue related to the integrated fields of science, engineering, politics, and space exploration. Paglen's satellite will be constructed of lightweight, highly reflective material similar to Mylar. In orbit, it will be a visible sculpture, observable from Earth with the naked eye and trackable via Internet and mobile device. The satellite will remain in orbit for several weeks before disintegrating upon re-entry into the Earth's atmosphere. Pre-inflation it is 10cm x 10cm x 34 cm '3 U' cubesat form factor. After a substantial time period after ejection from launch vehicle, a hatch opens and a double-tapered spar shaped balloon is inflated- 100' long, 5.2 feet maximum diameter in the middle, tapering to a narrow point at either end. The balloon stays attached to the spacecraft frame. The Spacecraft also includes a low power radio telemetry and command system, undergoing test exposure to LEO conditions to achieve TRL-9. The radio system only responds to ground-to-space interrogations; it does not beacon unless commanded. Note: there are no foreign governments involved in Orbital Reflector.

Technical Point of Contact – Mark Caviezel, Global Western (805)896-6494

Media Inquiries: Amanda Horn, Nevada Museum of Art (775)636-2567

Program Milestone History/Schedule	
Milestone	**Date**
Concept inception	2015
Program Inception	January 2017
PDR	April 2017
CDR	September 2017
Qualification Testing Complete	March 2018
Launch (planned)	Nov 15, 2018
End-of Mission- re-entry	L+ 140 days

Fig 1. Program Milestone Schedule

The SSO-A mission is aggregated by Spaceflight Industries. Orbital Reflector is one of over 70 satellites manifested on this flight. The planned launch is on a Space X Falcon 9 launch vehicle out of Vandenburg AFB to a 97 degree inclined, 575 km altitude circular sun synchronous orbit. The current launch window is a seven-day window opening November 15, 2018.

Section 2: Spacecraft Description

The Orbital Reflector Satellite is a 3U cubesat that has a large deployable balloon inside. The means of deployment is by nichrome-energized Spectra string cutter releases for both the door and the gas inflation means. The gas inflation means is two 25 gram CO_2 cartridges. The balloon is made from 0.35 mil polymer and it opaqued by TiO_2 powder which is evenly dispersed inside the balloon. The SC mass is 3.3 kg. The SC dry mass is 3.25kg. There is no propulsion system. The mass of the CO_2 inflating agent is 0.050 kg
There are no attitude control systems. There are no pyrotechnic devices. There are two electrical systems: The primary system is a countdown timer, activated upon SC ejection. The timer is powered by a Tenergy 30000-1 800mA*hr 3.7 Volt cell. The backup system (with radio) includes solar panels and charge regulator feeding a Tenergy 30000-1 800mA*hr 3.7 Volt cell.
There are no radioactive materials on board.

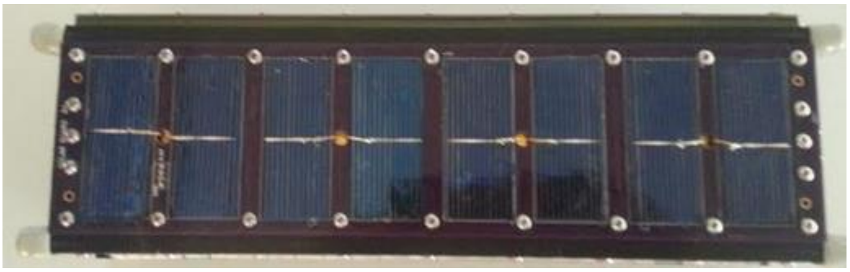


Fig 2. Ready for Flight: Orbital Reflector 3U cubesat.

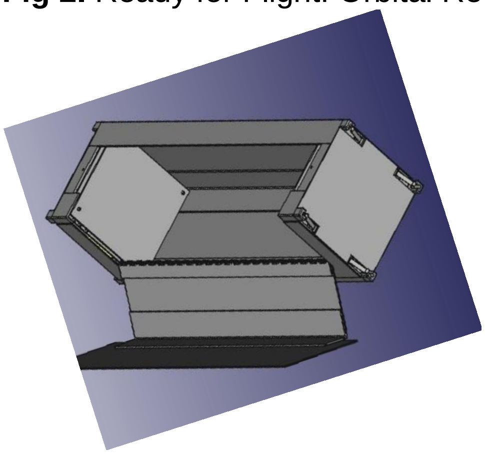


Fig 3. CAD-generated view of SC with door/hatch opened. (balloon assembly omitted)

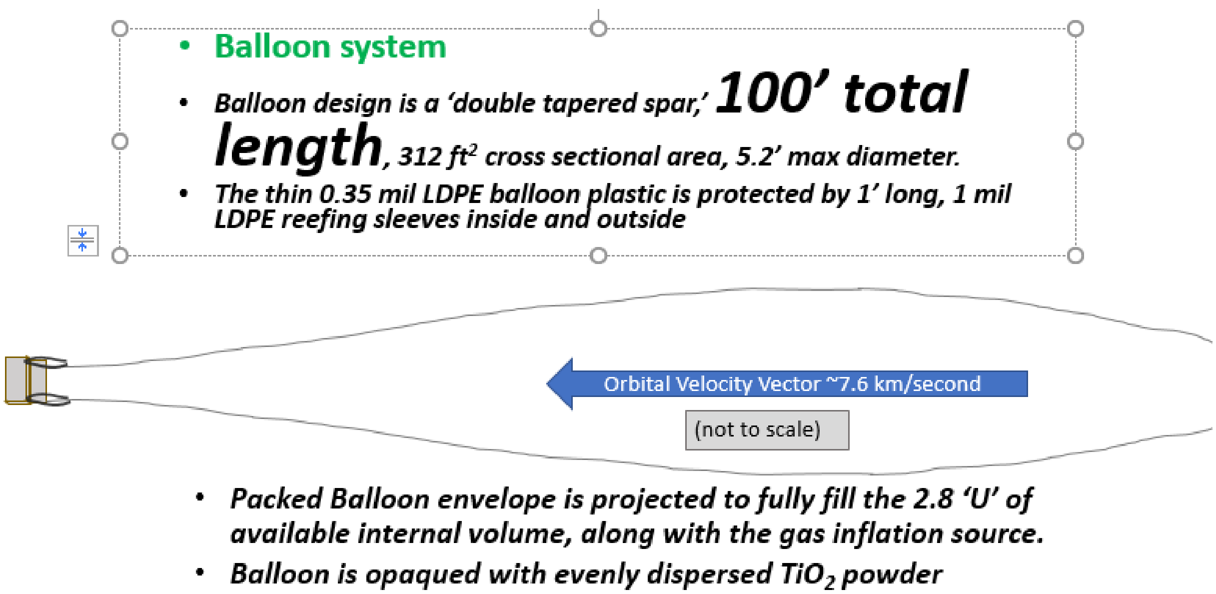


Fig. 4. Diagram of Orbital Reflector with deployed balloon.

Balloon System Description: 100 feet long, 5.2 foot diameter, double tapered opaqued white polymer. Skin stress while deployed (hot case) is 70 psi. Internal pressure when deployed is 0.009 psia. The balloon is normally deployed by timer – 10 hours delay after ejection from the carrier. As a back-up system, the balloon can also be commanded open by radio command if needed.

Orbital Reflector is comprised of custom designed and produced hardware (radio system, balloon membrane, balloon inflation source, etc.) The frame is 6061-T6 aluminum. Fasteners are 3mm 17-4ph stainless steel. The circuit boards and the antenna boards are G-10 fiberglass. The door panel is 6061-T6 aluminum. There are two on-board gas inflation sources: COTS 25 gram CO_2 cylinders. These cylinders are DOT rated for air and surface transport. They are hermetically sealed. The balloon (deployed in vacuum) will not over-inflate and rupture. 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 with no negative issues discovered. There are two small lithium rechargeable batteries. There are two solar panels. Small patch antennas are incorporated into each end of the satellite and give full-spherical RF coverage.

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

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

.

The section 3 requires rationale/necessity for release of each object, time of release of each object, relative to launch time, release velocity of each object with respect to spacecraft , expected orbital parameters (apogee, perigee, and inclination) of each object after release, calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO) , and an assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

Note: No releases are planned on the ORBITAL REFLECTOR mission therefore this section is Compliant or Not Applicable

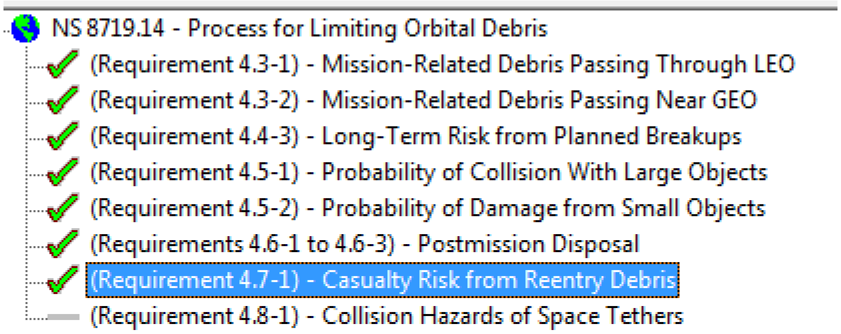


Fig 5. Summary of ODAR-calculated Requirements Compliance

Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosions.

Malfunction of lithium ion or lithium polymer batteries and/or associated control circuitry has been identified as a potential cause for spacecraft breakup during deployment and mission operations. While no passivation of batteries will be attempted, natural degradation of the solar cell and battery properties will occur over the post mission period, which may be as long as 80 days. (60 day nominal mission and 80 days additional orbital drag and decay before re-entry.)

Note: there are significant variations to the spacecraft's flight endurance: 10.7 cm solar flux (currently low) and exact behavior of spacecraft – continuous tumbling or partial 'streamlining' will have a variable impact, also. Analysis indicates that the gravity gradient forces are substantially lower than drag induced torque on this SC with a mass concentration on one end. Therefore we do not expect the worst-case high-drag gravity gradient nadir-pointing attitude to be sustained at any time during the mission.

These conditions pose a possible increased chance of undesired battery energy release. The battery capacity for storage will degrade over time, possibly leading to changes in the acceptable charge rate for the cells. Individual cells may also change properties at different rates due to time degradation and temperature changes. The control circuit may also malfunction as a result of exposure to the space environment

over long periods of time. The cell pressure relief vents could be blocked by small contaminants. Any of these individual or combined effects may
Theoretically cause an electro-chemical reaction that result in rapid energy release in the form of combustion. There are NO plans for designed spacecraft breakups, explosions, or intentional collisions on the Orbital Reflector SC mission.

Section 4 asks for a list of components, which shall be passivated at End of Mission (EOM), as well as the method of passivation and description of the components, which cannot be passivated. No passivation of components is planned at the End of Mission for any of the Orbital Reflector SC. Since the batteries used do not present a debris generation hazard even in the event of rapid energy release (see assessment directly below), passivation of the batteries is not necessary in order to meet the requirement 4.4-2 (56450) for passivation of energy sources "to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft." Because passivation is not necessary, and in the interest of not increasing the complexity of the spacecraft, there was no need to add this capability to their electrical power generation and storage systems
.
Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4
shows that the Orbital Reflector SC is compliant. Requirements 4.4-3 and 4.4-4 are not applicable. The following addresses requirement 4.4-2. Orbital Reflector SC has not been designed to disconnect onboard storage energy devices (lithium ion and lithium polymer batteries). However, the spacecraft's batteries still meet Req. 56450 by virtue of the fact that they cannot "cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft". The battery cells utilize lithium ion technology and are compliant with Underwriters Laboratory(UL) Standard 1642.

Table 3: Orbital Reflector Electrical Cells

Manufacturer	Name	Model
Tenergy	Lithium-Ion Recharageble Battery	30000-1

The batteries (single cells, actually) are COTS sourced from the consumer-oriented market. All battery cells have been recognized as Underwriters Laboratories (UL) tested and approved. Furthermore, safety devices incorporated in these batteries include pressure release valves, over current charge protection and over current discharge protection. The fact that these batteries are UL recognized indicates that they have passed the UL standard testing procedures that characterize their explosive potential. Of particular concern to NASA Req. 56450 is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 Projectile Test of UL 1642 (ref. (e)) subjects the test battery to heat by flame while within an aluminum and steel wire mesh octagonal box, "[where the test battery] shall remain on the screen until it explodes or the cell or battery has ignited and burned out"(UL 1642 20.5). To pass the test, "no part of an exploding cell or battery shall penetrate the wire screen such that some or all of the cell or battery protrudes through the screen" (UL 1642 20.10)

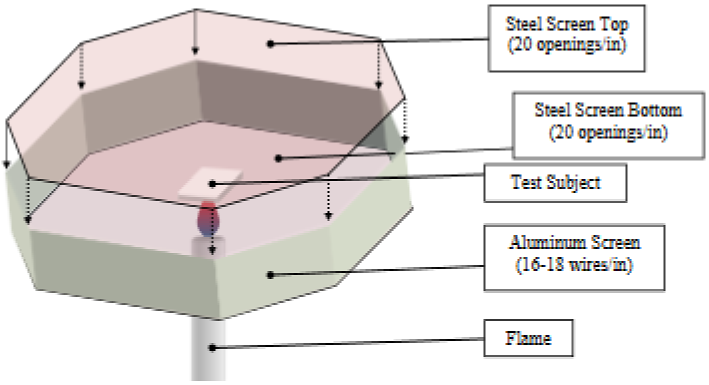


Fig 6. Underwriter's Laboratory Explosion Test Apparatus

The batteries being launched on Orbital Reflector will experience conditions on orbit that are generally much less severe that those seen during the UL test. While the source of failure would not be external heat on orbit, analysis of the expected mission thermal environment performed by NASA LSP Flight Analysis Division shows that given the Very low (<=3.0 W*hr), the batteries will be exposed to a maximum temperature that is well below their 212 degree F safe operation limit (ref. (f)). It is unlikely but possible that the continual charging with 1.2 to 1.6 W of average power from the solar panels over an orbital life span greater than a year may expose the two cells to overcharging which could cause similar heat to be generated internally.

Through the UL testing, it has been shown that these batteries do not cause an explosion that would cause a fragmentation of the spacecraft. A NASA Glenn Research Center guideline entitled Guidelines on Lithium ion Battery Use in Space Applications (ref. (d)) explains that the hazards of Li-Ion cells in an overcharge situation result in the breakdown of the electrolyte found in Li-ion cells causing an increase in internal pressure, formation of flammable organic solvents, and the release of oxygen from the metal oxide structure. From a structural point of view a battery in an overcharge situation can expect breakage of cases, seals, mounting provisions, and internal components. The end result could be “unconstrained movement of the battery” (ref. (d), pg 13). This document clearly indicates that only battery deformation and the escape of combustible gasses will be seen in an overcharging situation, providing further support to the conclusion that CubeSat fragmentation due to explosion is not a credible scenario for this application. It is important to note that the NASA guide to Li-ion batteries makes no mention of these batteries causing explosions of any magnitude whatsoever.

Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft takes into account both the mean cross sectional area and orbital lifetime. The largest mean cross sectional area (CSA) with one balloon deployable :

$$\boldsymbol{Mean\ CSA} = \frac{\sum \boldsymbol{Surface\ Area}}{\mathbf{4}} = \frac{[\mathbf{2} * (\boldsymbol{w} * \boldsymbol{l}) + \mathbf{4} * (\boldsymbol{w} * \boldsymbol{h})]}{\mathbf{4}}$$

Equation 1: Mean Cross Sectional Area for Convex Objects

$$\boldsymbol{Mean\ CSA} = \frac{(\boldsymbol{A_{max}} + \boldsymbol{A_1} + \boldsymbol{A_1})}{\mathbf{2}}$$

Equation 2: Mean Cross Sectional Area for Complex Objects

Orbital Reflector evaluated for this ODAR is stowed in a convex configuration. Thus, the mean CSA Orbital Reflector while stowed was calculated using Equation 1. This configuration renders the longest orbital life times for Orbital Reflector SC. Once a CubeSat has been ejected from the POD and deployables have been extended Equation 2 is utilized to determine the mean CSA. A_{max} is identified as the view that

yields the maximum cross-sectional area. A_1 and A_2 are the two cross-sectional areas orthogonal to A_{max}. Refer to Appendix A for dimensions used in these calculations
The Orbital Reflector SC orbit at deployment is 575 km apogee altitude by 575 km perigee altitude, with an inclination of 97.4 degrees. With an area to mass (3.3 kg) ratio of 7.18 m^2 / kg DAS yields 3.3 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. The CubeSat design and orbital lifetime see an average of $1X10^{-7}$

Table 4 below provides complete results:

Orbital Reflector Spacecraft		
Stowed	Mass (kg)	3.3
	Mean SC area m^2	0.0095
	Area-to-mass (m^2 / kg)	0.0029
	Orbital Lifetime (years)	11.3
	Probability of collision	1.0E-07
Deployed	Mass (kg)	3.3
	Mean SC area m^2	3.94
	Area-to-Mass (m^2/kg)	1.19
	Orbital Lifetime (days)	95
	Probability of collision	2.0E-09

Table 4. Orbital Reflector Endurance Detail

There will be no post-mission disposal operation. as such the identification of all systems and components required to accomplish post-mission disposal operation, including passivation and maneuvering, is not applicable.

The probability of Orbital Reflector spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than 10-7 , for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1. Since the Orbital Reflector SC has capability or plan for end-of-mission disposal, requirement 4.5-2 is not applicable. Assessment of spacecraft compliance with Requirements 4.5-1 shows Orbital Reflector SC to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

Orbital Reflector SC will naturally decay from orbit in less than 25 years after end of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option. Planning for spacecraft maneuvers to accomplish post-mission disposal is not applicable. Disposal is achieved via passive atmospheric reentry. The worst-case (smallest Area-to-Mass) post-mission disposal is Orbital Reflector SC in stowed configuration. The area-to-mass is calculated as follows:

$$\frac{Mean\ {}^{C}/_{S}\,Area\ (m^2)}{Mass\ (kg)} = Area - to - Mass\ (\frac{m^2}{kg})$$

Equation 3: Area to Mass

The assessment of the spacecraft illustrates it is compliant with Requirements 4.6-1 through 4.6-5. DAS 2.0.2 Orbital Lifetime Calculations: DAS inputs are: 575 km maximum perigee X 575 km maximum apogee altitudes with an inclination of 97.4 degrees at deployment in the year 2018. An area to mass ratio of 0.0029 m^2/kg for the Orbital Reflector SC sat was input. DAS 2.0.2 yields a 2.8 years orbit lifetime for Orbital Reflector SC in its stowed state. This meets the requirement 4.6-1. Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on Orbital Reflector was performed. The assessment used DAS 2.0 to provide bounding analysis to characterize component's risk. DAS 2.0 is a conservative tool used by the NASA Orbital Debris Office to verify Requirement 4.7-1. DAS employs a conservative analysis methodology to determine if a component will survive reentry. Since DAS does not explicitly model the oxidative or ablative heating that a given component will experience during reentry, it generally over-predicts component survivability. This is an especially relevant consideration for small components that are on the edge of survivability, particularly those that are predicted to survive with very low residual kinetic energy. The following steps are used to identify and evaluate a component's potential reentry risk.

1. Low melting temperature (less than 1000 °C) components are identified as materials that will

never survive reentry and pose no risk to human casualty. This is confirmed through DAS analysis that shows that
materials with melting temperatures equal to or below that of copper (1080°C) will always demise upon reentry for any size component up to the dimensions of a 1U CubeSat.

2.The remaining higher temperature materials are shown to pose negligible risk to human casualty through a bounding analysis of the highest temperature components. For the CubeSats comprising the Orbital Reflector mission, the material with the highest melting temperature is stainless steel (1500°C).If a component is of similar dimensions and has a melting temperature between 1000 °C and 1500°C, it can be expected to posses the same negligible risk as stainless steel components. (see Table 5)

Table 5. Orbital Reflector Steel/Stainless Steel DAS Analysis

Orbital Reflector	Component	diameter	length	demise alt	KE (J)
	long stainless screws	3 mm	20 mm	76.5 km	0
	short stainless screws	3 mm	10 mm	76.9 km	0
	spring	1.5 mm	290 mm	0 km	1
	gas cylinders	55 mm	223 mm	0 km	5

*additionally, the DAS analysis indicated Earth Surface impact of the inflation gas, result was disregarded.

The majority of stainless steel components demise upon reentry. For Orbital Reflector SC, the components that DAS conservatively identifies as reaching the ground have one joule of kinetic energy or less, far below the fifteen joule threshold. Since any injury incurred or inflicted by an object with such low energy would be negligible and would not require the individual to seek medical attention, these objects pose no risk of human casualty as defined by the Range Commander's Counsel in ref (j). Through the method described above, Table 5, and the full component list in the Appendix, the Orbital Reflector SC mission is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14 A.See the Appendix for a complete accounting of the survivability of all component

Section 8: Assessment for Tether missions
Orbital Reflector has no tethers; therefore is satisfies Section 8 requirement 4.8-1

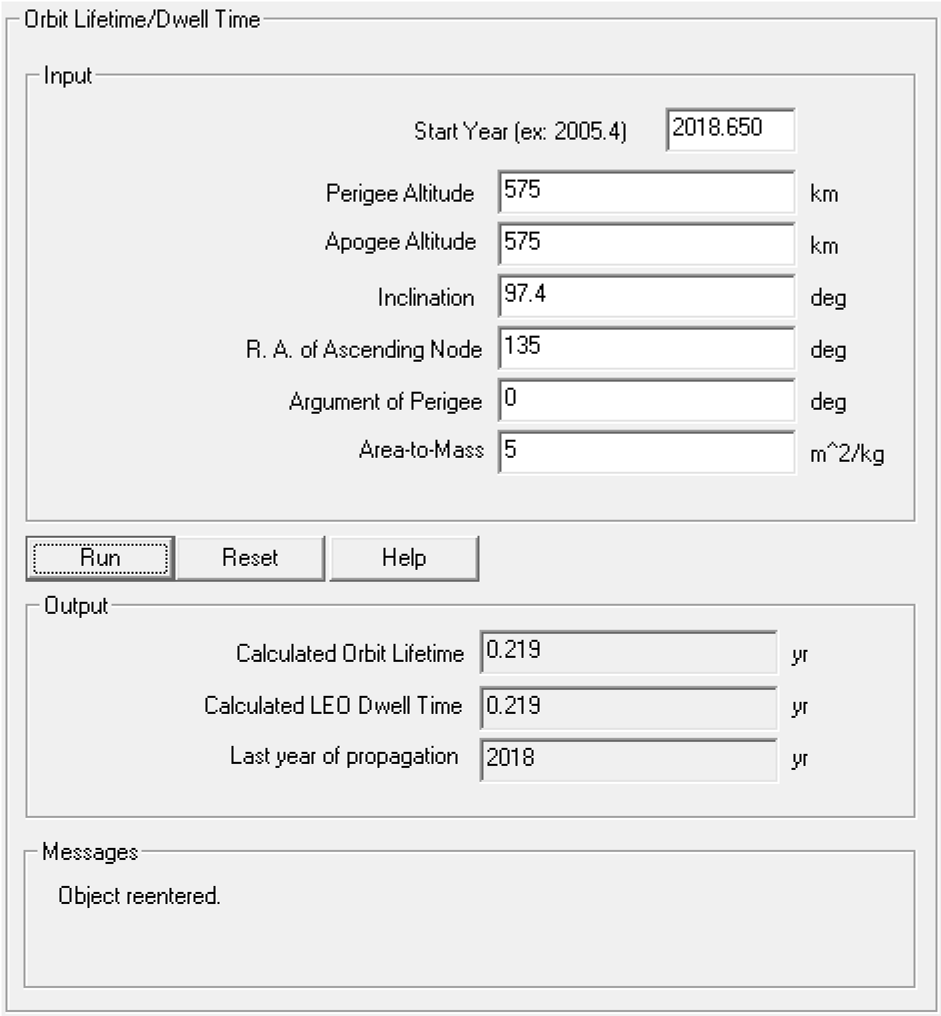
Sections 9-14
The ODAR Sections 9 through 14 for the launch vehicle will be answered by Spaceflight Industries for the SSO-A mission.

Appendix A. Orbital Reflector Spacecraft Component List

Major Parts listed by mass:

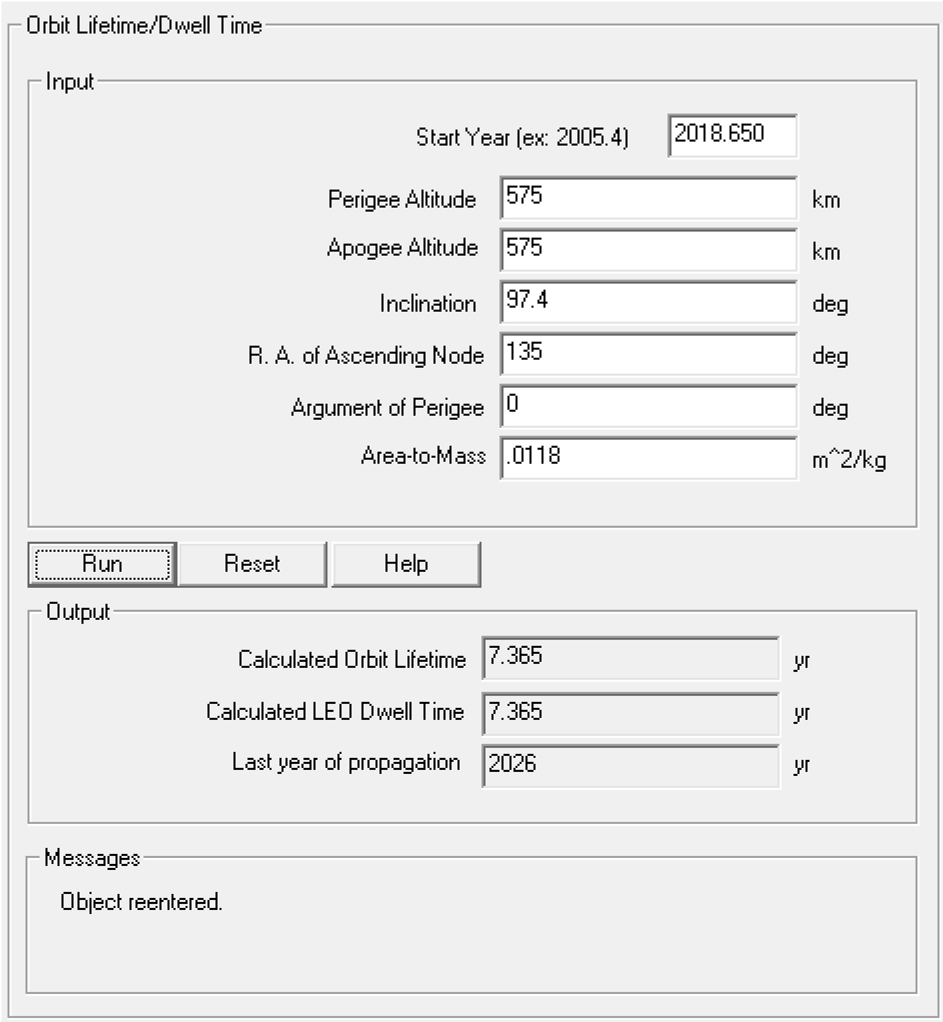
Item	Mass, g	Item	Mass, g	Item	Mass, g
Solar cell	7.5	Side 1	81.2	Ant A	13.0
Solar Cell	7.5	Side 2	81.2	Ant B	13.0
Switch A1	2.8	Side 3	81.2	Top	30.2
Switch A2	2.8	Side 4	81.2	Bottom	30.2
switch A3	2.8	Angle 1A	27.2	Balloon membrane	728.0
switch A4	2.8	Angle 1B	27.2	Inner Reefing Sleeve	19.0
Switch B1	2.8	Angle 2A	27.2	Outer Reefing Sleeve	21.0
Switch B2	2.8	Angle 2B	27.2	BALLAST door	974.6
Switch B3	2.8	Angle 3A	27.2	Ballast Top	627.0
Switch B4	2.8	Angle 3B	27.2	Ballast Bottom	627.0
Part A1	19.8	Angle 4A	27.2	Battery 1	19.8
Part A2	19.8	Angle 4B	27.2	Battery 2	19.8
Part B1	19.8	PCBA	26.1	Piercer 1	8.5
Part B2	19.8	PCBB	26.1	Piercer 2	8.5
Cylinder 1	99.0	Spring 1	82.2	BasePlate	826.7
Cylinder 2	99.0	Spring 2	82.2		

Appendix B. Orbital Lifetime for Orbital Reflector in normal, deployed condition. The balloon deploys no earlier than 10 hours after ejection from carrier



Deployed with partially damped continuous tumbling.

Appendix C. Orbital Lifetime for Orbital Reflector in non-deployed condition (anomaly).



Non-Deployed