2016

Spire Global, Inc.
Orbital Debris Assessment Report:

100 LEMUR-2 Phase IB and IC Satellites

Revision History

Revision	Description of Revisions	Release Date
1	Initial Release	11/11/2016
	An orbital debris risk assessment of 100 LEMUR-2 Phase IB and Phase IC satellites to reflect upcoming launches listed in this ODAR	

Section 1: Program Management and Mission Overview

Program / Project Manager	Peter Platzer
Mission Description	The purpose of the LEMUR-2 satellite fleet is to provide high-revisit maritime and aircraft domain monitoring data and weather data. This orbital debris risk assessment covers 100 LEMUR-2 Phase IB and Phase IC satellites proposed to be launched by Spire Global, Inc. (“Spire”) over 2017-2018.
Foreign Government Involvement	None

Project Milestones

Proposed Launch Date

Proposed Launch Vehicles

Proposed Launch Sites

Launch Vehicle Operator

LEMUR-2 Phase IB and Phase IC satellites will be launched up to 16 at a time depending on available capacity, quality of orbit, service and fleet replenishment needs, and risk profiles of the launch vehicle and campaign.

Given that Spire is applying for a number of orbits, this orbital debris risk assessment covers all such orbits. Spire is also seeking authority to deploy from the International Space Station (“ISS”) and so that orbit is also considered.

The following deployments are considered in this Orbital Debris Assessment Report (“ODAR”):[1]

Launch #	Launch Provider/Vehicle	Launch Date (NET)	Altitude (km)	Inclination (+/- 1 deg)
Launch 1	SpaceX/Falcon9	Q1 2017	450x720	SSO (98)
Launch 2	ISRO/PSLV	Q1 2017	580	SSO (98)
Launch 3	Roscosmos/Soyuz	Q1 2017	600	SSO (98)
Launch 4	ISRO/PSLV	Q2 2017	500	SSO (98)
Launch 5	Orbital/Minotaur4	Q3 2017	400 x 600	24
Launch 6	Roscosmos/Soyuz	Q2 2017	600	SSO (98)
Launch 7	Roscosmos/Soyuz	Q3 2017	600	SSO (98)
Launch 8	Orbital/Antares	Q1 2017	Up to 500	ISS (51.6)
Launch 9	Orbital/Antares	Q2 2017	Up to 500	ISS (51.6)
Launch 10	ISRO/PSLV	Q3 2017	500	SSO (98)
Launch 11	SpaceX/Falcon9	Q4 2017	575	SSO (98)
Launch 12	Rocket Lab/Electron	Q2 2017	500	SSO (98)
Launch 13	Rocket Lab/Electron	Q3 2017	450	45
Launch 14	Virgin/LauncherOne	Q3 2017	500	90
Launch 15	Virgin/LauncherOne	Q4 2017	500	87.9
Launch 16	Roscosmos/Soyuz	Q4 2017	585	SSO (98)
ISS Resupply	Varies	Varies	~400	~51.6

[1] Note that the Formosat-5 launch was previously analyzed in an ODAR, and no changes have occurred to that previous analysis. Spire does not seek authority to launch more than 8 satellites on Formosat-5, as agreed with ORBCOMM License Corp, but includes the orbit here for completeness.

Mission Duration	The operational lifetime of each LEMUR-2 Phase IB and Phase IC satellite is estimated to be up to 2 years following deployment from the launch vehicle.
Selection of Orbit	Orbits are selected based on current availability.
Potential Physical Interference with Other Orbiting Objects	Because the LEMUR-2 Phase IB and Phase IC satellites do not have any propulsion systems, their orbit will naturally decay following deployment from either the launch vehicle or the ISS. As detailed in Section 5, the probability of physical interference between the LEMUR-2 Phase IB and Phase IC satellites and other space objects complies with Requirement 4.5 of NASA-STD-8719.14A.

ODAR Section 2: Spacecraft Description

Physical Description:

Property	Value
Total Mass at Launch	4.5 kg
Dry Mass at Launch	4.5 kg
Form Factor	3U CubeSat
COG	<3 cm radius from geometric center
Envelope (stowed)	100 mm x 100 mm x 340.5 mm (excluding dynamic envelope)
Envelope (deployed)	1 m x 1 m x 300 mm
Propulsion Systems	None
Fluid Systems	None
AOCS	Stabilization/pointing with 3x orthogonal reaction wheels, desaturation + coarse pointing with magnetorquers, and GPS navigation
Range Safety / Pyrotechnic Devices	None
Electrical Generation	Triple-junction GaAs solar panels
Electrical Storage	Rechargeable lithium-polymer battery pack
Radioactive Materials	None

ODAR Section 3: Assessment of Debris Released During Normal Operations

Spire’s LEMUR-2 Phase IB and Phase IC satellites do not release objects during deployment or operation. Therefore, Requirements 4.3-1 and 4.3-2 of NASA-STD-8719.14A are not applicable.

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

Potential causes for spacecraft breakup:

LEMUR-2 Phase IB and Phase IC satellites have no propulsion and accordingly do not carry highly volatile rocket propellant. The only energy sources (kinetic, chemical, or otherwise) onboard the spacecraft are a Lithium-Polymer battery system and reaction wheels. Thus, the only two plausible causes for breakup of the LEMUR-2 Phase IB and Phase IC satellites are the following:

1. energy released from onboard batteries, and
2. 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 batteries aboard the LEMUR-2 Phase IB and Phase IC satellites are two 42Wh Lithium-Polymer batteries, which represent the only credible failure mode during which stored energy is released. The main failure modes associated with Lithium Polymer batteries result from overcharging, over-discharging, internal shorts, and external shorts.

The only failure mode of the reaction wheel assemblies that could lead to creation of debris would be breakup of the wheels themselves due to mechanical failure while operating at a high angular rate.

Risk Mitigation Plan:

The battery pack onboard the LEMUR-2 Phase IB and Phase IC satellites has been designed and built to comply with all controls / process requirements identified in NASA Report JSC-20793 Section 5.4.3 to mitigate the chance of any accidental venting / explosion caused by the above failure modes.

The reaction wheels onboard the LEMUR-2 Phase IB and Phase IC satellites are limited with respect to maximum rotational speed of the wheels and are contained within a sealed compartment, thus mitigating any risk of breakup of the wheels themselves into debris.

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

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

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:	**N/A**
4.4-3, Limiting the long-term risk to other space systems from planned breakups: There are no planned breakups of any of the satellites.	**N/A**

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.	**N/A**

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

Probability for collision with objects larger than 10 cm:

The probability of a collision of any of the LEMUR-2 Phase IB and Phase IC satellites with an orbiting object larger than 10 cm in diameter was calculated using the National Aeronautics and Space Administration's ("NASA's") Debris Assessment Software ("DAS") 2.0.2 software. Table 1 below shows the risk for all orbits into which LEMUR-2 Phase IB and Phase IC satellites may be deployed in each of three different area/mass ratio scenarios, including a worst case scenario. The table shows the risk both at the expected (nominal) orbital dwell times and at the worst-case dead on arrival dwell time. Because Launch 8 and Launch 9 are potential Above Station Deployments where the ultimate altitude will be determined by NASA (including potentially requiring a below station deployment), the table below shows a worst case analysis of 500 km. ISS deployments are from in front and below the ISS at the time of deployment, typically in a range of 385 km to 400 km, as directed by the ISS Program. The table below shows a worst case of 400 km. Certain deployments have similar inclinations but slightly different altitudes. Where the altitude is slightly different, Spire groups the launches together under the worst case (highest) altitude.

Table 1 –Collision Risk with Objects Larger Than 10 cm

Launch Name	Effective Area-to-Mass (m2/kg)	600 km, 98 degrees	580 km, 98 degrees	450x720 km, 98 degrees	400x600 km, 24 degrees	500 km, 98 degrees	500 km, 51.6 degrees	500 km, 90 degrees	500 km, 87.9 degrees	450 km, 45 degrees	400 km, 51.6 degrees
Satellite Nonfunctional	**0.0074**	2×10^{-6}	1×10^{-6}	1×10^{-6}	0	0	0	0	0	0	0
ADCS Nonfunctional	**0.0169**	2×10^{-6}	1×10^{-6}	1×10^{-6}	0	0	0	0	0	0	0
Operational, Nominal	**0.0208**	2×10^{-6}	2×10^{-6}	1×10^{-6}	0	0	0	0	0	0	0

Probability for collision with objects 10 cm or less:

NASA's DAS returned a response of Compliant with Requirement 4.5-2 of NASA-STD-8719.14A in all deployment scenarios.

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**

ODAR Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

Description of disposal option selected:

Following its deployment, a LEMUR-2 Phase IB and Phase IC satellite's orbit will naturally decay until it reenters the atmosphere. Table 2 describes the mission scenarios for which lifetime analysis of a LEMUR-2 Phase IB and Phase IC satellite was considered and the effective area-to-mass ratio of the satellite in each scenario. The ratio was calculated using the external dimensions of the LEMUR-2 Phase IB and Phase IC satellite and deployed arrays.

For purposes of Section 6, drag area from deployed antennas was omitted; as such, the effective area-to-mass calculated below is a conservative case.

Table 2 - Area-to-Mass Ratio of LEMUR-2 Phase IB and Phase IC Satellites in Various Mission Scenarios

Scenario	**Description**	**Effective Area-to-Mass (m2/kg)**
Satellite Nonfunctional	▪ Solar arrays fail to deploy ▪ Satellite tumbles randomly	0.0074 for 5 years 0.0169 thereafter[2]
Operational, nominal	▪ Solar panels deploy ▪ Satellite maintains +Z axis nadir ▪ Position around Z axis as planned for mission operations	0.0208
ADCS Nonfunctional	▪ Solar arrays deploy ▪ Satellite tumbles randomly	0.0169

Table 3 below shows the simulated orbital dwell time for a LEMUR-2 Phase IB and Phase IC satellite in each of the deployment scenarios. Because Launch 8 and Launch 9 are potential Above Station Deployments where the ultimate altitude will be determined by NASA (including potentially requiring a below station deployment), the table below shows a worst case analysis of 500 km. ISS deployments are from in front and below the ISS at the time of deployment, typically in a range of 385 km to 400 km, as directed by the ISS Program. The table below shows a worst case of 400 km. Certain deployments have similar inclinations but slightly different altitudes. Where the altitude is slightly different, Spire groups the launches together under the worst case (highest) altitude.

[2] This conservatively assumes the solar panels do not deploy in the first five years and deployment only occurs after nylon burn wire degrades in natural sunlight (*i.e.*, double fault situation).

Table 3 – Orbit Dwell Time for LEMUR-2 Phase IB and Phase IC Satellite in Each Planned Deployment

Description	Effective Area-to-Mass (m2/kg)	600 km, 98 degrees	580 km, 98 degrees	450x720 km, 98 degrees	400 km x 600 km, 24 degrees	500 km, 98 degrees	500 km, 51.6 degrees	500 km, 90 degrees	500 km, 87.9 degrees	450 km, 45 degrees	400 km, 51.6 degrees
Satellite Nonfunctional	**0.0074**	12.8[3]	11.9[3]	9.39	4.9	6	6.1	6	6	4.7	2.7
ADCS Nonfunctional	**0.0169**	7.8	6.9	6.20	3.9	4.7	4.8	4.7	4.7	3.7	.8
Operational, Nominal	**0.0208**	7	6.4	5.81	3.7	4.5	4.6	4.5	4.5	3.2	.7

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[3] To ensure that Spire exceeds the NASA standard in all scenarios, Spire has included a double fault-tolerant solar panel deployment mechanism, which will provide sufficient surface area and drag to comply with the NASA standard even if the LEMUR-2 Phase IB and Phase IC satellites are dead on arrival. The LEMUR-2 Phase IB and Phase IC satellite's solar panels are part of a built-in, post-deployment sequence programmed into onboard software prior to launch, which requires no direction from the ground. If for some reason the onboard sequence fails, solar array deployment can be commanded from the ground. If a LEMUR-2 Phase IB and Phase IC satellite is non-communicative, an entirely passive, redundant fail-safe is included on all LEMUR-2 Phase IB and Phase IC satellites in the form of a burn wire. The tensile strength of the burn wire has been tested and verified to degrade to a breaking point after 3600 hours or 150 days of UV radiation exposure.[3] Spire's worst-case scenario for dwell time above conservatively models 5 years of non-deployed solar panels and no loss of altitude during those 5 years, followed by the dwell times for an Attitude Determination and Control nonfunctional satellite, even though a non-deployed solar panel LEMUR-2 would still have some surface area that would cause some loss of altitude during that period. As such, this is a conservative worst-case scenario.

Identification of systems required for postmission disposal: None

Plan for spacecraft maneuvers required for postmission disposal: N/A

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 low-Earth orbit ("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 geostationary orbit ("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**

ODAR Section 7: Assessment of Spacecraft Reentry Hazards

NASA DAS was used to test the major spacecraft components for re-entry hazards. The major components tested included:

- Solar panels and cells
- GPS antennas
- PCB circuit boards
- Primary structure
- Cameras
- Reaction wheel assembly

Summary of objects expected to survive an uncontrolled reentry (using DAS 2.0.2 software): None

Calculation of probability of human casualty for expected reentry year and inclination: 0%

Assessment of spacecraft compliance with Requirement 4.7-1:	
4.7-1, Casualty risk from reentry debris:	**COMPLIANT**

ODAR Section 7A: Assessment of Spacecraft Hazardous Materials

Summary of hazardous materials contained on spacecraft: None

ODAR Section 8: 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**