2017

Spire Global, Inc.
Orbital Debris Assessment Report

LEMUR-2 Satellites
Phase IC (with Hosted Payloads) and Phase II

Revision History

Revision	Description of Revisions	Release Date
1	Initial Release	10/13/2017
	An orbital debris risk assessment of LEMUR-2 Phase IC (with hosted payload) and Phase II satellites	

Section 1: Program Management and Mission Overview

Program / Project Manager	Jenny Barna
Mission Description	The purpose of the LEMUR-2 satellite constellation is to provide high-revisit global maritime and aircraft domain monitoring data, weather data, and hosted payload services. This orbital debris risk assessment report ("ODAR") covers any LEMUR-2 Phase IC satellites with a hosted payload and Phase II satellites proposed to be launched by Spire Global, Inc. ("Spire").
Foreign Government Involvement	None
Project Milestones	LEMUR-2 satellites are usually launched in small deployments depending on available capacity, quality of orbit, service and constellation replenishment needs, and risk profiles of the launch vehicle and campaign. Given the potential long lead time for the instant application and state of the low-Earth orbit launch market for secondary payloads, Spire is filing this application early and is not capable of providing launch parameters for the Phase II satellites at this time. However, it notes that these satellites (similar to the Phase I, IB, and IC satellites) will only deploy at orbital altitudes from 385 to 650 km and inclinations ranging from equatorial to polar sun-synchronous (98 degrees). This analysis considers the range of representative orbits and includes a debris assessment of the worst-case altitude and lifetime in order to provide the most conservative results. Spire is also seeking authority to deploy from and above the International Space Station ("ISS"), so that orbit is also considered.
Proposed Launch Date	
Proposed Launch Vehicles	
Proposed Launch Sites	
Launch Vehicle Operator	
Mission Duration	The planned operational lifetime of each LEMUR-2 satellite is 2 years following deployment from the launch vehicle.
Selection of Orbit	Orbits are selected based on availability of launches, an established range of acceptable deployment altitudes (385 km – 650 km), and inclinations (equatorial to polar sun-synchronous (98 degrees)) that support the operational purpose of the constellation.
Potential Physical Interference with Other Orbiting Objects	The LEMUR-2 Phase IC satellites with a hosted payload and Phase II satellites do not have any propulsion systems to actively maintain orbital altitude. Therefore, 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 satellites and other space objects complies with Requirement 4.5 of NASA-STD-8719.14A.
Phase IC (with hosted payload) and Phase II	Spire will add a third solar "drag" panel on any LEMUR-2 Phase IC satellite bus with a hosted payload and Phase II satellite bus, increasing the amount of drag on its satellite and shortening the orbital lifetimes by between 0.50 and 0.75 years (dependent on solar cycle changes) from

Satellite Bus Configuration Notes	launch at its highest orbit of 650 km. *See infra* § 6. The LEMUR-2 Phase IC satellite and Phase II satellite will have a nominal launch mass configuration of 4.5kg; however, the mass capacity may be up to 6kg maximum, which accommodates potential other Spire or hosted payload(s). Surface area and spacecraft specifications are otherwise identical. Both nominal and maximum cases are included in this ODAR for collision risk and lifetime analyses. *See infra* §§ 5-6.

ODAR Section 2: Spacecraft Description

Physical Description:

Property	Value
Total Mass at Launch	4.5 kg nominal; 6 kg maximum
Dry Mass at Launch	4.5 kg nominal; 6 kg maximum (no propellant/propulsion system)
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 Global Positioning System ("GPS") navigation
Range Safety / Pyrotechnic Devices	None
Electrical Generation	Triple-junction GaAs solar panels
Electrical Storage	Rechargeable Lithium-Ion battery pack
Radioactive Materials	None

ODAR Section 3: Assessment of Debris Released During Normal Operations

Spire's LEMUR-2 Phase IC satellites with a hosted payload and Phase II 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 IC satellites with a hosted payload and Phase II satellites have no propulsion and accordingly do not carry highly volatile propellant. The only energy sources (kinetic, chemical, or otherwise) onboard the spacecraft are a Lithium-Ion battery system and reaction wheels. Thus, the only two plausible causes for breakup of these LEMUR-2 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 battery aboard these LEMUR-2 satellites is an 80Wh Lithium-Ion battery pack, which represents the only credible failure mode during which stored energy is released. The main failure modes associated with Lithium Ion 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 these LEMUR-2 satellites has been designed and qualified to comply with controls / process requirements identified in NASA Report JSC-20793 'Crewed Space Vehicle Battery Safety Requirements' to mitigate the chance of any accidental venting / explosion caused by the above failure modes.

The reaction wheels on board these LEMUR-2 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 any LEMUR-2 Phase IC satellites with a hosted payload or Phase II 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 satellites may be deployed in each of five different area/mass ratio scenarios, including a worst-case scenario. The table shows the risk both at the expected nominal orbital dwell time and at the worst-case dead-on-arrival orbital dwell time. ISS deployments are from in front and below the ISS, typically in a range of 385 km to 400 km, at the time of deployment as directed by the ISS Program. Table 2 below shows a worst-case analysis 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 –LEMUR-2 Phase IC (with hosted payload) or Phase II Satellites
Collision Risk with Objects Larger Than 10 cm (Run at Worst-Case Orbit of 650 km, 98 deg)

	Nominal Mass Configuration (4.5 kg) 650 km, 98 degrees (Worst-Case Orbit)			Maximum Mass Configuration (6 kg) 650 km, 98 degrees (Worst-Case Orbit)		
Satellite Operational State	**Effective Area/Mass (m^2/kg)**	**Orbital Dwell Time (years):**	**Collision Risk per NASA DAS Analysis**	**Effective Area/Mass (m^2/kg)**	**Orbital Dwell Time (years):**	**Collision Risk per NASA DAS Analysis**
Satellite Nonfunctional	0.0082	19.7	**3×10^{-6}**	0.0061	21.8	**1×10^{-5}**
ADCS Nonfunctional, Partial Deploy	0.0140	18.01	**4×10^{-6}**	0.0105	21.8	**1×10^{-5}**
ADCS Nonfunctional, Fully Deployed	0.0201	14.7	**4×10^{-6}**	0.0151	16.8	**1×10^{-5}**
Operational, Partial Deploy	0.0194	14.9	**4×10^{-6}**	0.0146	17.2	**1×10^{-5}**
Operational, Nominal	0.0290	7.5	**4×10^{-6}**	0.0217	14.2	**1×10^{-5}**

Table 2 –LEMUR-2 Phase IC (with hosted payload) or Phase II Satellites
Collision Risk with Objects Larger Than 10 cm (Run at ISS Orbit of 400 km, 51.6 deg)

	Nominal Mass Configuration (4.5 kg) 400 km, 51.6 degrees (ISS Orbit)			Maximum Mass Configuration (6 kg) 400 km, 51.6 degrees (ISS Orbit)		
Satellite Operational State	**Effective Area/Mass (m^2/kg)**	**Orbital Dwell Time (years):**	**Collision Risk per NASA DAS Analysis**	**Effective Area/Mass (m^2/kg)**	**Orbital Dwell Time (years):**	**Collision Risk per NASA DAS Analysis**
Satellite Nonfunctional	0.0082	2.5	**0**	0.0061	2.7	**0**
ADCS Nonfunctional, Partial Deploy	0.0140	2.0	**0**	0.0105	2.3	**0**
ADCS Nonfunctional, Fully Deployed	0.0201	1.6	**0**	0.0151	1.97	**0**
Operational, Partial Deploy	0.0194	1.6	**0**	0.0146	2.0	**0**
Operational, Nominal	0.0290	1.0	**0**	0.0217	1.4	**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 a number of potential orbits and configurations, including a worst-case scenario of 650 km, 98 degrees.

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 Post-Mission Disposal Plans and Procedures

Description of disposal option selected:

Following its deployment, a LEMUR-2 Phase IC satellite with a hosted payload and Phase II satellite will naturally decay until it reenters the atmosphere. Table 3 describes the mission scenarios for which lifetime analysis of these LEMUR-2 satellites 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 satellite and deployed arrays. Note that Spire will add a third solar "drag" panel on any Phase IC satellite bus with a hosted payload and Phase II satellite bus, increasing the amount of drag on its satellite and shortening the orbital lifetimes (compared to its Phase I satellites).[1]

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 3 - Area-to-Mass Ratio of LEMUR-2 Phase IC (with hosted payload) and Phase II Satellites in Various Mission Scenarios

Scenario	Description	Effective Area/Mass Ratio (m^2/kg)	
		Nominal Mass 4.5 kg	Maximum Mass 6 kg[2]
Operational, Nominal	▪ Spacecraft pointing, position is nominal, operational ▪ Solar arrays deployed	0.0290	0.0217
Operational, Partial Deploy Failure	▪ Spacecraft pointing, position is nominal, operational ▪ 1 of 2 solar arrays deployed	0.0194	0.0146
ADCS Nonfunctional Fully Deployed	▪ Spacecraft tumbling randomly ▪ Both solar panels deployed	0.0201	0.0151
ADCS Nonfunctional Partially Deployed	▪ Spacecraft tumbling randomly ▪ 1 of 2 solar panel deployed	0.0140	0.0105

[1] *See* Application of Spire Global, Inc., File No. SAT-AMD-20161114-00107, Orbital Debris Assessment Report: 100 LEMUR-2 Phase IB and IC Satellites, Exhibit C (filed Nov. 14, 2016).

[2] As mentioned, LEMUR 2 Phase IC satellites and Phase II satellites will have capacity to add up to 1.5kg of total mass in the accommodation of new Spire or hosted payload(s). This orbital debris assessment evaluates lifetime and collision risk with both the nominal and maximum possible mass configurations. Surface area and spacecraft specifications are otherwise identical.

Satellite Nonfunctional	▪ Spacecraft tumbling randomly ▪ No solar panels deployed	0.0082 for 5 years 0.0201 thereafter[3]	0.0061 for 5 years 0.0151 thereafter[3]

Table 4 below shows the simulated orbital dwell time for a LEMUR-2 Phase IC satellite with a hosted payload and Phase II satellite in a number of potential orbits and configurations, including a worst-case scenario of 650 km, 98 degrees.

[3] This calculation conservatively assumes that the solar panels do not deploy in the first 5 years and that deployment only occurs after nylon burn wire degrades in natural sunlight (*i.e.*, double-fault situation). *See infra* note *.

Table 4 – Orbit Dwell Time for Phase IC (with hosted payload) and LEMUR-2 Phase II Satellites in Representative Low-Earth Orbits

	Nominal Mass (4.5 kg)						Maximum Mass (6 kg)					
Spacecraft Operational State	**Effective Area/Mass (m^2/kg)**	**400 km, 51.6 deg**	**450 km, 98 deg**	**500 km, 98 deg**	**600 km, 98 deg**	**650 km, 98 deg**	**Effective Area/Mass (m^2/kg)**	**400 km, 51.6 deg**	**450 km, 98 deg**	**500 km, 98 deg**	**600 km, 98 deg**	**650 km, 98 deg**
Satellite Nonfunctional	0.0082	2.5	3.3	4.4	10.7*	19.7*	0.0061	2.7	3.6	5	12.2*	21.8*
ADCS Nonfunctional, Partial Deploy	0.0140	2	2.8	3.6	8.14*	18.01*	0.0105	2.3	3	4	12.2*	21.8*
ADCS Nonfunctional, Fully Deployed	0.0201	1.6	2.6	3.2	5.7	14.7	0.0151	1.97	2.8	3.5	7.2	16.8
Operational, Partial Deploy	0.0194	1.6	2.6	3.2	5.8	14.9	0.0146	2	2.8	3.5	7.5	17.2
Operational, Nominal	0.0290	1	2.4	2.9	4.8	7.5	0.0217	1.4	2.5	3.1	5.5	14.2

* To ensure 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 IC satellites with a hosted payload and Phase II satellites are dead on arrival. These LEMUR-2 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 satellite is non-communicative, an entirely passive, redundant fail-safe is included on all LEMUR-2 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. 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 System ("ADCS") 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, the scenario is a conservative worst-case one.

Identification of systems required for post-mission disposal: None

Plan for spacecraft maneuvers required for post-mission 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 satellites will reenter the atmosphere within 25 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 post-mission 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 the following.

- Solar panels and cells
- GPS antennas
- PCB circuit boards
- Primary structure
- 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 post-mission disposal: N/A

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

Probability of tether being severed during mission or after post-mission 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**

Spire Global, Inc. ("Spire") Orbital Debris Risk Mitigation Plan

Spire believes that (i) LEMUR-2 Phase IC satellites with a potential hosted payload and Phase II satellites create relatively little additional orbital debris risks compared to existing systems approved by the Federal Communications Commission ("Commission") and (ii) these satellites meet applicable orbital debris requirements as listed in Section 25.114(d)(14) of the Commission's rules.[1]

Any Phase IC satellite bus with a hosted payload and Phase II satellite bus may have slightly different surface area and mass values from those values associated with the Phase I satellites bus.

- Spire will add a third solar "drag" panel on all of its Phase IC satellites with a hosted payload and Phase II satellites, increasing the amount of drag on the satellites and shortening the orbital lifetimes by between 0.50 and 0.75 years (dependent on solar cycle changes) from launch at their highest orbit of 650 km.
- The Phase IC satellite bus and Phase II satellite bus will have a nominal launch mass configuration of 4.5 kg; however, the mass capacity may be up to 6 kg maximum, which accommodates potential other Spire or hosted payload(s). Surface area and spacecraft specifications are otherwise identical. Both nominal and maximum cases are included in the ODAR for collision risk and lifetime analyses.[2]

[1] *See* 47 C.F.R § 25.114(d)(14); *see also* Orbital Debris Assessment Report: LEMUR-2 Satellites Phase IC (with Hosted Payloads) and Phase II, Exhibit C ("Exhibit C").
[2] *See* Exhibit C.

Each section below addresses specific measures taken by Spire, as required under Section 25.114(d)(14), to limit the possibility that its space station operations will generate orbital debris.

Like the Phase I satellites that preceded them, Phase IC satellites with a potential hosted payload and Phase II satellites continue to be one of the lowest risk satellite busses ever approved by the Commission.

I. Orbital Dwell and Post-Mission Disposal

The Commission's rules call for indication of the anticipated evolution over time of the satellites' orbits.[3] Specifically, using the National Aeronautics and Space Administration ("NASA") Debris Assessment Software ("DAS"), Spire has calculated the dwell times of the Phase IC satellites with a hosted payload and Phase II satellites.

At the highest orbit sought of 650 km, total orbital lifetime would not exceed 21.8 years from launch in a conservative worst-case scenario. This calculation is based on a conservative worst-case scenario of a dead-on-arrival LEMUR-2 satellite, launched in its maximum mass configuration,[4] and is still well within the standard of twenty-five years of mission completion and thirty years of launch set forth in Requirement 4.6.1 of NASA-STD-8719.14A ("Requirement 4.6.1").[5] This analysis is more conservative than the analysis conducted by most other operators, who do not calculate orbital dwell time and do not limit themselves to an orbit based on a worst-case, dead-on-arrival basis.[6] The actual expected lifetime is seven to fourteen years at this worst-case altitude, depending on the initial mass of the satellite.

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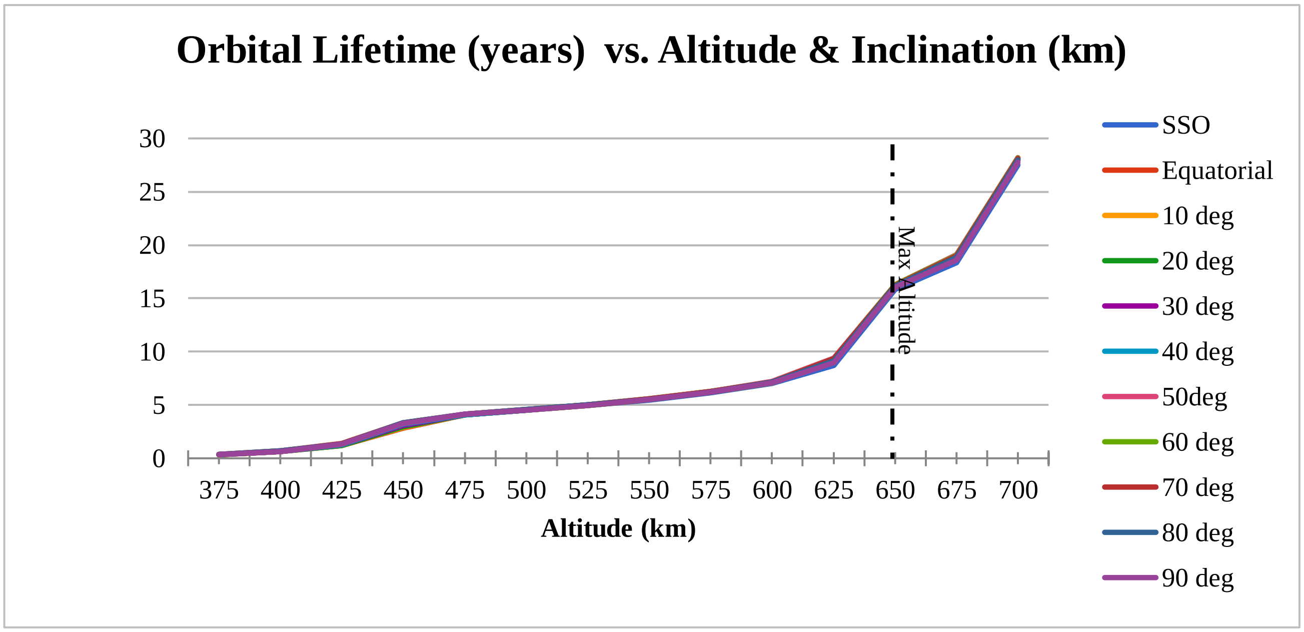
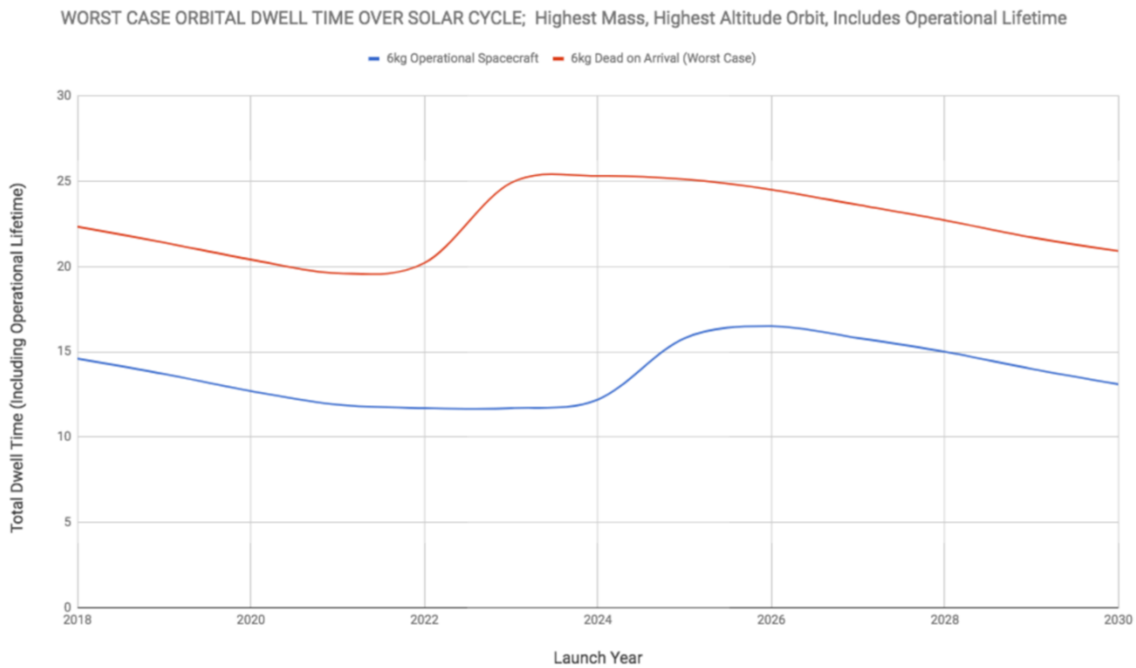
[3] *See* 47 C.F.R. § 25.114(d)(14)(iii).
[4] As mentioned, LEMUR-2 Phase IC and Phase II satellites have a nominal launch configuration of 4.5 kg; however, the mass capacity may be up to 6 kg maximum to accommodate any hosted payload scenarios. Both nominal and maximum cases are included in the ODAR for collision risk and lifetime analyses. *See* Exhibit C.
[5] *See Process for Limiting Orbital Debris*, NASA-STD-8719.14A § 4.6.1 (Dec. 2011).
[6] As of today, no LEMUR-2 satellite has been dead on arrival.

Spire has run an analysis measuring dwell times at inclinations from equatorial to sun synchronous to ensure that changes in inclination do not cause Spire to violate Requirement 4.6.1 at a maximum deployment apogee of 650 km. The results indicate that changes in inclination do not meaningfully affect orbital dwell times and that at any inclination at 650 km the 25-year requirement is met.[7]



Spire has also run an analysis measuring dwell times across the entire solar cycle to ensure that changes in launch schedule do not cause Spire to violate Requirement 4.6.1 at a maximum deployment apogee of 650 km.

[7] *See* NASA-STD-8719.14A § 4.6.1; *see also Mitigation of Orbital Debris*, Second Report and Order, 19 FCC Rcd 11567 ¶¶ 61, 83 (2004).



The dwell times for all orbits under 650 km are predictably less than the 650 km orbit, meeting Requirement 4.6.1. Full details of the NASA DAS analysis with respect to orbital dwell times for all deployments sought by Spire with respect to the Phase IC satellites with a hosted payload and Phase II satellites are contained in the ODAR.[8]

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 a Phase IC satellite with a hosted payload or Phase II satellite is dead on arrival. This deployment mechanism is the same as the one installed on board the Phase I satellites previously approved by the Commission. These satellites' solar panels are part of a built-in, post-deployment sequence programed into onboard software prior to launch, which requires no direction from the ground. If for some reason the

[8] *See* Exhibit C.

onboard sequence fails, solar array deployment can be commanded from the ground. If a satellite is non-communicative, an entirely passive and redundant fail-safe is included on all 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.[9] Spire's worst-case scenario for dwell time conservatively models five years of non-deployed solar panels and no loss of altitude during those five years even though a dead-on-arrival satellite still has surface area that would cause at least some altitude loss.

II. Re-entry Hazards

Spire's post-mission disposal plan is to allow its satellites to passively re-enter the atmosphere and completely burn up upon re-entry.[10] Spire has used NASA DAS to review the survivability of major components upon re-entry and found that no objects are expected to survive re-entry, putting the risk to human life (both on the ground and in aircraft) at 0. This calculation is orders of magnitude lower than legacy satellite busses.

III. Planned Release of Debris

Spire's Phase IC satellites with a hosted payload and Phase II satellites will not undergo any planned release of debris. Spire also conducts extensive acceptance level environmental testing of all of its satellites to provide further confidence in the structural integrity of the satellite in launch and space environments. In fact, because Spire launches with every major launch rocket that takes secondary payloads, including Falcon 9; Antares/Cygnus; Atlas-5; PSLV; Soyuz; and H-II, the satellite will be subjected to a battery of different testing standards,

[9] *See* Application of Spire Global, Inc., File No. SAT-LOA-20151123-00078, Test Summary: Tensile Properties Test with Accelerated UV Aging *A Demonstration of NOAA DeOrbit Guideline Compliance in an 'Edge Case' Scenario*, Exhibit E (filed Nov. 23, 2015).
[10] *See* 47 C.F.R. § 25.114(d)(14)(iv).

including those required by NASA for International Space Station ("ISS") deployments.

IV. Limiting the Probability of Accidental Explosions

Phase IC satellites with a hosted payload and Phase II satellites have no propulsion and accordingly do not carry highly volatile rocket propellant. The only energy sources (kinetic, chemical, or otherwise) onboard the spacecraft is a Lithium-Ion battery system and reaction wheels.

The battery pack on board the Phase IC satellites with a hosted payload and Phase II satellites complies with all controls/process requirements identified in NASA Report JSC-20793 Section 5.4.3 to mitigate the chance of any accidental venting/explosion.[11] A battery cell protection circuit manages the charging cycle, performs battery balancing, and protects against over and undercharge conditions. The batteries will not be passivated at End-of-Mission due to the low risk and low impact of explosive rupturing. The maximum total chemical energy stored in the battery pack is ~144kJ (~288kJ total).

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 strategies for breakups due to the reaction wheels include limiting the maximum rotational speed of the wheels and containing them within a sealed compartment.

V. Collisions with Large Debris

The collision risk posed by the Phase IC satellites with a hosted payload and Phase II satellites continues to be among the lowest in the satellite industry due to their very small surface

[11] *See Crewed Space Vehicle Battery Safety Requirements*, NASA Report JSC-20793 § 5.4.3 (Jan. 2014), https://standards.nasa.gov/file/657/download?token=DUcHF-J7.

area and mass. Using NASA DAS, Spire has calculated the risk of collision for all deployments sought in this application. The highest probability of collision occurs for the highest orbit of 650 km. Even that probability is 1×10^{-5} over its entire orbital lifetime for a fully deployed satellite (*i.e.*, the maximum surface area).[12] This probability is hundreds of times lower than legacy satellite busses' probability of collision in their worst-case orbits. Full details of the NASA DAS analysis with respect to collision with large objects for each deployment sought in this application are contained in the ODAR attached to this application.[13]

Spire participates in a sharing agreement with the Joint Space Operations Center ("JSpOC") to better coordinate collision avoidance measures and receive conjunction threat reports. Spire's satellites carry onboard Global Positioning System ("GPS") receivers that provide for precise orbital position determination. Spire also receives from JSpOC updated two-line element sets, or "TLEs," which facilitate the identification and tracking of Spire's satellites. JSpOC has a direct line to Spire's satellite operations team that is accessible twenty-four hours per day/seven days per week to ensure that Spire can take immediate action to coordinate collision avoidance measures. Spire's GPS-Radio Occultation instrument has capabilities that allow it to determine the precise location of a satellite down to two <u>*centimeters*</u>. To Spire's knowledge, such precise location capabilities are non-existent outside the context of very large government satellites and do not exist for *any* commercial operator.[14] This hyper-precise location data will allow the satellites to have orbits projected out with extreme precision, thus greatly lowering the number of false positive conjunction alerts and making collision avoidance

[12] *See* Exhibit C.
[13] *See id.*
[14] For reference, Spire's agreement with Orbcomm License Corp. specifies location accuracy of 20 meters as a threshold. *See* Application of Spire Global, Inc., File No. SAT-LOA-20151123-00078, Spire Global - ORBCOMM Agreement (filed Sept. 15, 2016). TLEs received from JSpOC have accuracy measured in kilometers.

measures far more well informed. Spire currently provides ephemeris data, available from public sources, online.[15] In the near future, Spire will begin publically sharing enhanced ephemeris data, using the hyper-precise location data from its proprietary GPS-Radio Occultation instrument.

Special care is also given to minimizing the potential for collision with manned spacecraft, including the ISS. The operational altitude of the ISS is approximately 400 km. Spire will coordinate with NASA to assure protection of the ISS on an ongoing basis. Because Spire participates in many ISS deployments (including above station deployments expressly approved by the ISS program on a launch-by-launch basis), ISS program management has a detailed understanding of the Phase IC satellites with potential hosted payloads and Phase II satellites.

Spire will work closely with its launch providers to ensure that the satellites are deployed in such a way as to minimize the potential for in-plane collision. The risk is further mitigated with the typical small deployments undertaken by Spire.

Further, in advance of this filing, Spire has reached out to the other low-Earth orbit operators at or below 650 km that are identified in the Commission's Approved Space Station List and has informed them of Spire's intention to coordinate to further mitigate any collision risks.[16]

The Commission's rules call upon applicants to specify the accuracy, if any, with which the orbital parameters of their non-geostationary satellite orbit space stations will be

[15] *See Open TLE Service*, Spire, tle.spire.com (last viewed Oct. 17, 2017). To obtain the ephemeris data for any particular LEMUR-2 satellite, type in the LEMUR-2's NORAD ID after "tle.spire.com/" in the URL bar.
[16] *See Approved Space Station List*, FCC, https://www.fcc.gov/approved-space-station-list (last updated Sept. 25, 2017).

maintained.[17] Because the Phase IC satellites with a hosted payload and Phase II satellites will not carry maneuvering propellant, Spire will not maintain satellite inclination angles, apogees, perigees, and right ascension of the ascending node to any specified degrees of accuracy.

VI. Collisions with Small Debris or Meteoroids

Spire used NASA DAS to confirm that the Phase IC satellites with a hosted payload and Phase II satellites meet the requirements of 4.5-2.[18]

[17] *See* 47 C.F.R § 25.114(d)(14)(iii).
[18] *See Process for Limiting Orbital Debris*, NASA-STD-8719.14A § 4.5-2 (Dec. 2011).