2019

Spire Global, Inc.
Orbital Debris Assessment Report

MINAS Satellites

Revision History

Revision	Description of Revisions	Release Date
1	Initial Release An orbital debris risk assessment of LEMUR-2 Phase IC (with hosted payload) and Phase II satellites	10/13/2017
2	Updated reference from “Phase II” satellites to “MINAS” satellites and year on cover page	02/26/2019

Section 1: Program Management and Mission Overview

Project Managers	Jenny Barna and George John
Mission Description	The purpose of the LEMUR-2 System (LEMUR-2 and MINAS satellites) 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 MINAS satellites proposed to be launched by Spire Global, Inc. ("Spire").
Foreign Government Involvement	None
Project Milestones	MINAS 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 MINAS 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 MINAS 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 MINAS 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 MINAS satellites and other space objects complies with Requirement 4.5 of NASA-STD-8719.14A.
MINAS Satellites	Spire will add a third solar "drag" panel on any MINAS 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 launch at its highest orbit of 650 km. *See infra* § 6. The MINAS 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 MINAS 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:

MINAS 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 MINAS 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 MINAS 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 MINAS 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 MINAS 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 MINAS 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 MINAS 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 – MINAS 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 – MINAS 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 MINAS satellite will naturally decay until it reenters the atmosphere. Table 3 describes the mission scenarios for which lifetime analysis of these MINAS 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 MINAS satellite and deployed arrays. Note that Spire will add a third solar "drag" panel on any MINAS 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 MINAS 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, MINAS 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 MINAS 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 MINAS 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

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* 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 MINAS satellites are dead on arrival. These MINAS 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 MINAS satellite is non-communicative, an entirely passive, redundant fail-safe is included on all MINAS 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 MINAS 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**