<u>Spire Global, Inc. ("Spire") Orbital Debris Risk Mitigation Plan</u>

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]

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[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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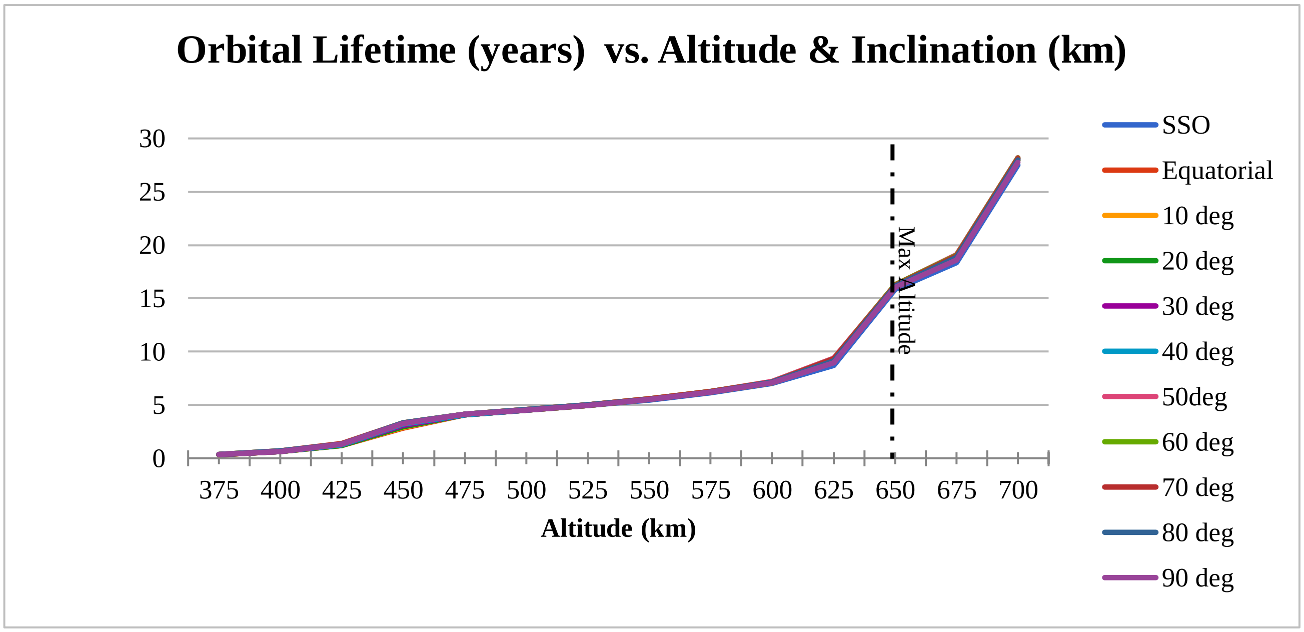
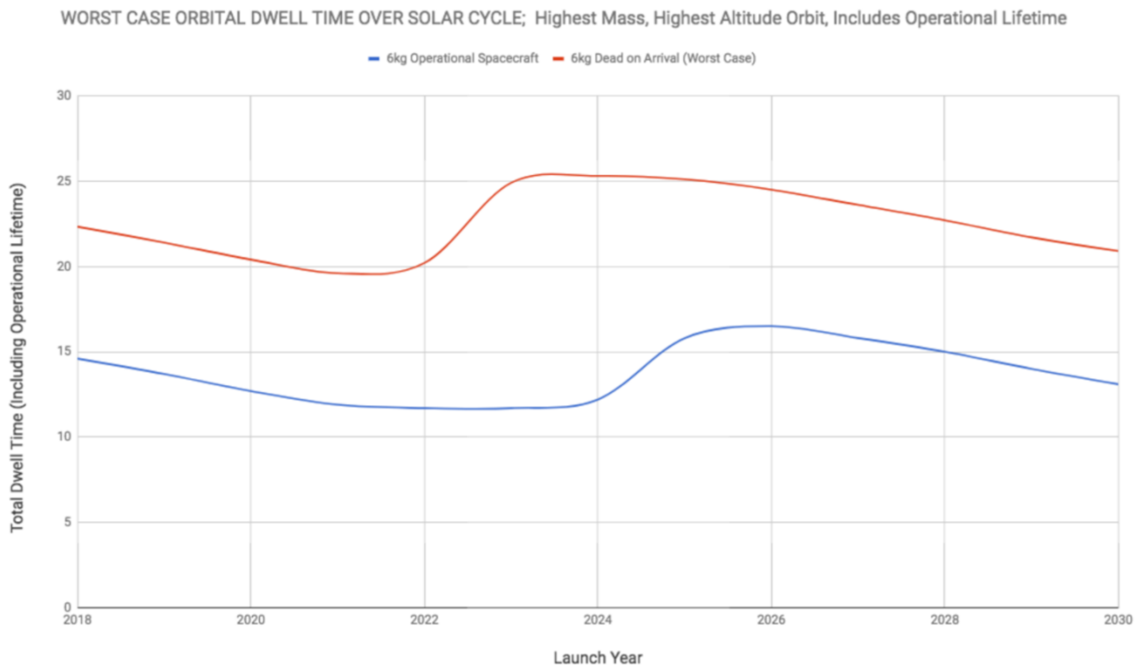
[3] *See* 47 C.F.R. § 25.114(d)(14)(iii).
[4] As mentioned, LEMUR-2 Phase IC and Phase II satellites have a nominal launch configuration of 4.5 kg; however, the mass capacity may be up to 6 kg maximum to accommodate any hosted payload scenarios. Both nominal and maximum cases are included in the ODAR 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).