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Supplement to Aggregate Orbital Debris Assessment Report for the Flock Constellation

At the request of the International Bureau, Planet Labs Inc. (Planet) provides the following information to supplement its Aggregate Orbital Debris Assessment Report for the Flock Constellation (dated Jan. 18, 2018):

1. The difference between the STK Conjunction Analysis Toolkit (STK CAT) and the NASA Debris Assessment Software (NASA DAS) tool and the basis for using NASA DAS results for more reliable lifetime collision risk assessments.
2. The extent to which Planet controls physical satellite operations after decommissioning the imaging operations of a Dove satellite.
3. The effectiveness of the mitigation measures Planet uses, including differential drag, for the avoidance of potential collisions with other space objects.

1. Lifetime Collision Risk Assessment Tools

Planet previously provided collision risk assessment results using both STK CAT and NASA DAS tools. The results between the two differ by an order of magnitude with NASA DAS results showing a lower risk probability.

The NASA-STD-8719.14 document and the NASA DAS tool is the NASA developed and industry accepted standard and software for orbital lifetime and collision risk assessments. NASA DAS determines the orbital collision risk based on a well-established analytical statistical model for the weighted cross-sectional area flux for the orbital debris environment exposure, and based on the satellites initial orbit, area-to-mass ratio, and launch date. STK CAT analysis, on the other hand, takes a user input initial condition of the satellite and propagates it through a snapshot of the current space catalog, making the results highly dependent on the initial conditions. STK CAT is therefore best used for a deterministic analysis when a specific time window, satellites, orbits, and launch dates are considered. In order to have a similar confidence in the STK CAT analysis as that of the NASA DAS analysis for a lifetime risk assessment, STK CAT would need to be run in a Monte Carlo analysis. Thousands of simulations have to be carried out where the initial conditions of the orbit and characteristics of the satellite are changed. There are also a large number of free parameters such as the object sizes and the encounter uncertainties (*i.e.,* the uncertainty associated with the two objects involved in an encounter at the time of closest approach) which all have a large impact on the collision probabilities. A single result from an STK CAT simulation is one of many possible outcomes; potentially one with a comparatively higher probability of collision. However, running a Monte Carlo analysis on the STK CAT simulation for the lifetime of the Dove constellation is

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computationally intractable. Therefore an analytical model such as DAS provides a more complete and reliable picture of the long-term risk.

2. Satellite Control After Decommissioning Imaging Operations

After a Dove satellite is decommissioned from imaging operations (typically after 2-3 years) and is no longer treated as part of Planet's operational imaging constellation, Planet continues to maintain control of the satellite attitude (orientation) in high-drag mode, where technically possible, until its control authority degrades such that atmospheric drag forces exceed the satellite's ability to maintain attitude, which is typically below 250 km orbital altitude. In addition, Planet continues to conduct ranging down to 200 km altitude in order to maintain accurate ephemerides. Planet conducts these orbital operations to facilitate the responsible use of space resources.

3. Effectiveness of Collision Avoidance Operations

Planet has previously shared its experience with differential drag as an in-space maneuvering capability with the Commission.[1,2] Planet continues to produce technical publications on this subject in support of validating this method of flight operations within the space industry,[3,4,5] joining others also publishing on this topic.[6] In summary, Planet can conduct differential-drag maneuvers until attitude control authority degrades, which is typically below 250 km orbital altitude, to eliminate or reduce the potential for collisions.

Planet receives conjunction data messages (CDMs) from Joint Space Operations Center (JSPoC) for potential collision events, which includes a time of closest approach (TCA) estimate, a miss distance estimate, state vector and covariance information, from which a probability of a

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[1] *See* Ex Parte Letter from Tony Lin, Counsel to Planet Labs, Inc., to Marlene H. Dortch, FCC, IBFS File Nos. SAT-MOD-20150802-00053 *et al*.; SAT-STA-20150821-00060; SAT-LOA- 20151123-00078 (August 24, 2016).

[2] *See* Opposition to Petition to Dismiss, Deny or Hold in Abeyance, File No. SAT-MOD-20150802-00053, Call Sign S2912 (February 3, 2016).

[3] Foster, C., Hallam, H, Mason, J., "Orbit Determination and Differential-drag Control of Planet Labs Cubesat Constellations", AAS/AIAA Astrodynamics Specialist Conference, Vail, Colorado, August 9-13, 2015, arXiv:1509.03270.

[4] Nicolls, M., Vittaldev, V., Ceperley, D., Creus-Costa, J., Foster, C., Griffith, N., Lu, E., Mason, J., Park, I., Rosner, C., and Stepan, L. "Conjunction Assessment for Commercial Satellite Constellations Using Commercial Radar Data Sources". Advanced Maui Optical and Space Surveillance Technologies Conf., Wailea, Maui, Hawaii, September 19-22, 2017, http://adsabs.harvard.edu/abs/2017amos.confE..18N

[5] Foster, C., Mason, J., Vittaldev, V., Leung, L., Beukelaers, V., Stepan, L., Zimmerman, R., "Constellation Phasing with Differential Drag on Planet Labs Satellites", Journal of Spacecraft and Rockets, Vol. 55, No. 2 (2018), pp. 473-483. https://doi.org/10.2514/1.A33927

[6] Mishne, D., and Edlerman, E., "Collision-Avoidance Maneuver of Satellites Using Drag and Solar Radiation Pressure," Journal of Guidance, Control, and Dynamics, Vol. 40, No. 5, 2017, pp. 1191–1205.

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collision (PoC) and uncertainty can be determined. The median advance notice from JSPoC for Dove conjunctions with other space objects is 120 hours (5 days). As the potential event nears, JSPoC provides CDM updates further refining the prediction and confidence. The final expected miss distance estimate typically settles and becomes actionable approximately 3-4 days prior to the TCA. In most cases, no orbital maneuver is ultimately required, as the PoC decreases as the TCA nears. To date, Planet has not needed to conduct differential drag maneuvers to avoid a close approach or potential collision.

If in the event of a close approach or potential collision, Planet will determine an appropriate collision avoidance response to implement, as follows:

1. If the other object is an operational spacecraft, consult with the other party and co-develop a collision avoidance strategy.
2. Conduct differential drag maneuvers, by changing the Dove satellite ballistic coefficient and atmospheric drag, to extend the minimum miss distance between objects to at least 0.5 to 1 km, thus reducing the PoC to less than 1E-4, which is less than the JSPoC criteria for conjunction alerts.[7,8]
3. Orient the satellite attitude for a minimum interaction area relative to the other object at the TCA.[9] This reduces the risk of a collision by approximately 30% for objects with an interaction area around 1 m^2 and even more for smaller objects (which are the majority of objects in low-Earth orbit).

Accordingly, given the notice periods provided by JSPoC and the time required to execute differential drag collision avoidance maneuvers, differential drag can be an effective solution for eliminating or reducing collision risks, particularly because:

- 92% of close approaches are reported to Planet by JSPoC 40 hours or more in advance of a close approach or potential collision, providing sufficient time for a Dove at 550 km to execute differential drag maneuvers to avoid a close approach or collision; and,
- 96% of close approaches are reported to Planet by JSPoC 28 hours or more in advance of a close approach or potential collision, providing sufficient time for a Dove at 500 km to execute differential drag maneuvers to avoid a close approach or collision.

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[7] *See* JFCC SPACE, Joint Space Operations Center publication "Spaceflight Safety Handbook for Satellite Operators", version 1.3, January 2017, page 6.

[8] A Planet Dove satellite in high drag orientation, relative to a normal orientation, experiences a 5:1 change (increase) in cross-sectional area relative to the direction of flight. At 550 km altitude, and with operational constraints considered, the time required to induce a change in orbital position of about 500 m to 1 km is about 28 - 40 hours. For a satellite at 500 km altitude, about 19 to 28 hours is required. As the altitude of the Dove decreases due to orbital decay, the time required for the maneuver also decreases due to the increasing atmospheric density.

[9] The collision probability is a function of the combined hardbody radii of the two conjuncting objects.

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TECHNICAL CERTIFICATE

I, Craig Scheffler, hereby certify, under penalty of perjury, that I am the technically qualified person responsible for the preparation of the engineering information contained in the technical portions of the foregoing report, that I am familiar with Part 25 of the Commission's rules, and that the technical information is complete and accurate to the best of my knowledge and belief.

Craig Scheffler
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Planet Labs Inc.