1. Introduction

1.1 Purpose

This document provides clarification on the accidental collision risk assessment for the entire Kepler Constellation over a period of 15 years.

Kepler has conducted the assessment to ensure the aggregate constellation risk complies with the NASA Orbital Debris Requirement 4.5.2.1 of less than 0.001 [AD02], operating under the assumption that the constellation mission acts as a single spacecraft.

1.2 Applicable Documents

Applicable documents are supporting documents that must be read in conjunction with this document in order to ensure a complete understanding of the information presented herein.

AD01	Kepler ODAR for MULTUS Filing		21-05-2017
AD02	Process for Limiting Orbital Debris	NASA-STD-8719.14A	25-05-2012

1.3 Notes on previous assessments

Out of an abundance of care, Kepler's policy has been to assess worst case scenarios when evaluating operational risk. Such assessments do not translate to effective risk when in operation, as the likelihood of all systems failing consistently across all satellites placed in orbit is near zero, and non-representative of real world operations. This assessment builds off of report version 1.0, 21/05/2017 to provide a real-world assessment of orbital debris risk. Conservatism is maintained in the assessment, beyond what is reasonably expected operationally.

Version 1.0 of the report has the following assumptions that are irrelevant and excessive when modeling the risks associated with the entire constellation. Some of these assumptions are highlighted below:

- All satellites were assumed to be deployed to 600 Km despite the vast majority of satellites planned for orbits of 575 Km or below. An assessment of the entire constellation at 600 Km is irrelevant and should be disregarded. This assessment was undertaken to ensure compliance for a single satellite.
- While the risk of satellite failure post deployment is not insignificant, the underlying risk associated with the deployment from the rocket and subsequent solar panel deployment are negligible. These systems are heavily flight tested and have multiple failsafe mechanism in place. While the assumption that this system may fail is reasonable for a single spacecraft, constituting a 100% failure rate, such an assumption is nonsensical when assessing the entire constellation and should be completely disregarded.
- Maneuverability of the spacecraft was not taken into consideration, given no differential drag as a result of the failed solar panel deployment. This is non-representative for the constellation and eliminates a primary method by which the majority of conjunctions could be avoided.

- An overly conservative threat ellipsoid was used to model conjunctions based on the lack of ability to maneuver. This results in an increased number of simulated conjunctions without substantiation.

While the assumptions above provide some meaning when assessing a single spacecraft, they cascade to amplify each other to the point where the assessment is meaningless for an entire constellation. As such the assumptions are overly constraining, non-representative and should be disregarded when deriving risk models associated with an entire constellation.

2. Updated Analysis

2.1 Summary of Results

The following summarizes the results of the analysis for the complete solution. The analysis assumes a launch cadence of 50 spacecraft per year for both constellation building and replenishments for a total period of 15 years. The following driving assumptions for the total mission are used for the analysis:

- Over the course of 15 years, 750 Kepler spacecraft are placed into operational orbit
- Spacecraft and array deployment reliability exceeds 99%
- A conservative 1% failure rate of spacecraft deployments is assumed, with all failed spacecraft being inserted at a 600 km altitude rather than following the spread associated with the constellation.
- Deployed spacecraft passively assume the brake configuration when not actively actuated
- Injection altitudes spread with 50% at 575 km or below, 40% at 550 km or below, and 10% at 600 km or below (375, 300, 75 spacecraft, respectively)
- An average orbit life of 4.9 years
- Spacecraft having experienced system wide-failure during their operational life following a successful deployment, are not actively replaced.

The following aggregate risk profile is obtained:

total mission risk of collision of 0.0007915 assuming no maneuverability
total mission risk of collision on the order of 0.00002 assuming maneuverability and adequate notice

The non-maneuverable risk is overly conservative and should be disregarded given the probabilistic ability of 99% of spacecraft to maneuver out of a collision trajectory. As such, the real mission risk is reflected by the 1%, or 8 spacecraft, that do not have maneuverability and result in a probability closer to $2e^{-5}$.

These risk values remain well below NASA requirements, less than 0.001 as required by NASA Orbit Debris Requirement 4.5.2.1, despite the conservative assumption of all failed satellites being deployed at 600 Km.

Table 1: Lifetime collision risk of different injection altitudes

Injection Orbit Altitude (km)	Lifetime Spacecraft Collision Risk	No. of Spacecraft	Total Orbit Aggregate Risk (DAS)
600 (deployment Failure)	0.000002	8	0.000016
600	0.000001 -0.000002	67	0.0001005
575	0.000001	375	0.000375
550	<0.00000099	300	0.000300

While the analysis considers satellites of both the 3U and 6U class, the difference in cross sectional area does not significantly increase the risk of collision. Any increase in collision risk is driven by lifetime spent in higher altitudes, wherein lifetime is largely a function of the drag area to mass ratio.

Following the deployment scheme and lifetime analysis, Kepler targets to maintain a total simultaneous number of spacecraft above 500 km at 150. In the worst case, analysis demonstrates a year with 200 spacecraft simultaneously above 500 km.

2.2 *Analysis and Clarification*

The following report describes the process, assumptions, methods and output of an analysis on the lifetime and collision risk of the constellation. The report presents a more realistic scenario. The report covers 15 years of the constellation and considers the aggregate affects and risks of operating maintaining the constellation throughout this time.

2.2.1 Spacecraft Deployment Reliability

While every commercially sensible action is taken to reduce the risk of failure of the spacecraft and its deployment, all spacecraft including those built as per batch standards are incapable of reaching 100% reliability. Kepler and its partners use rigorous testing and analysis of deployment chain activities to target greater than 99.0% reliability. This reliability considers only those items required to achieve complete deployment such that the spacecraft could passively enter the brake configuration if/when needed.

Fault tolerant redundant mechanisms are used to ensure a reliable deployment of solar panels. In the event that the spacecraft is injected dead-on-arrival these systems will provide the mechanism for a faster de-orbit.

In this analysis, the very conservative approach is taken that 1% of the launches are DOA in addition to a failed deployment and further operator commanded deployment is not possible. For conservatism, it is assumed that all of these failures occur at 600 km.

2.2.2 Spacecraft Attitude:

The analysis considers two principle attitude states required to derive the drag cross-sectional area:

- Operational Pointing/Tumble:
  The controlled state of the spacecraft is in a combination of an inertial-locked attitude combined with a body/Solar array pointed state to both ground and space targets. Over time this resembles that of a random tumbling spacecraft neglecting any gravity gradient or aerodynamic effects. For these models, the average tumbling cross section of 0.083 m^2 was used for a 5 kg class spacecraft. A cross section of 0.15 m^2 is used for 10-15 kg class spacecraft.

- Brake Configuration:
  As described in the ODAR [AD01], the Kepler spacecraft configuration allows for passive aerodynamic stabilization into a brake configuration wherein the largest drag cross section is aligned with the velocity vector. For these models a brake cross section of 0.21 m^2 was used for a 5 kg class spacecraft. A cross section of 0.3 m^2 is used for 10-15 kg class spacecraft.

2.2.3 Orbit Lifetime:

Spacecraft orbit lifetime is generated with a number of tools as a means of determining variation of prediction. It is noted that the average lifetime as generated by DAS aligns with the result of the SGP4 propagated lifetime of KIPP using on-orbit drag data for KIPP, as gathered via JSpOC. Consequently, the lifetime predictions generated by DAS will be considered the status-quo. Additional model lifetimes are presented in order to demonstrate variability with solar flux. These lifetimes were generated with the STK lifetime tool.

Lifetime Models assume that active pointing concludes after the 3rd year of operation, after which the spacecraft passively assumes the brake configuration.

Table 2: Predicted average orbit lifetimes for risk analysis

Spacecraft Class	Orbit Insertion Altitude (km)	Orbit Lifetime (years)	Time Above 500 km (years)
5 kg	600	5.1	4.1
5 kg	575	3.8	3.1
5 kg	550	3.0	2.1
12 kg	600	5.6	4.9
12 kg	575	4.9	3.5
12 kg	550	3.6	2.5

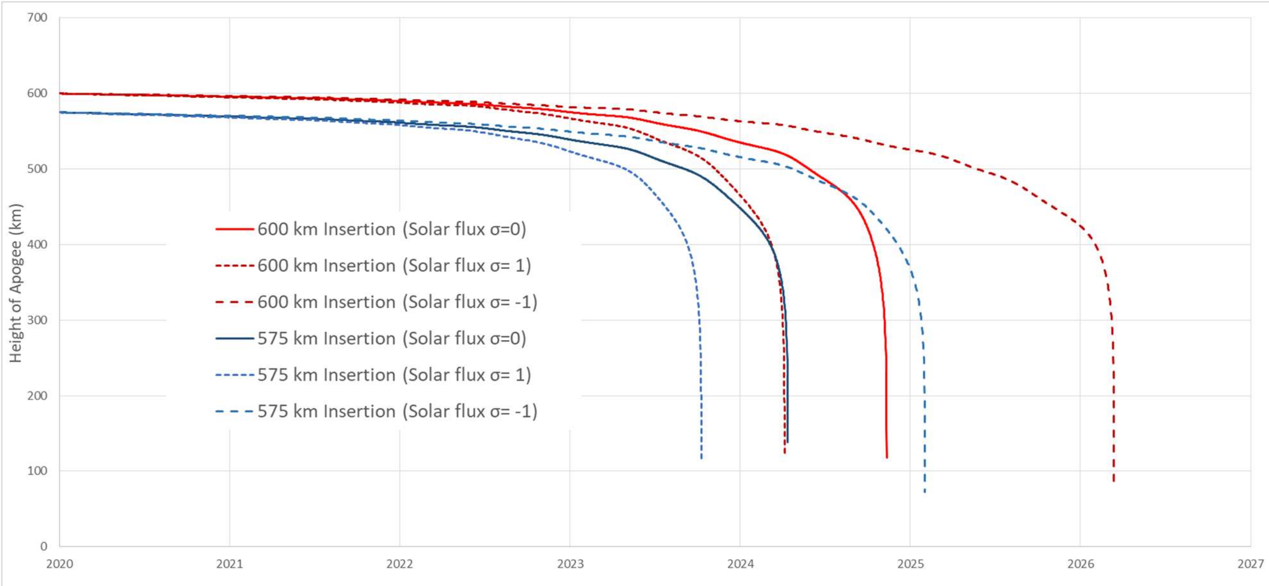

Figure 1: Predicted lifetime variance with solar flux activity

2.2.4 Active Collision Avoidance:

While only required to operate for 3 years, Kepler designs all systems with adequate margin to account for model and analysis error. Consequently, the built-in design margin will likely allow for an extension of operator control of the spacecraft for the total orbit lifetime duration.

Current Kepler spacecraft have the capability to conduct conjunction avoidance through the use of adaptive drag profile. Kepler is registered for CDM notification with JSpoC and has the capability to command a spacecraft attitude change within a maximum of 6 hours (average 2 hours) upon learning of a possible CDM. Each spacecraft has the capability of controlling its attitude to acquire a low or high drag configuration with a maximum drag ratio of 21:1 between the two states.

First order analysis demonstrates that an along-track maneuver of 10 km separation from the original CDM can be obtained if a drag profile maneuver is initiated 2 days prior to the predicted conjunction. A maximum of 50 km phasing from the conjunction can be obtained if the maneuver is initiated 5 days in advance.

2.3 Collision Risk Output

As highlighted in Table 1, the following probability of collisions were generated using the assumptions above. The DAS logs below show the inputs and outputs.

2.3.1 DAS Run Details:

600 Km Injection (Deployment Failure)

```
**INPUT**
```

```
        Space Structure Name = KC1-Failed Deploy Tumble
        Space Structure Type = Payload
        Perigee Altitude = 600.000000 (km)
        Apogee Altitude = 600.000000 (km)
        Inclination = 97.740000 (deg)
        RAAN = 0.000000 (deg)
        Argument of Perigee = 0.000000 (deg)
        Mean Anomaly = 0.000000 (deg)
        Final Area-To-Mass Ratio = 0.004660 (m^2/kg)
        Start Year = 2020.000000 (yr)
        Initial Mass = 5.000000 (kg)
        Final Mass = 5.000000 (kg)
        Duration = 3.000000 (yr)
        Station-Kept = False
        Abandoned = True
        PMD Perigee Altitude = -1.000000 (km)
        PMD Apogee Altitude = -1.000000 (km)
        PMD Inclination = 0.000000 (deg)
        PMD RAAN = 0.000000 (deg)
        PMD Argument of Perigee = 0.000000 (deg)
        PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

        Collision Probability = 0.000002
        Returned Error Message: Normal Processing
        Date Range Error Message: Normal Date Range
        Status = Pass
```

600 Km Injection:

```
**INPUT**

        Space Structure Name = KC1-tumble
        Space Structure Type = Payload
        Perigee Altitude = 600.000000 (km)
        Apogee Altitude = 600.000000 (km)
        Inclination = 97.740000 (deg)
        RAAN = 0.000000 (deg)
        Argument of Perigee = 0.000000 (deg)
        Mean Anomaly = 0.000000 (deg)
        Final Area-To-Mass Ratio = 0.0166000 (m^2/kg)
        Start Year = 2020.000000 (yr)
        Initial Mass = 5.000000 (kg)
        Final Mass = 5.000000 (kg)
        Duration = 3.000000 (yr)
        Station-Kept = False
        Abandoned = True
        PMD Perigee Altitude = -1.000000 (km)
        PMD Apogee Altitude = -1.000000 (km)
        PMD Inclination = 0.000000 (deg)
        PMD RAAN = 0.000000 (deg)
        PMD Argument of Perigee = 0.000000 (deg)
        PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

        Collision Probability = 0.000002
        Returned Error Message: Normal Processing
        Date Range Error Message: Normal Date Range
        Status = Pass
```

575 Km Injection:

```
**INPUT**
```

```
        Space Structure Name = KC1-tumble
        Space Structure Type = Payload
        Perigee Altitude = 550.000000 (km)
        Apogee Altitude = 550.000000 (km)
        Inclination = 97.740000 (deg)
        RAAN = 0.000000 (deg)
        Argument of Perigee = 0.000000 (deg)
        Mean Anomaly = 0.000000 (deg)
        Final Area-To-Mass Ratio = 0.0166000 (m^2/kg)
        Start Year = 2020.000000 (yr)
        Initial Mass = 5.000000 (kg)
        Final Mass = 5.000000 (kg)
        Duration = 3.000000 (yr)
        Station-Kept = False
        Abandoned = True
        PMD Perigee Altitude = -1.000000 (km)
        PMD Apogee Altitude = -1.000000 (km)
        PMD Inclination = 0.000000 (deg)
        PMD RAAN = 0.000000 (deg)
        PMD Argument of Perigee = 0.000000 (deg)
        PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

        Collision Probability = 0.000001
        Returned Error Message: Normal Processing
        Date Range Error Message: Normal Date Range
        Status = Pass
```

550 Km Injection:

```
**INPUT**

        Space Structure Name = KC1
        Space Structure Type = Payload
        Perigee Altitude = 600.000000 (km)
        Apogee Altitude = 600.000000 (km)
        Inclination = 97.740000 (deg)
        RAAN = 0.000000 (deg)
        Argument of Perigee = 0.000000 (deg)
        Mean Anomaly = 0.000000 (deg)
        Final Area-To-Mass Ratio = 0.016600 (m^2/kg)
        Start Year = 2020.000000 (yr)
        Initial Mass = 5.000000 (kg)
        Final Mass = 5.000000 (kg)
        Duration = 3.000000 (yr)
        Station-Kept = False
        Abandoned = True
        PMD Perigee Altitude = -1.000000 (km)
        PMD Apogee Altitude = -1.000000 (km)
        PMD Inclination = 0.000000 (deg)
        PMD RAAN = 0.000000 (deg)
        PMD Argument of Perigee = 0.000000 (deg)
        PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

        Collision Probability = 0.000000
        Returned Error Message: Normal Processing
        Date Range Error Message: Normal Date Range
        Status = Pass
```

It is noted here that DAS does not resolve any probabilities below six significant digits. For this reason, it is presumed that 0.000000 represents a collision probability of 9.999×10^{-7}.

2.3.2 STK AdvCat Run

As per the ODAR, STK AdvCat was used to provide a second source of verification for the collision risk. A reduced fixed threat ellipsoid of 3km Along-track, 0.5 km cross-track, and 0.5 km Normal to the velocity vector of its spacecraft was assumed for the run. The Kepler spacecraft is considered a 1-m radius sphere at the center of the threat ellipsoid. These values are enforced by their use in Planet's ODAR. Conjunction assessments assumed the majority injection altitude of 575 km. A single Kepler spacecraft was simulated in 8 different orbital planes and at 8 different initial true anomalies, resulting in 64 simulations each for the duration of a year.

The simulations aggregated all possible conjunctions between the spacecraft and the complete TLE catalog. Cataloged items were given threat ellipsoids as determined by their orbital class. Kepler considered any close-encounter to be a possible conjunction if determined to be an intersection by the analysis, or if the minimum range separation between spacecraft was less than 1 km. The individual encounter probabilities were subsequently used to calculate the aggregate probability of collision for the entire year of simulation. This was averaged against the other 64 runs. Note that the probability of the life time is calculated as the sum of probabilities for each year at 575. This results in a very conservative aggregate risk given the risk of collision reduces with altitude due to the reduction in orbit density.

- Single spacecraft probability of collision for 1 year at 575 km: 0.00000021
- Probability of collision over 5.1 year lifetime: 0.00000108
- Constellation probability of collision: **0.000807**

The aggregate collision risk is comparable to **0.0007915** as calculated by DAS. Both values assume no maneuvering to avoid collisions and are overly conservative.

3. Additional points:

The current constellation considers the bare minimum architecture required for constellation performance. As development progresses with deployment of the technology demonstration satellites. There are multiple trades being considered for inclusion in future missions. One of these is the inclusion of active maneuvering in the event of a rapid population of the sub 600 Km orbits in which Kepler operates. Given the low collision risk associated with Kepler's spacecraft that are capable of maneuvering, added to the minimal risk of a failed deployment, this is not currently deemed required.