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Kepler Orbital Debris Assessment Report (ODAR)

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This report is presented in compliance with NASA-STD-8719.14, APPENDIX A.

Report Version: 1.0, 21/05/2017

Document Data is Not Restricted

This document contains no proprietary, ITAR, or export controlled information

DAS Software Version Used in Analysis: v2.0.2

STK Software Version Used in Analysis: 10.1.3

1 Self-assessment of the ODAR using the format in Appendix A.2 of NASA-STD-8719.14:

An assessment is provided below in accordance with the assessment format provided in Appendix A.2 of NASA-STD-8719.14

Orbital Debris Self-Assessment Report Evaluation: Kepler 1-2 Mission

Requirement #	Launch Vehicle				Spacecraft			Comments
	Compliant	Not Compliant	Incomplete	Standard Non Compliant	Compliant	Not Compliant	Incomplete	
4.3-1.a			X		X			No debris released in LEO
4.3-1.b			X		X			No debris released in LEO
4.3-2			X		X			No debris released in GEO
4.4-1			X		X			No credible scenario of explosion
4.4-2			X		X			No credible scenario of explosion
4.4-3			X		X			No planned breakups
4.4-4			X		X			No planned breakups
4.5-1			X		X			Collision probability within compliance requirements
4.5-2			X		X			Collision probability within compliance requirements
4.6-1(a)			X		X			Atmospheric re-entry within 10.3 year from start of mission
4.6-1(b)			X		X			Atmospheric re-entry within 10.3 year from start of mission
4.6-1(c)			X		X			Atmospheric re-entry within 10.3 year from start of mission
4.6-2			X		X			Spacecraft not in GEO
4.6-3			X		X			Spacecraft not between LEO and GEO
4.6-4			X		X			No EOM subsystem required
4.7-1			X		X			No controlled reentry
4.8-1			X		X			No tethers used

Assessment Report Format

ODAR Technical Sections Format Requirements

As Kepler Communications Inc. (Kepler) is a Canadian company, this ODAR follows the format recommended in NASA-STD-8719.14, Appendix A.1 and includes the content indicated at a minimum in each section 2 through 8 for the satellites in the Kepler system. Section 9 through 14 apply to the launch platform, and are not covered here.

2 Program Management and Mission Overview

Project Manager: Kepler Communications

Foreign government or space agency participation: N/A

Mission Milestones:

Launch: No earlier than October 2017

Mission Overview:

The Kepler system will be delivered to sun-synchronous orbits (SSO) or polar orbits (PO) at an altitude between 500-600 km. The satellites will be deployed in tandem, and the mission operational lifetime is at least 2 years, with the time until disposal a maximum of 9.7 years after start of mission with deployed solar panels.

Anticipate Launch Vehicle and Site: PSLV, Satish Dhawan Space Centre, India

Description of the launch and deployment profile: The first Kepler satellites will deploy into SSO, from which they will naturally decay due to atmospheric drag. The satellites are not equipped with propulsion and thus do not actively change orbits, and there is no parking or transfer orbit. After at least 2 years' mission duration, each spacecraft will transition into an aerodynamic breaking attitude to allow for re-entry within acceptable time limits. The deployment altitude will depend on the final launch vehicle selection, and as such the altitude ranges below are considered for this analysis:

High insertion case: **Apogee:** 630 km **Perigee:** 630 km
Low insertion case: **Apogee:** 500 km **Perigee:** 500 km
Inclination: 98.6 degrees (SSO)

Reason for orbit selection: Ground track and launch availability

3 Spacecraft Description

Physical Description:

The Kepler satellites are variants of the 3U CubeSat specification, with a mass of 5.0 kg and physical dimensions of 100 x 100 x 340 mm^3. The CubeSats will contain two deployable solar arrays of deployed planar dimensions 240 x 300 mm^2.

The load bearing structure is comprised 4 anodized aluminum rails connected with 4 skeleton aluminum plates of dimensions 100 x 340 mm. Machined struts connect the plates at a distance of 100 mm to add rigidity. The solar arrays are spring loaded, and actuated via a non-explosive actuator consisting of burn wire.

Power storage will be provided by two 40W Lithium-Ion batteries. The batteries will be recharged via solar cells mounted on the external chassis, and the deployed solar array. The combined battery dimension is 90x96x57 mm with an average mass of 670 g.

Total satellite mass at launch, incl. propellants and fluids: 5.0 kg

Dry mass at mass, exl. propellants and fluids: 5.0 kg

Description of propulsion systems: None

Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes: None

Fluids in Pressurized Batteries: N/A. Satellite batteries are unpressurized standard COTS Li-Ion cells.

Description of attitude control system and indication of the normal attitude of the spacecraft with respect to the velocity vector: Satellite attitude is controlled by a combination of magnetorquers and reaction wheels. Mission operations includes three attitude modes, shown in Figure 1. Nominal and Low Drag modes are use during mission operations, and Brake is used during end-of-life de-orbit operations, and is dynamically stable.

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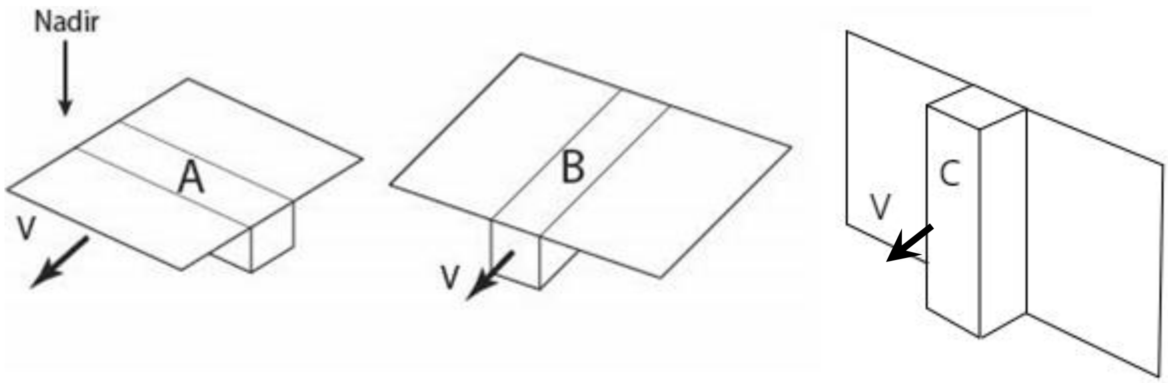

Figure 1: Attitude modes used for Kepler satellites. A – Nominal, B – Low Drag, C – Brake

Description of any range safety or other pyrotechnic devices: No pyrotechnic devices are used.

Description of the electrical generation and storage system: Electrical power is generated via body mounted Ga-As solar panels and the two arrays. Power storage is done via Li-Ion batteries as previously mentioned. The electrical power subsystem manages battery charging, battery balancing, and protects against over/under current conditions.

Identification of any other sources of stored energy not noted above: None.

Identification of any radioactive materials on board: None**.**

4 Assessment of Spacecraft Debris Release during Normal Operations

Not applicable as there are no intentional releases of debris.

5 Assessment of Space Intentional Breakups and Potential for Explosions

Potential causes of spacecraft breakup during deployment and mission operations:

There is no foreseen scenario in which the spacecraft would breakup during normal deployment and operations.

Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion:

The only foreseen risk of explosion would be as a result of battery overheating and the resulting low probability of cell explosion. A FMEA (failure mode and effects analysis) was done to demonstrate the combined, mutually exclusive failures that must occur in order to result in the potential for accidental explosion of the batteries. Seven independent scenarios were analyzed to consider the risk that battery explosion could occur, with an exceptionally low cumulative probability that explosion will occur.

Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions: No planned breakups

List of components which shall be passivated at End of Mission (EOM) including method of passivation and amount which cannot be passivated: None. Batteries will not be passivated at end-of-mission as the total combined stored energy is less than 288 kJ.

Rationale for all items which are required to be passivated, but cannot be due to their design:

Chemical storage devices, such as batteries, are required to be passivated at EOM. However, the low total stored energy combined with being fixtured internal to the spacecraft container minimized the risk of debris generation because of the lack of penetrating energy. Thus, batteries will not be passivated at EOM.

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4:

Requirement 4.4-1**:** Limiting the risk to other space systems from accidental Orbital Debris explosions during deployment and mission operations while in orbit about Earth or the Moon:

For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449).

Compliance statement:

Required Probability: 0.001.

Expected probability: << 0.001.

Supporting Rationale and FMEA details:

Battery explosion:

Effect: The following presents all failure modes that may theoretically result in battery explosion, with the possibility of debris generation. However, in the unlikely event of battery explosion the low stored chemical energy combined with being located internal to the spacecraft container minimizes the risk of debris generation because of the lack of penetration energy.

Probability: Extremely low. Battery explosion in all failure modes requires two simultaneous faults or systematic user failure that are of extremely low probability in themselves.

Failure mode 1: Short circuit
Mitigation: Functional testing of charge/discharge, as well as environmental testing including shock, vibration, thermal cycling, and vacuum testing to prove no internal short circuit sensitivity exists. Cells & protection circuits are COTS which have flight heritage.
Combined Faults Required: Failure of environmental testing **AND** failure for functional testing to discover short circuit sensitivities **AND** failure of COTS vendor in testing components.

Failure Mode 2: Above-nominal current draw inducing battery thermal rise
Mitigation: Thermal cycling on cells to test upper temperature limits, testing of batteries at above-nominal discharge levels.
Combined Faults Required: Inaccurate spacecraft thermal design **AND** over-current failure to detect off-nominal discharge rates

Failure Mode 3: Terminal contact with conductors not at battery voltage levels causing above-nominal current draw.
Mitigation: Qualification-test short circuit protection on each circuit, design of battery holders to ensure to unintended conductor contact without mechanical failure, minimize risk of mechanical failures via shock, vibration testing.
Combined Faults Required: Mechanical failure induced short circuit **AND** failure of over-current protection.

Failure Mode 4: Inoperable vents on battery holders.
Mitigation: Battery vents are not inhibited by the battery holder design or the spacecraft.
Combined Faults Required: Final assembler fails to install proper venting.

Failure Mode 5: Batteries are crushed during operation
Mitigation: No moving parts in proximity of battery. Spacecraft is tested to simulate launch loadings to ensure no damage to cells.
Combined Faults Required: A catastrophic mechanical failure has occurred **AND** the failure must be sufficient to cause a crushing of the batteries, leading to an internal short circuit **AND** the satellite must be in a naturally sustained orbit at the time of crushing.

Failure Mode 6: Low level current leakage or short circuit through battery holder due to moisture-induced degradation of insulators
Mitigation: Non-conductive plastic for battery holders, operation in vacuum thus moisture cannot affect insulators
Combined Faults Required: Failure of battery insulators **AND** dislocation of batteries in holder **AND** failure to detect fault in environmental testing

Failure Mode 7: Thermal rise due to space environment and high discharge combined
Mitigation: Spacecraft thermal design to prevent situation, testing of batteries above expected operating conditions, use of COTS components with flight heritage
Combined Faults Required: Inaccurate thermal design **AND** failure to detect fault in thermal cycling and environmental testing **AND** failure of COTS supplier to provide qualified batteries.

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon:

Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450).

Compliance statement:

In the unlikely event of battery explosion the low stored chemical energy combined with being located internal to the spacecraft container minimizes the risk of debris generation because of the lack of penetration energy.

Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups:

Compliance statement:
N/A as there are no planned breakups

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups:

Compliance statement:
N/A as there are no planned breakups

6 Assessment of Spacecraft Potential for On-Orbit Collision

Requirement 4.5-1: Limiting debris generated by collisions with large objects when operating in Earth orbit:

For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506).

A probability of collision analysis was performed using NASA's DAS 2.0.2 software. This analysis was done for single satellite over a mission duration of 25.2 years at an altitude of 600 km. The mission duration of 10.3 years is used as this is maximum lifetime prior to reentry, as will be shown in Section 6. As density of space objects decreases steadily below 800 km altitude, the high insertion scenario of 600 km apogee was considered as a worst-case scenario.

Large Object Impact and Debris Generation Probability per Spacecraft:
Collision Probability: 0.000002; COMPLIANT

```
==============
Run Data
==============
**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 = 2018.000000 (yr)
       Initial Mass = 5.000000 (kg)
       Final Mass = 5.000000 (kg)
       Duration = 2.000000 (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

==============
=============== End of Requirement 4.5-1 ===============
```

Supporting Collision Risk Analysis

In addition, STK's Conjunction Analysis Toolkit (STK/CAT) was used to perform a conjunction analysis for the satellite deployment and orbit. The Kepler satellites all had an assumed covariance that resulted in a fixed threat volume ellipsoid defined as 10 km tangential (along-track), 2 km cross-track, and 2km normal (nadir) to the trajectory and assumed as hard spheres of diameter 1 m. All other satellites and TLEs were allocated threat volumes as per their orbit class assigned by STK. This was done across the entire 25.2-year satellite lifetime should the solar panels not deploy as this is the worst case.

Kepler vs. All TLEs

Maximum Analytic Probability of Collision:	2.15 E -09	COMPLIANT
Maximum Probability of Collision	2.36 E-04	COMPLIANT

Requirement 4.5-2: Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit**:**

> *For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal requirements is less than 0.01 (Requirement 56507).*

The Kepler satellites are to be deployed into a low Earth orbit, where the density of resident space objects, and therefore the probability of collisions, reduces with altitudes below about 800 km. Therefore, the "high insertion" scenario, where satellites are deployed at 600 km, represents the highest collision probability insertion scenario, and the DAS analysis was performed for this scenario.

Small Object Impact and Debris Generation Probability per Spacecraft:

Collision Probability (2 yr Mission Duration): 0.000672 COMPLIANT
Collision Probability (25.2 yr Orbital Life): 0.001871 COMPLIANT

```
===================================================
Spacecraft = KC1
Critical Surface = +X
===================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.030000 (m^2)
    Vector = (-1.000000 (u), 0.000000 (v), 0.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range

===================================================
Spacecraft = KC1
Critical Surface = -X
===================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
```

```
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.030000 (m^2)
    Vector = (1.000000 (u), 0.000000 (v), 0.000000 (w))
    Page 1
    DAS Activity Log
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range

==================================================
Spacecraft = KC1
Critical Surface = -y
==================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.030000 (m^2)
    Vector = (0.000000 (u), -1.000000 (v), 0.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range

==================================================
Spacecraft = KC1
Critical Surface = +y
==================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Page 2
    DAS Activity Log
    Orientation = Fixed Oriented
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.030000 (m^2)
    Vector = (0.000000 (u), 1.000000 (v), 0.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000619
    Returned Error Message: Normal Processing
```

```
    Date Range Error Message: Normal Date Range

==================================================
Spacecraft = KC1
Critical Surface = -Z
==================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.010000 (m^2)
    Vector = (0.000000 (u), 0.000000 (v), -1.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000024
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range

==================================================
Spacecraft = KC1
Critical Surface = +z
==================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Page 3
    DAS Activity Log
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
    CS Areal Density = 2.900000 (g/cm^2)
    CS Surface Area = 0.010000 (m^2)
    Vector = (0.000000 (u), 0.000000 (v), 1.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000024
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range

    ==================================================
    Spacecraft = KC1
    Critical Surface = SA
    ==================================================
    **INPUT**
    Apogee Altitude = 600.000000 (km)
    Perigee Altitude = 600.000000 (km)
```

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```
    Orbital Inclination = 97.740000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass = 0.016600 (m^2/kg)
    Initial Mass = 5.000000 (kg)
    Final Mass = 5.000000 (kg)
    Station Kept = No
    Start Year = 2018.000000 (yr)
    Duration = 2.000000 (yr)
    Orientation = Fixed Oriented
    CS Areal Density = 2.000000 (g/cm^2)
    CS Surface Area = 0.180000 (m^2)
    Vector = (1.000000 (u), 0.000000 (v), 0.000000 (w))
    CS Pressurized = No
    **OUTPUT**
    Probabilty of Penitration = 0.000005
    Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range
```

Identification of all systems or components required to accomplish any post mission disposal operation, including passivation and maneuvering: None.

7 Assessment of Spacecraft Post-Mission Disposal Plans and Procedures

Description of spacecraft disposal option selected: The satellite will de-orbit naturally by atmospheric re-entry within a maximum of 9.7 years after start of mission, as described below.

Plan for any spacecraft maneuvers required to accomplish post mission disposal:

Operational lifetime of the spacecraft is two years from the date of deployment. At which time the spacecraft will be oriented into its Break configuration via on-board attitude control system in order to ensure rapid atmospheric reentry at a maximum of 2.6 years after end of mission duration. In a Random tumble Reentry will occur at a maximum of 7.7 years after end of mission operations However, as the Break configuration is the dynamically stable configuration, in the event of attitude control failure the spacecraft will passively orient in this attitude. Passive dynamic stability in roll about the spacecraft Z-axis is maintained at orbit altitudes through separation of the Deployed Center-of-Mass (CoM) and the Center of Aerodynamic Pressure. When the X-axis is aligned with the velocity vector for the stable brake configuration, the positive separation of the CoM and Cp is 0.0257m resulting in a positive static margin necessary for static stability and a stabilizing moment. With the predicted positive margin, preliminary analysis suggests this configuration has a stiffness that results in a steady state error of ±30° with varying disturbances.

Calculation of area-to-mass ratio after post mission disposal, if the controlled reentry option is not selected:

Spacecraft Mass:	5 kg	
Cross-Sectional Area:	Nominal configuration:	0.03 m^2 (drag area)
	Low Drag configuration:	0.01 m^2 (drag area)
	Break configuration:	0.21 m^2 (drag area)
Area to mass ratio:	Nominal configuration:	0.006 m^2/kg
	Low Drag configuration:	0.002 m^2/kg
	Break configuration:	0.042 m^2/kg

The break configuration is the dynamically stable orientation of the satellite, and thus in a state of control loss, the spacecraft will naturally assume this configuration

Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5 (per DAS v 2.0.2 and NASA-STD-8719.14 section):

Requirement 4.6-1: Disposal for space structures passing through LEO:

A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods: (Requirement 56557) *a. Atmospheric reentry option:*

- *Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or*
- *Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.*

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission

At the end of operational life, the Kepler satellites will be oriented via on-board attitude control systems to the Break configuration, which will allow for atmospheric reentry (Option "a"). End of operational life will commence after 2 years of on-orbit operations, during which time the spacecraft is in Nominal configuration. Moreover, in the event of an actuator failure, the spacecraft will passively orient towards a Break configuration as per *Section 7 Paragraph 2*. Should the spacecraft fail to passively maintain a stable break configuration, the tumbling average drag area is calculated as 0.083 m^2. Taking this as a worst case post-mission scenario, STK was used to estimate expected on-orbit lifetime, as described below. Min and max operational lifetimes take into account space weather fluctuations, assuming a solar flux sigma level of $\sigma = 0.5$ to 1.0, as well as the high and low insertion cases. As shown, maximum possible lifetime is 10.3 years, which is well within the disposal requirements.

Case Name	High Insertion Case	
Drag Coefficient	2.2	
Drag Area	Mission: 0.03 m^3 End of Operations: 0.083 m^2	
Initial Orbit	600 x 600 km	
	Low Solar Activity ($\sigma = 0.5$)	High Solar Activity ($\sigma = 1.0$)
Post Mission Lifetime	9.7 years	7.8 years

Case Name	Low Insertion Case	
Drag Coefficient	2.2	
Drag Area	Mission: 0.03 m^3 End of Operations: 0.083m^2	
Initial Orbit	500 x 500 km	
	Low Solar Activity ($\sigma = 0.5$)	High Solar Activity ($\sigma = 1.0$)
Post Mission Lifetime	3.0 years	2.8 years

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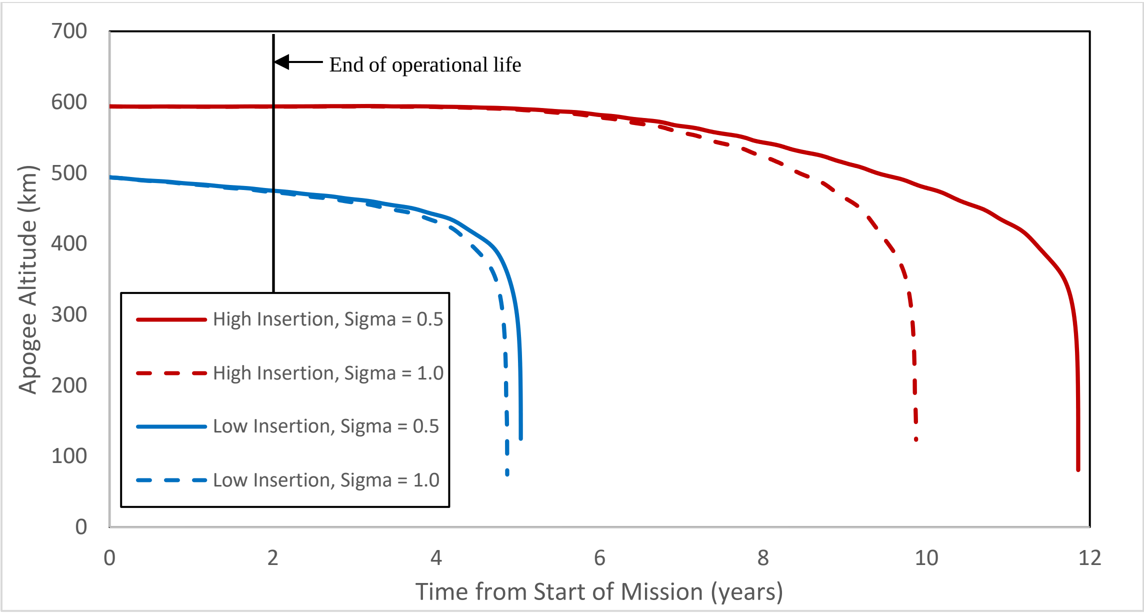

Figure 2: Spacecraft apogee from mission onset until reentry.

```
**INPUT**

        Start Year = 2017.000000 (yr)
        Perigee Altitude = 600.000000 (km)
        Apogee Altitude = 600.000000 (km)
        Inclination = 98.600000 (deg)
        RAAN = 0.000000 (deg)
        Argument of Perigee = 0.000000 (deg)
        Area-To-Mass Ratio = 0.026400 (m^2/kg)

**OUTPUT**

        Orbital Lifetime from Startyr = 6.395619 (yr)
        Time Spent in LEO during Lifetime  = 6.395619 (yr)
        Last year of Propagation = 2023 (yr)
        Returned Error Message: Object reentered
```

Requirement 4.6-2. Disposal for space structures near GEO.
Analysis: Not applicable.

Requirement 4.6-3. Disposal for space structures between LEO and GEO.
Analysis: Not applicable.

Requirement 4.6-4. Reliability of Postmission Disposal Operations
Analysis: Not applicable.

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8 Assessment of Spacecraft Reentry Hazards

Requirement 4.7-1: Limit the risk of human casualty:
The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:
a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

Analysis performed using DAS v2.0.2 shows that no part of the satellite is expected to survive re-entry, therefore the risk of human casualty is ~0.

```
11 21 2015; 18:31:10PM *********Processing Requirement 4.7-1
       Return Status :  Passed

***********INPUT****
 Item Number = 1

name = Kepler1
quantity = 1
parent = 0
materialID = 5
type = Box
Aero Mass = 5.000000
Thermal Mass = 5.000000
Diameter/Width = 0.100000
Length = 0.340000
Height = 0.100000

name = Payload
quantity = 1
parent = 1
materialID = 23
type = Box
Aero Mass = 1.000000
Thermal Mass = 1.000000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.100000

name = Structure
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 1.500000
Thermal Mass = 1.500000
Diameter/Width = 0.100000
Length = 0.340000
Height = 0.100000

name = SolarPanels
quantity = 7
parent = 1
materialID = 24
type = Box
Aero Mass = 0.200000
Thermal Mass = 0.200000
Diameter/Width = 0.100000
Length = 0.340000
Height = 0.025000
```

```
name = Batteries
quantity = 1
parent = 1
materialID = 9
type = Box
Aero Mass = 0.300000
Thermal Mass = 0.300000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.050000

name = Avionics
quantity = 1
parent = 1
materialID = 23
type = Box
Aero Mass = 0.800000
Thermal Mass = 0.800000
Diameter/Width = 0.100000
Length = 0.200000
Height = 0.100000

**************OUTPUT****
Item Number = 1

name = Kepler1
Demise Altitude = 77.997472
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Payload
Demise Altitude = 72.714058
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Structure
Demise Altitude = 73.132183
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = SolarPanels
Demise Altitude = 77.647324
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Batteries
Demise Altitude = 74.769879
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Avionics
Demise Altitude = 75.535136
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************

=============== End of Requirement 4.7-1 ===============
```

Requirement 4.7-1, b) *For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).*

Not applicable as there is no use of controlled reentry

Requirement 4.7-1 c) *For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).*

Not applicable as there is no use of controlled reentry

9 Assessment for Tether Missions

Not applications as there are no tethers in this mission.

End of ODAR for Kepler 1/2