# Capella (Sequoia - Whitney 1&2) Orbital Debris Assessment Report (ODAR)

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

Report Version: 2, 09/10/2020

DAS Software Version Used In Analysis: v2.1.1

**VERSION APPROVAL and/or FINAL APPROVAL:**

Duncan Eddy, Space Operations

**PREPARED BY:**

Lucas Riggi, Mission Design

# Table of Contents

# Self-assessment of the ODAR

This ODAR follows the format recommended in NASA-STD-8719.14, Appendix A.1, sections 1 through 8 for the Capella satellite. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

**Orbital Debris Self-Assessment Report Evaluation: Capella Mission**

(based upon ODAR version 2, dated September 10, 2020)

| Reqm # | Launch Vehicle | | | | Spacecraft | | | Comments |
|---|---|---|---|---|---|---|---|---|
| | Compliant | Not Compliant | Incomplete | Standard Not Compliant | Compliant or N/A | Not Compliant | Incomplete | |
| 4.3-1.a | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.3-1.b | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.3-2 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.4-1 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.4-2 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.4-3 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.4-4 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.5-1 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.5-2 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-1.a | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-1.b | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-1.c | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-2 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-3 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.6-4 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.7-1 | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☐ | |
| 4.8-1 | ///// | ///// | ///// | ///// | ☑ | ☐ | ☐ | |

Figure 1: ODAR Review Check sheet

# 1. Mission Overview

**Project Manager:** Duncan Eddy

**Mission Overview:** Sequoia will be launched in August 2020. It will be launched in an inclined (45 deg) orbit at an average altitude of 525 km. It will be operated for a tentative minimum of 3 years. Whitney 1&2 will be launched no earlier than December 2020, on a sun-synchronous orbit at an altitude between 475km and 575km. For the purpose of this document, the worst case altitude in terms of lifetime of 575 km will be used.

**ODAR Summary:** All the debris generated in orbit are compliant with Requirements 4.3, there is no credible scenario for breakups, the collision probability with other objects is compliant with NASA standards, the estimated nominal decay lifetime due to atmospheric drag is less than 6 years, much less than 25 years (as calculated by DAS 2.1.1).

**Launch:** Sequoia will be launched in August 2020 on a Rocket Lab Electron launcher. Whitney 1&2 are currently planned to be launched on a SpaceX Falcon 9 rocket, in December 2020.

**Mission Duration:** Maximum Nominal Operations: 3 years, Post-Operations Orbit lifetime: 2 year until reentry via atmospheric orbital decay (worst case less than 5 years in total).

**Orbit Profile:** Sequoia will deploy from the launch vehicle into its near-circular 45 deg inclined orbit at an altitude of 525 km. There is no transfer or parking orbit. It will maintain an altitude between 475 and 575 km using a water-based resistojet propulsion system for 3 years. Whitney 1&2 will deploy from the launch vehicle into a near-circular sun-synchronous orbit at an altitude of 525 km. They will maintain an altitude between 475 and 575 km using a RF xenon propulsion system for 3 years.

# 2. Spacecraft Description

**Physical Description of the Spacecraft:** Capella satellites have a launch mass between 90 kg and 120 kg. Two 500mm x 900mm deployable solar arrays, a 8 $m^2$ deployable antenna and a 3m long boom deploy from the principal bus structure.

All deployables use a frangibolt and motor based deployment system from which no debris will be generated.

Power storage is provided by Lithium-Ion cells. The batteries will be recharged by solar cells mounted on on the two deployable solar panels.

Capella attitude is estimated with an accuracy of 50 arcsec using filtering of sensor data from 2 star trackers, an IMU, sun sensors and a magnetometer. Capella attitude will be controlled by 3 reaction wheels for nominal operation and a 3-axis magnetorquer during detumbling and for wheel desaturation.

**Total satellite mass at launch, including all propellants and fluids:** 90 - 120 kg for all launches.

**Dry mass of satellites at launch, excluding solid rocket motor propellants:** 90 - 120 kg for all launches.

**Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear):** Sequoia will be equipped with a water-based resistojet. It contains 1.5 kg of liquid water that is heated with redundant thermistors to ensure the water stays liquid. The maximum thrust force is 25 mN. Whitney 1&2 will be equipped with a propulsion system for station keeping. The baseline system is a xenon-based RF magnetic thruster from Phase Four. It is an electromagnetic electric propulsion system that accelerates the xenon propellant using magnetic mechanisms. It uses 1 $kg$ of xenon for a maximum thrust force of 6 $mN$.

**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:** For Sequoia, the tanks will not be pressurized and will only contain up to 1.5 kg of water. The maximum pressure is less than 100 psia. On Whitney 1&2, the only fluid will be in the propulsion system tank. There will be 1.0 *kg* of xenon propellant. Xenon will be loaded onto the system to a target density which equates approximately 1,200 *psia* at room temperature (25degC). The maximum operating pressure (MEOP) that the system will experience is 3,000 *psia* at 75degC assuming a full propellant load. The propulsion system can be filled with propellant either as a standalone system of while integrated into the satellite bus via external-facing fluid and electronic interface locations. Phase Four has designed and built ground support equipment to achieve the desired xenon density load. The design has been verified using the approach described in MIL-STD-1522A, approach B (page 28).

**Fluids in Pressurized Batteries:** None. Capella uses unpressurized standard Lithium-Ion battery cells. Each battery has a height of 65mm, a diameter of 18mm.

**Description of attitude control system and indication of the nominal attitude of the spacecraft:** Capella uses 3 magnetic rods to despin the satellites during the initial tumbling phase. 3 reaction wheels oriented in the direction of the principal axes allow 3-axis control during nominal operation. The magnetorquers are also used for desaturation of the wheels. The nominal attitude will be with the solar panels in the radial direction (R for radial) and the SAR antenna pointing in the nadir direction (-R). At the end of operations, the 3-axis controller can be used to rotate the satellite into maximum drag configuration, with the SAR antenna in the opposite direction of the velocity (-T for tangential), to accelerate orbital decay.

# 3. Spacecraft Debris Released during Normal Operations

## Requirement 4.3-1: Debris passing through LEO, released debris with diameters of 1mm or larger

No release of debris will occur during the lifetime of Capella satellites. All deployments use a frangibolt and motor based system that does not generate any debris. Additionally, there is no probable scenario for unintentional debris generation.

**Result for Requirement 4.3-1:** COMPLIANT

## Requirement 4.3-2: Debris passing near GEO

There will be no intentional release of debris during the lifetime of the mission, as Capella's mission is contained in Low Earth Orbit.

**Result for Requirement 4.3-2:** COMPLIANT

# 4. Spacecraft Intentional Breakups and Potential for Explosions

## Requirement 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

The probability of battery or pressurized tank explosion is very low, believed to be much less than 0.001 and, due to the small mass of the satellite and its short orbital lifetime, the long-term effects of an unlikely explosion on the LEO environment are negligible. During the development process, the heat pipes have been space qualified through pressure testing, burst pressure testing, vibration testing and thermal vacuum cycling. At the end of the 3 years of nominal operations, any leftover propellant can be used to accelerate the reentry of the satellite.

**Failure mode 1:** Internal short circuit.

*Mitigation 1:* Qualification and acceptance shock, vibration, thermal cycling, and vacuum tests followed by maximum system rate-limited charge and discharge will prove that no internal short circuit sensitivity exists.

*Combined faults required for realized failure:* Environmental testing AND functional charge / discharge tests must both be ineffective in discovery of the failure mode.

**Failure mode 2:** Internal thermal rise due to high load discharge rate.

*Mitigation 2:* Cells will be tested in lab for high load discharge rates in a variety of flight like configurations to determine if the feasibility of an out of control thermal rise in the cell. Cells will also be tested in a hot environment to test the upper limit of the cells capability.

*Combined faults required for realized failure:* Spacecraft thermal design must be incorrect

AND external over current detection and disconnect function must fail to enable this failure mode.

**Failure mode 3:** Excessive discharge rate or short circuit due to external device failure or terminal contact with conductors not at battery voltage levels (due to abrasion or inadequate proximity separation).

*Mitigation 3:* This failure mode will be negated by a) qualification tested short circuit protection on each external circuit, b) design of battery packs and insulators such that no contact with nearby board traces is possible without being caused by some other mechanical failure, c) obviation of such other mechanical failures by proto-qualification and acceptance environmental tests (shock, vibration, thermal cycling, and thermal-vacuum tests).

*Combined faults required for realized failure:* An external load must fail/short-circuit AND external over-current detection and disconnect function must all occur to enable this failure mode.

**Failure mode 4:** Inoperable vents.

*Mitigation 4:* Battery vents are not inhibited by the battery holder design or the spacecraft.

*Combined faults required for realized failure:* The manufacturer fails to install proper venting.

**Failure mode 5:** Crushing.

*Mitigation 5:* This mode is negated by spacecraft design. There are no moving parts in the proximity of the batteries.

*Combined faults required for realized failure:* A catastrophic failure must occur in an external system AND the failure must cause a collision sufficient to crush the batteries leading to an internal short circuit AND the satellite must be in a naturally sustained orbit at the time the crushing occurs.

**Failure mode 6:** Low level current leakage or short-circuit through battery pack case or due to moisture-based degradation of insulators.

*Mitigation 6:* These modes are negated by a) battery holder/case design made of non-conductive plastic, and b) operation in vacuum such that no moisture can affect insulators.

*Combined faults required for realized failure:* Abrasion or piercing failure of circuit board coating or wire insulators AND dislocation of battery packs AND failure of battery terminal insulators AND failure to detect such failures in environmental tests must occur to result in this failure mode.

**Failure mode 7:** Excess temperatures due to orbital environment and high discharge combined.

*Mitigation 7:* The spacecraft thermal design will negate this possibility. Thermal rise will be analyzed in combination with space environment temperatures showing that batteries do not exceed normal allowable operating temperatures which are well below temperatures of concern for explosions.

*Combined faults required for realized failure:* Thermal analysis AND thermal design AND mission simulations in thermal-vacuum chamber testing AND over-current monitoring and control must all fail for this failure mode to occur.

**Result for Requirement 4.4-1:** COMPLIANT

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

Passivation will happen naturally at the end of mission by depletion of any remaining energy contained in the batteries (either through uncontrolled tumbling in case of ADCS failure or attitude control in case of nominal ADCS operations) and natural orbit decay and re-entry within 5 years.

**Result for Requirement 4.4-2:** COMPLIANT

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

There are no planned breakup during the mission.

**Result for Requirement 4.4-3:** COMPLIANT

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

There are no planned breakup during the mission.

**Result for Requirement 4.4-4:** COMPLIANT

# 5. Spacecraft Potential for On-Orbit Collisions

Since the orientation of the spacecraft during operations will vary, the probability of collision with other objects is computed in the worst case scenario of the SAR antenna being in the direction tangential to the velocity. DAS v2.1.1 is used for orbit and collision analysis. It is to be noted that Capella's on-orbit collision avoidance scheme has already been implemented and TESTED SUCCESSFULLY on orbit.

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

The worst case initial orbit of Sequoia is a circular orbit at an altitude of 575 km and an inclination of 45deg. The aera/mass ratio of the spacecraft is 0.028 $m^2/kg$ in the worst-case attitude. The computed probability of collision with large objects for Sequoia is 0.00003. The worst case initial orbit of Whitney is a circular orbit at an altitude of 575 km and an inclination of 97.5deg. The aera/mass ratio of the spacecraft is 0.028 $m^2/kg$ in the worst-case attitude. The computed probability of collision with large objects for a Whitney satellite is 0.0001. The compounded probability of collision with a large object for the 3 satellites is 0.00023, below the maximum acceptable probability of 0.01.

**Result for Requirement 4.5-1:** COMPLIANT

## Requirement 4.5-2. Limiting the probability of damage from small objects when operating in Earth or lunar orbit

The component critical for post-mission operations are the communication hardware, the attitude control system, the solar panels and the batteries. The results for each critical subsystem, for a Capella satellite, are given in the table below. The probability of damage from small objects for Sequoia is computed to be 0.00005. The probability of damage from small objects for Whitney is computed to be 0.00033.

The probability of damage from small objects for the 3 satellites is 0.00077, below the 0.01 requirement.

Table 1: Small Object Damage Analysis for Sequoia

| Critical Surface | Probability of Penetration |
|---|---|
| ADCS | 0.000008 |
| COMS | 0.000004 |
| Solar Panels | 0.000096 |
| Batteries | 0.000002 |
| **Probability of PMD Failure** | **0.00011** |

Table 2: Small Object Damage Analysis for Whitney

| Critical Surface | Probability of Penetration |
|---|---|
| ADCS | 0.000029 |
| COMS | 0.000014 |
| Solar Panels | 0.00028 |
| Batteries | 0.000006 |
| **Probability of PMD Failure** | **0.00033** |

**Result for Requirement 4.5-2:** COMPLIANT

# 6. Spacecraft Post-mission Disposal Plans and Procedures

The orbit of the satellite will decay because of atmospheric drag and the satellites will eventually naturally de-orbit by atmospheric reentry. At the end of the spacecraft lifetime, Capella will begin the deorbit process. At the end of the mission operations, Capella will use the attitude control system to orient the satellites into a maximum drag configuration with the solar panels and SAR antenna in the direction of the velocity, accelerating the orbital decay. These high-drag periods will be interleaved with sun-pointing periods to ensure spacecraft reserve power is maintained throughout the deorbit process. Capella will maintain enough fuel in the propulsion system to maintain maneuverability as the spacecraft passes through the ISS and Tiangong-2 orbits. In the case where there propellant in excess of what is needed to safely traverse the space station orbits it will be used in a series of propulsive maneuvers to further accelerate orbital decay and reentry. Even in the case of ADCS failure and tumbling spacecraft at end of life, all Capella satellites will de-orbit well within the maximum allowable 25 year lifetime. This analysis is assuming a worst-case scenario, for lifetime purposes, of a tumbling spacecraft.

## Requirement 4.6-1. Disposal for space structures in or passing through LEO

The altitude of the satellite is computed from its worst case initial circular orbits at the altitude of 575 km, in its end of mission configuration. The average area to mass ratio for the tumbling spacecraft is used ($0.035\ m^2/kg$). The lifetime of Sequoia and Whitneys with no orbit maintenance are computed by DAS to be 2.18 years and 2.00 years, respectively, for a maximum orbital lifetime, after 3 years of operations, of 5.18 years and 5.00 years, much below the 25 year orbital lifetime threshold.

**Result for Requirement 4.6-1:** COMPLIANT

## Requirement 4.6-2. Disposal for space structures near GEO

There are no space structures near GEO involved in this mission.

**Result for Requirement 4.6-2:** COMPLIANT

## Requirement 4.6-3. Disposal for space structures between LEO and GEO

There are no space structures between LEO and GEO involved in this mission.

**Result for Requirement 4.6-3:** COMPLIANT

## Requirement 4.6-4. Reliability of post-mission disposal operations in Earth orbit

The above analysis has been performed with an average area to mass ratio, which means that even in the case of massive power or ADCS failure, a tumbling spacecraft, the spacecrafts will deorbit in a worst case of 6 years.

**Result for Requirement 4.6-4:** COMPLIANT

# 7. Spacecraft Reentry Debris Casualty Risks

## Requirement 4.7-1. Limit the risk of human casualty

The risk of human casualty was computed by DAS v2.1.1 for an uncontrolled reentry to be 1:100000000 for the Sequoia and 1:100000000 for Whitney satellites. The spacecraft models and results are summarized in the tables below.

Table 3: Spacecraft Model

| Component | Subcomponent |
|---|---|
| Bus | |
| | Batteries |
| | Reaction Wheels |
| | Avionics |
| | Propulsion Tanks |
| | Radio Stack 1 |
| | Radio Stack 2 |
| SAR Antenna | |
| Solar Array | |
| Torque Rods | |
| Star Trackers | |
| Thruster | |
| Antennae | |
| Payload | |

Table 4: Human Casualty Risk Analysis - Sequoia

| Component | Qty | Material | Shape | Mass (kg) | Dem. Alt. (km) | Cas. Area (m^2) | En. (J) |
|---|---|---|---|---|---|---|---|
| Bus Structure | 1 | Aluminum | Box | 24 | 63.0 | 0 | 0 |
| Batteries | 64 | Aluminum | Cylinder | 0.0625 | 76.5 | 0 | 0 |
| Reaction Wheels | 3 | Aluminum | Cylinder | 3.2 | 63.1 | 0 | 0 |
| Avionics | 1 | Aluminum | Box | 24.7 | 62.6 | 0 | 0 |
| Tanks | 1 | Titanium | Box | 0.5 | 73.9 | 0 | 0 |
| Radio Stack 1 | 1 | Aluminum | Box | 1 | 71.4 | 0 | 0 |
| Radio Stack 2 | 1 | Aluminum | Box | 2.5 | 63.1 | 0 | 0 |
| SAR Antenna | 40 | Aluminum | Cylinder | 0.5 | 75.0 | 0 | 0 |
| Solar Array | 2 | Aluminum | Flat Plate | 2.4 | 74.7 | 0 | 0 |
| Torque Rods | 3 | Copper | Cylinder | 0.6 | 72.0 | 0 | 0 |
| Star Trackers | 2 | Aluminum | Box | 0.3 | 74.8 | 0 | 0 |
| Thruster | 1 | Aluminum | Box | 2.5 | 63.1 | 0 | 0 |
| Payload | 1 | Aluminum | Box | 4 | 65.0 | 0 | 0 |

Table 5: Human Casualty Risk Analysis - Whitney

| Component | Qty | Material | Shape | Mass (kg) | Dem. Alt. (km) | Cas. Area (m^2) | En. (J) |
|---|---|---|---|---|---|---|---|
| Bus Structure | 1 | Aluminum | Box | 24 | 65.6 | 0 | 0 |
| Batteries | 64 | Aluminum | Cylinder | 0.0625 | 76.4 | 0 | 0 |
| Reaction Wheels | 3 | Aluminum | Cylinder | 3.2 | 66.0 | 0 | 0 |
| Avionics | 1 | Aluminum | Box | 24.7 | 49.8 | 0 | 0 |
| Tanks | 1 | Aluminum | Box | 0.5 | 75.8 | 0 | 0 |
| Radio Stack 1 | 1 | Aluminum | Box | 1 | 72.3 | 0 | 0 |
| Radio Stack 2 | 1 | Aluminum | Box | 2.5 | 65.2 | 0 | 0 |
| SAR Antenna | 40 | Aluminum | Cylinder | 0.5 | 74.5 | 0 | 0 |
| Solar Array | 2 | Aluminum | Flat Plate | 2.4 | 75.6 | 0 | 0 |
| Torque Rods | 3 | Copper | Cylinder | 0.6 | 73.8 | 0 | 0 |
| Star Trackers | 2 | Aluminum | Box | 0.3 | 75.1 | 0 | 0 |
| Thruster | 1 | Aluminum | Box | 2.5 | 65.2 | 0 | 0 |
| Payload | 1 | Aluminum | Box | 4 | 66.7 | 0 | 0 |

**Result for Requirement 4.7-1:** COMPLIANT

# 8. Collision risk posed by tether systems

## Requirement 4.8-1. Mitigate the collision hazards of space tethers in Earth or Lunar orbits

No tethers are to be used in Capella missions.

**Result for Requirement 4.8-1:** COMPLIANT

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**END OF ODAR FOR CAPELLA**

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|---|---|
| **Approved**: | Lucas Riggi |
| | Constellation Architect |
| | 09/10/2020 |