Capella 9&10 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, 9/13/2022

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

DAS Software Version Used In Analysis: v3.2.2

VERSION APPROVAL and/or FINAL APPROVAL:

Christian Lenz, CTO

PREPARED BY:

Lucas Riggi, System & 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 satellites. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

Orbital Debris Self-Assessment Report Evaluation: Capella 910 Mission

(based upon ODAR version 2, dated September 13, 2022)

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: Christian Lenz

Mission Overview: Capella 9 & 10 will be launched no earlier than January 2023, on a circular inclined orbit with an altitude between 550 km and 650 km. The maximum nominal operational altitude will be 650 km. The launch operational inclination of the spacecrafts will be 44 deg and the spacecrafts will operate between a maximum altitude of 650 km and a minimum altitude of 550 km. For the purposes of this document, the worst case altitude of 650 km will be used during the mission duration of 3 years, after which the satellites will reenter the atmosphere through natural orbit decay. During the 3 year mission duration, Capella expects normal operations of Capella 9 & 10 to be in the range of 550 km to 625 km, however, the initial deployment of the satellites during launch could be up to 650 km. As the satellites experience natural orbital decay, Capella anticipates continuing to conduct imaging operations down to approximately 450 km. But this lower operational altitude is not considered to be a nominal operational altitude.

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 (as calculated by DAS 3.2.2) and there is a 0 probability of human casualty after orbital reentry.

Launch: Capella 9 & 10 are currently planned to be launched on a Rocket Lab rocket, no earlier than January 10, 2023.

Mission Duration: Maximum Nominal Operations: 3 years, Post-Operations Orbit lifetime: less than 3 years until reentry via atmospheric orbital decay (worst case less than 6 years in total).

Orbit Profile: Capella 9 & 10 will deploy from the launch vehicle into a near-circular inclined orbit at an altitude of 650 km, at an inclination of 44 degrees. They will maintain an altitude between 650 and 550 km using a RF xenon propulsion system for 3 years of operational mission.

2. Spacecraft Description

Physical Description of the Spacecraft: Capella satellites have a launch mass between 110 kg and 115 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: 110 - 115 kg for all launches.

Dry mass of satellites at launch, excluding solid rocket motor propellants: 110 - 115 kg for all launches.

Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear): Capella 9 & 10 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 1.3 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: On Capella 9 & 10, the only fluid will be in the propulsion system tank. There will be 1.3 kg of xenon propellant. Xenon will be loaded onto the system to a target density which equates approximately 1,300 $psia$ 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 of the propulsion system has been verified using the approach described in MIL-STD-1522A, approach B (page 28).

Fluids in Pressurized Batteries: None. Capella 9 & 10 use 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 9 & 10 use 3 magnetic rods to despin the satellites during the initial tumbling phase after deployment from the launch vehicle. 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 during nominal operations. 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, if desired.

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 9 & 10 satellites. All deployments use a frangibolt and motor based systems that do 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 9 & 10'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 with the average area to mass ratio of 0.039. DAS v3.2.2 is used for orbit and collision analysis. It is to be noted that Capella 9 & 10's on-orbit collision avoidance scheme has already been implemented and TESTED SUCCESSFULLY on orbit. Additionally, Capella's spacecrafts have a combined 10+ years on orbit with no collisions or spacecraft failures.

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

The worst case initial orbit of Capella 9 & 10 is a circular orbit at an altitude of 650 km and an inclination of 44deg. The aera/mass ratio of the spacecraft is 0.039 m^2/kg in the average attitude. The computed probability of collision with large objects for the individual satellites is 8.7354e-5. The compounded probability of collision with a large object for the combined Capella 9 & 10 satellites is 0.00018, below the maximum acceptable probability of 0.001.

The detailed results including the DAS logs are reported in Appendix A.1.

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

Capella 9 & 10 do not need active post-mission disposal. The natural orbital decay of the spacecrafts will happen within 6 years, without the need for post-mission disposal maneuvers. However, Capella still wants to understand the probability that control subsystems would become disabled before spacecraft reentry, and the likelihood that Capella 9 & 10 could perform any desired maneuvers during the lifetime of the satellites. The component critical for spacecraft control operations are the systems that will enable the control of the attitude and orbit of the spacecraft. Namely, the Attitude Control System (reaction wheels, torque rods, control avionics) and the Propulsion System. The results for each critical subsystem, for Capella 9 & 10, are given in the table below. The detailed results from the DAS logs are reported in Appendix A.2. The probability of damage from small objects for the individual spacecrafts is computed to be 0.003115.

The probability of damage from small objects for the 2 combined Capella 9 & 10 satellites is 0.006231, below the 0.01 requirement.

Table 1: Small Object Damage Analysis for Capella 9 & 10

Critical Surface	**Probability of Penetration**
ADCS Avionics	1.5608e-4
RW1	5.1660e-7
RW2	5.1660e-7
RW3	5.1660e-7
TR1	1.0020e-5
TR2	1.0020e-5
TR3	1.0020e-5
Prop System	2.9282e-3
Probability of PMD Failure	**0.003115**

Result for Requirement 4.5-2: COMPLIANT

6. Spacecraft Post-mission Disposal Plans and Procedures

The orbit of the Capella 9 & 10 satellites 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 9 & 10 will begin 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 is propellant in excess of what is needed to safely traverse the space station orbits, it can be used in a series of propulsive maneuvers to further accelerate orbital decay and reentry. The natural reentry of the Capella 9 & 10 satellites will happen within 3 years after the end of nominal operations.

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

The altitudes of Capella-9 and Capella-10 are computed from their worst-case initial circular orbits at the altitude of 650 km, in its end of mission configuration. The average area to mass ratio for the tumbling spacecraft is used (0.039 m^2/kg). A prediction of the solar flux f10.7 index that will reach 230 sfu in the year 2025 is used, to match the current behavior of solar activity predictions. The lifetime of Capella 9 & 10 with no orbit maintenance is computed by DAS to be 2.721 years. After 3 years of orbit maintenance at 650 km, the spacecrafts will deorbit within 2.872 years, for a maximum lifetime of less than 6 years. The detailed DAS logs are reported in Appendix A.3.

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

Capella has 7 spacecrafts on orbit that have a combined lifetime of more than 10 years. Capella has performed thousands of routine collision avoidance maneuvers and orbit raising and maintenance maneuvers for several years on orbit.

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 v3.2.2 for an uncontrolled reentry to be 0 for Capella 9 & 10. The spacecraft model is summarized in the tables below. The detailed DAS results can be found in the logs provided with this report in Appendix A.4.

Table 2: Spacecraft Model

Component	**Subcomponent**
Bus	
	Bus Structure
	Batteries
	Reaction Wheels
	ADCS Avionics
	Propulsion Tanks
	Radio Stack 1
	Radio Stack 2
	IDRS Terminal
	GPS Box
	Avionics
SAR Antenna	
	SAR Antenna Battens
	SAR Antenna Ribs
	SAR Antenna Hub
	Boom
Solar Array	
Torque Rods	
Star Trackers	
Thruster	
Antennae	
Payload	

There are a number of carbon fiber epoxy components in the satellites. These components are being modelled in DAS using the default properties of Graphite Epoxy 1.

Table 3: Human Casualty Risk Analysis - Capella 9&10

Component	Qty	**Material**	**Shape**	**Mass (kg)**	**Dem. Alt. (km)**	**Cas. Area (m^2)**	**En. (J)**
Bus Structure	1	Aluminum	Box	32	67.5	0	0
Batteries	64	Aluminum	Cylinder	0.0625	77.6	0	0
Reaction Wheels	3	Aluminum	Cylinder	3.2	65.6	0	0
ADCS Avionics	1	Aluminum	Box	0.8	74.5	0	0
Avionics	1	Aluminum	Box	15.0	60.2	0	0
Tank	1	Aluminum	Box	1.5	72.4	0	0
Radio Stack 1	1	Aluminum	Box	2.5	69.1	0	0
Radio Stack 2	1	Aluminum	Box	2.5	69.1	0	0
Ant Battens	13	Carb Fiber	Cylinder	0.4	77.7	0	0
Solar Array	2	Carb Fiber	Flat Plate	2.4	77.6	0	0
Torque Rods	3	Copper	Cylinder	0.6	74.4	0	0
Star Trackers	2	Aluminum	Box	0.3	76.0	0	0
Thruster	1	Aluminum	Box	2.5	69.1	0	0
Payload	1	Aluminum	Box	4	70.0	0	0
Boom	3	Carb Fiber	Cylinder	1.3	77.5	0	0
SAR Ant Ribs	13	Aluminum	Flat Plate	0.5	77.5	0	0
SAR Ant Hub	1	Aluminum	Box	5	66.6	0	0
IDRS Terminal	1	Aluminum	Box	1.2	74.1	0	0
GPS Box	1	Aluminum	Box	1	75.7	0	0
IDRS Antenna	1	Aluminum	Box	1	75.0	0	0
GPS Antenna	1	Aluminum	Box	0.5	76.6	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

END OF ODAR FOR CAPELLA

Approved: Lucas Riggi
Senior Space Systems Engineer
9/13/2022

Appendix A.1 – Requirement 4.5-1 – DAS Logs

09 13 2022; 10:55:31AM Processing Requirement 4.5-1: Return Status : Passed

==============
Run Data
==============

INPUT

Space Structure Name = Capella9
Space Structure Type = Payload
Perigee Altitude = 650.000 (km)
Apogee Altitude = 650.000 (km)
Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0390 (m^2/kg)
Start Year = 2023.000 (yr)
Initial Mass = 110.000 (kg)
Final Mass = 108.000 (kg)
Duration = 3.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 8.7354E-05
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

==============

INPUT

Space Structure Name = Capella10
Space Structure Type = Payload
Perigee Altitude = 650.000 (km)
Apogee Altitude = 650.000 (km)
Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0390 (m^2/kg)
Start Year = 2023.000 (yr)

Initial Mass = 110.000 (kg)
Final Mass = 108.000 (kg)
Duration = 3.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 8.7354E-05
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

==============

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

Appendix A.2 – Requirement 4.5-2 – DAS Logs

09 13 2022; 11:29:53AM Requirement 4.5-2: Compliant

==
Spacecraft = Capella9
Critical Surface = TR1
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1 Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella9
Critical Surface = TR2
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)

Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella9
Critical Surface = TR3
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella9
Critical Surface = RW1
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella9
Critical Surface = RW2
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)

Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella9
Critical Surface = RW3
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella9
Critical Surface = ADCS Avionics
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 3.700 (g/cm^2)
CS Surface Area = 0.0100 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1 Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.5608E-04 (1.5609E-04)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella9
Critical Surface = Prop Tank
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)

Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 2.500 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = Yes
Outer Wall 1   Density: 3.000 (g/cm^2) Separation: 1.000 (cm)
Outer Wall 2   Density: -1.000 (g/cm^2) Separation: -1.000 (cm)

OUTPUT

Probability of Penetration = 2.9282E-03 (2.9325E-03)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella10
Critical Surface = TR1
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella10
Critical Surface = TR2
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella10
Critical Surface = TR3
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)

RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 7.500 (g/cm^2)
CS Surface Area = 0.0060 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1 Density: 0.100 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.0020E-05 (1.0020E-05)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella10
Critical Surface = RW1
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1 Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella10
Critical Surface = RW2
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella10
Critical Surface = RW3
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)

RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 16.000 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 5.1660E-07 (5.1660E-07)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

===
Spacecraft = Capella10
Critical Surface = ADCS Avionics
===

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 3.700 (g/cm^2)
CS Surface Area = 0.0100 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = No
Outer Wall 1   Density: 2.000 (g/cm^2) Separation: 0.100 (cm)

OUTPUT

Probability of Penetration = 1.5608E-04 (1.5609E-04)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

==
Spacecraft = Capella10
Critical Surface = Prop Tank
==

INPUT

Apogee Altitude = 650.000 (km)
Perigee Altitude = 650.000 (km)
Orbital Inclination = 44.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass = 0.0390 (m^2/kg)
Initial Mass = 108.000 (kg)
Final Mass = 108.000 (kg)
Station Kept = Yes
Start Year = 2023.000 (yr)
Duration = 3.000 (yr)
Orientation = Random Tumbling
CS Areal Density = 2.500 (g/cm^2)
CS Surface Area = 0.0200 (m^2)
Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))
CS Pressurized = Yes
Outer Wall 1   Density: 3.000 (g/cm^2) Separation: 1.000 (cm)
Outer Wall 2   Density: -1.000 (g/cm^2) Separation: -1.000 (cm)

OUTPUT

Probability of Penetration = 2.9282E-03 (2.9325E-03)
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range

=============== End of Requirement 4.5-2 ===============

Appendix A.3 – Requirement 4.6-1 – DAS Logs

09 13 2022; 10:27:50AM Science and Engineering - Orbit Lifetime/Dwell Time

INPUT

Start Year = 2023.000000 (yr)
Perigee Altitude = 650.000000 (km)
Apogee Altitude = 650.000000 (km)
Inclination = 44.000000 (deg)
RAAN = 0.000000 (deg)
Argument of Perigee = 0.000000 (deg)
Area-To-Mass Ratio = 0.039000 (m^2/kg)

OUTPUT

Orbital Lifetime from Startyr = 2.721424 (yr)
Time Spent in LEO during Lifetime = 2.721424 (yr)
Last year of Propagation = 2025 (yr)
Returned Error Message: Object reentered

09 13 2022; 10:28:23AM Science and Engineering - Orbit Lifetime/Dwell Time

INPUT

Start Year = 2026.000000 (yr)
Perigee Altitude = 650.000000 (km)
Apogee Altitude = 650.000000 (km)
Inclination = 44.000000 (deg)
RAAN = 0.000000 (deg)
Argument of Perigee = 0.000000 (deg)
Area-To-Mass Ratio = 0.039000 (m^2/kg)

OUTPUT

Orbital Lifetime from Startyr = 2.872005 (yr)
Time Spent in LEO during Lifetime = 2.872005 (yr)
Last year of Propagation = 2028 (yr)
Returned Error Message: Object reentered

Appendix A.4 – Requirement 4.7-1 – DAS Logs

09 08 2022; 11:07:13AM *********Processing Requirement 4.7-1
Return Status : Passed

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

name = Capella9
quantity = 1
parent = 0
materialID = 5
type = Box
Aero Mass = 108.000000
Thermal Mass = 108.000000
Diameter/Width = 0.300000
Length = 1.000000
Height = 0.300000

name = Batteries
quantity = 64
parent = 1
materialID = 5
type = Cylinder
Aero Mass = 0.062500
Thermal Mass = 0.062500
Diameter/Width = 0.020000
Length = 0.100000

name = Bus Structure
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 32.000000
Thermal Mass = 32.000000
Diameter/Width = 0.300000
Length = 0.800000
Height = 0.300000

name = RW
quantity = 3
parent = 1
materialID = 5

type = Cylinder
Aero Mass = 3.200000
Thermal Mass = 3.200000
Diameter/Width = 0.100000
Length = 0.150000

name = ADCS Avionics
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 0.800000
Thermal Mass = 0.800000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.080000

name = TR
quantity = 3
parent = 1
materialID = 19
type = Cylinder
Aero Mass = 0.600000
Thermal Mass = 0.600000
Diameter/Width = 0.030000
Length = 0.200000

name = Star Tracker
quantity = 2
parent = 1
materialID = 5
type = Box
Aero Mass = 0.300000
Thermal Mass = 0.300000
Diameter/Width = 0.050000
Length = 0.100000
Height = 0.050000

name = Prop Tank
quantity = 1
parent = 1
materialID = 5
type = Cylinder
Aero Mass = 1.500000

Thermal Mass = 1.500000
Diameter/Width = 0.100000
Length = 0.200000

name = Thruster
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 2.500000
Thermal Mass = 2.500000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.100000

name = Radio Stack 1
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 2.500000
Thermal Mass = 2.500000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.100000

name = Radio Stack 2
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 2.500000
Thermal Mass = 2.500000
Diameter/Width = 0.100000
Length = 0.100000
Height = 0.100000

name = Solar Array
quantity = 2
parent = 1
materialID = -1
type = Flat Plate
Aero Mass = 2.800000
Thermal Mass = 2.800000

Diameter/Width = 0.500000
Length = 0.900000

name = Payload Box
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 4.000000
Thermal Mass = 4.000000
Diameter/Width = 0.100000
Length = 0.200000
Height = 0.100000

name = IDRS Terminal
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 1.000000
Thermal Mass = 1.000000
Diameter/Width = 0.110000
Length = 0.120000
Height = 0.070000

name = GPS Box
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 1.000000
Thermal Mass = 1.000000
Diameter/Width = 0.110000
Length = 0.180000
Height = 0.100000

name = HDR Antenna
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 1.000000
Thermal Mass = 1.000000
Diameter/Width = 0.100000

Length = 0.200000
Height = 0.050000

name = GPS LGA
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 0.500000
Thermal Mass = 0.500000
Diameter/Width = 0.100000
Length = 0.300000
Height = 0.020000

name = Boom
quantity = 3
parent = 1
materialID = -1
type = Cylinder
Aero Mass = 1.500000
Thermal Mass = 1.500000
Diameter/Width = 0.075000
Length = 1.000000

name = SAR Antenna Ribs
quantity = 13
parent = 1
materialID = 54
type = Flat Plate
Aero Mass = 0.100000
Thermal Mass = 0.100000
Diameter/Width = 0.010000
Length = 1.500000

name = SAR Antenna Battens
quantity = 13
parent = 1
materialID = -1
type = Cylinder
Aero Mass = 0.400000
Thermal Mass = 0.400000
Diameter/Width = 0.050000
Length = 0.600000

name = SAR Antenna Hub
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 6.000000
Thermal Mass = 6.000000
Diameter/Width = 0.150000
Length = 0.150000
Height = 0.150000

name = Avionics
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 15.000000
Thermal Mass = 15.000000
Diameter/Width = 0.200000
Length = 0.200000
Height = 0.200000

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

name = Capella9
Demise Altitude = 77.995755
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Batteries
Demise Altitude = 76.598455
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Bus Structure
Demise Altitude = 67.458737
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = RW

Demise Altitude = 65.647091
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = ADCS Avionics
Demise Altitude = 74.496730
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = TR
Demise Altitude = 74.440722
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Star Tracker
Demise Altitude = 76.028349
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Prop Tank
Demise Altitude = 72.444340
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Thruster
Demise Altitude = 69.082375
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Radio Stack 1
Demise Altitude = 69.082375
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Radio Stack 2
Demise Altitude = 69.082375
Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****
name = Solar Array
Demise Altitude = 77.574503
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Payload Box
Demise Altitude = 70.042232
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = IDRS Terminal
Demise Altitude = 74.101690
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = GPS Box
Demise Altitude = 75.707467
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = HDR Antenna
Demise Altitude = 75.025770
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = GPS LGA
Demise Altitude = 76.564867
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Boom
Demise Altitude = 77.461227
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = SAR Antenna Ribs
Demise Altitude = 77.521199
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = SAR Antenna Battens
Demise Altitude = 77.692522
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = SAR Antenna Hub
Demise Altitude = 66.590856
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Avionics
Demise Altitude = 60.171788
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
=============== End of Requirement 4.7-1 ===============