Supplementary Material for

A Multi-Lander New Frontiers Mission Concept Study for Enceladus: SILENUS

**Erica Nathan1\*, Katiyayni Balachandran2, Paolo Cappuccio3, Julia Di4, Kelsey Doerksen5, Alessia Gloder6, Monica Li7, Lotfi Massarweh8, Thomas Peev9, Shreya Santra10, Marc Rovira-Navarro11, Dan Limonchik12**

1Brown University, Department of Earth, Environmental, and Planetary Sciences, Providence, RI, United States

2In Orbit Aerospace, Torrance, CA, United States

3Sapienza University of Rome, Italy

4Stanford University, Department of Mechanical Engineering, Stanford, CA, United States

5University of Oxford, Department of Computer Science, United Kingdom

6Technische Universität Dresden, Chair of Space Systems, Germany

7University of California at Berkeley, Department of Mechanical Engineering, Berkeley, CA, United States

8Delft University of Technology, The Netherlands.

9Benchmark Space Systems, Burlington, VT, United States

10Tohoku University, Department of Aerospace Engineering, Sendai, Japan

11University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ, United States

12Product Design Manager, Brevitē LLC, United States

**\* Correspondence:**Erica Nathan  
erica\_nathan@brown.edu

# Supplementary Figures and Tables

## Supplementary Tables

**Table S1:** List of instruments for data collection and storage, from section 4.2.3.

|  |  |
| --- | --- |
| **Instrument** | **Data Estimates** |
| **Mass Spec (Orbiter)** | 9k bits/flyby  Min: 10 flybys for science |
| **Capillary electrophoresis** | 192 kbits/flyby  Min: 10 flyby |
| **Ion selective electrodes (ISE)** | 348 bits/flyby  Min: 10 flyby |
| **Altimeter** | 1130 bits/s  Requires sample per flyby |

**Table S2:** Component cost by spacecraft subsystem, from section 5.1. Includes unit prices and approximations.

|  |  |  |
| --- | --- | --- |
| **Subsystem** | **Component** | **Price** |
| ADCS | Digital Electronics | $62.43 K/lb |
|  | Sensor | $9.54 M |
|  | Reaction Wheel Assembly | $2.68 M |
| Communications\* | Antenna | $44.44 K/lb |
|  | Transmitter | $87.57 K/lb |
|  | Transponder | $68.67 K/lb |
|  | 1 to 10 channels | $5442.33 K/channel |
|  | 11 to 25 channels | $1824.62 K/channel |
| EPS | Average cost | $13.34 K/lb |
|  | Average cost | $8.12 K/Watt |
|  | Battery at Beginning-of-life (BOL) - 1 to 1000 W | $10.36 K/Watt |
|  | Power Conditioning & Distribution | $13.98 K/lb |
| IA&T | % of spacecraft cost | 46% |
| Propulsion | Propellant reaction control system (RCS) with Apogee kick motors (AKM) | $17.58 K/lb |

\*Communications subsystem prices were not available for Science/Surveillance mission type. Instead, these values were obtained from Communication/Navigation/Environmental mission type. Costs are for components with MILSTAR.

**Table S3:** Spacecraft Power Budget, from section 5.2. Power requirements for select subsystems. Budget is based on Worst-case Power Requirements

|  |  |
| --- | --- |
| **Instrument** | **Peak Power (W)** |
| **Mass Spectrometer** | 50 |
| **Capillary electrophoresis** | 15 |
| **Ion selective electrodes** | 3 |
| **Altimeter** | 20 |
| **Onboard Computer** | 20 |
| **Peak Comms Operating Power** | 100 |
| **ADCS** | 30 |
| **Propulsion** | 50 |
| **Total:** | **288** |

**Table S4:** Uplink communication budget between Earth’s DSN Station and orbiter, from section 5.2.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Uplink** | | | | | | |
|  | **Modulation: BPSK, QPSK** | |  |  |  |  |
| Transmitter Parameters | | |  | Carrier Performance | | |
| Transmitter Frequency | 9 | GHz |  | Command Carrier suppression | -4.15 | dB |
| Total Transmitter Power | 72.67 | dBm |  | Ranging Carrier Suppression | -3 | dB |
| Tx loss | -0.25 | dBm |  | Carrier Power | -118.05 | dB |
| DSN Antenna Gain | 67.07 | dBi |  | Received Pc/No | 55.49 | dB-Hz |
| Antenna Pointing Loss | -0.1 | dB |  | Carrier Loop Noise BW | 12.58 | dB-Hz |
| EIRP | 139.39 | dBm |  | Carrier Loop SNR(CNR) | 42.91 | dB |
|  |  |  |  | Recommended CNR | 12 | dB |
| Path Parameters | | |  | Carrier Loop SNR Margin | 30.91 | dB |
| Space Loss | -293.1 | dB |  |  |  |  |
| Atmospheric Attenuation | -0.27 | dB |  |  |  |  |
|  |  |  |  | Channel Performance | | |
| Receiver Parameters | | |  | Command Data Suppression | -2.64 | dB |
| Polarization Loss | -0.1 | dB |  | Ranging Data Suppression | -3 | dB |
| S/C Antenna Pointing control Loss | 0 | dB |  | Received Pd/No | 57 | dB-Hz |
| S/C Antenna Gain | 44.7 | dBi |  | 3-sigma Pd/No | 53.79680628 | dB-Hz |
| Obscuration loss | 0 | dB |  | Data Rate | 19.85 | dB-Hz |
| RFS Circuit Loss | -1.95 | dB |  | Spacecraft System Loss | -0.8 | dB |
| Antenna Circuit Loss | -0.2 | dB |  | Available Eb/No | 36.35 | dB |
|  |  |  |  | Required Eb/No | 9.6 | dB |
| Total Power Summary | | |  | Eb/No Margin | 26.75 | dB |
| Total Rcv Power | -111.53 | dBm |  | BER | 5.00E-18 |  |
| Noise Spectral Density | -174.17 | dBm/Hz |  |  |  |  |
| System Noise Temperature | 286.67 | K |  |  |  |  |
| Received Pt/No | 62.64 | dB-Hz |  |  |  |  |

**Table S5:** Downlink communication budget between orbiter and Earth’s DSN Station and orbiter, from section 5.2.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Downlink** | | | | | | |
| Transmitter Parameters | | |  | Carrier Performance | | |
| Transmitter Frequency | 9 | GHz |  | Telemetry Carrier Suppression | -15.52 | dB |
| Total Transmitter Power | 44.7 | dBm |  | Ranging Carrier Suppression | -0.16 | dB |
| S/C Transmitter Loss | -1.2 | dBm |  | DOR Carrier Suppression | 0 | dB |
| S/C Circuit Loss | -0.15 | dBm |  | Carrier Power | -152.41 | dBm |
| S/C Antenna Gain | 46.6 | dBi |  | Received Pc/No | 30.65 | dBm |
| Degrees off Boresight Loss | 0 | dB |  | Carrier Loop Noise BW | 4.77 | dB-Hz |
| S/C Antenna Pointing control Loss | 0 | dB |  | Carrier Loop SNR (CNR) | 25.88 | dBm |
| Obscuration Loss | 0 | dB |  | Recommended CNR | 10 | dB |
| EIRP | 89.95 | dBm |  | Carrier Loop SNR Margin | 15.88 | dB |
|  |  |  |  |  |  |  |
| Path Parameters | | |  | Telemetry Performance | | |
| Space Loss | -294.5 | dB |  | Telemetry Data Suppression | -0.13 | dB |
| Atmospheric Attenuation | -0.27 | dB |  | Ranging Data Suppression | -0.16 | dB |
|  |  |  |  | DOR Data Suppression | 0 | dB |
| Receiver Parameters | | |  | Received Pd/No | 46.04 | dB-Hz |
| DSN Antenna Gain | 68.24 | dBi |  | 2-sigma Pd/No | 45.62987807 | dB-Hz |
| DSN Antenna Pnt Loss | -0.1 | dB |  | Data Rate | 41.53 | dB-Hz |
| Polarization Loss | -0.05 | dB |  | DSN System Loss | -0.5 | dB |
|  |  |  |  | Available Eb/No | 4.01 | dB |
| Total Power Summary | | |  | Required Eb/No | 0.31 | dB |
| Total Rcv Power | -136.73 | dBm |  | Eb/No Margin | 3.7 | dB |
| System Noise Temperature | 35.88 | K |  | BER | 2.0902e–08 |  |
| Noise Spectral Density | -183.06 | dBm/Hz |  |  |  |  |
| Received Pt/No | 46.33 | dB-Hz |  |  |  |  |

**Table S6:** Technology Readiness Matrix, referenced in section 6.3.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **System** | **TRL** | **System Heritage** |
| **Science Instrument** | Mass Spec (Orbiter) | 8 | Europa Mass Spectrometer (MASSPEX) |
| Capillary electrophoresis  Ion selective electrodes (ISE) (Orbiter) | 8 | PISCES  WCL heritage |
| Context Camera (Penetrators) | 8 | OSO-3 Camera |
| Altimeter (Orbiter) | 8 | BELLA - BepiColombo |
| Seismometer (Penetrators) | 5 | N/A |
| **Orbiter Systems** | Thrusters | 9 | Aerojet HiPAT |
| Solar Panel Arrays | 8 | Sol Aero Triple Junction Cells, Dawn |
| Li-Ion Batteries | 9 |  |
| Communication | 8+ | Dual-band Radio communication with Earth DSN and with penetrators |
| Onboard handling | 9 | Cassini |
| Data Storage | 9 | InSight |
| Orbiter Structure | 8 | Cassini-Type Spacecraft, no boom |
| ADCS | 9 | Cassini type |
| MLI | 9 |  |
| Imager | 9 | ICC from Insight |
| Startracker | 9 |  |
| Sun Sensors | 9 |  |
| **Penetrator Systems** | Li-CFx Battery | 4 | Ultralife Li-CFx |
| UHF/VHF band antennas | 8 | CubeSat UHF Antennas |
| Transmitter | 8 | COTS UHF |
| Photon Source | 4 | COTS LED |
| Self-orienting Spacecraft system | 3 | Gravity Vector Sensor with Gyroscope |
| Insulation | 8 | Aerogel |
| Heaters | 9 |  |
|  | Bullet-shaped structure | 3 | Titanium Casing |