Supplementary Material for

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

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# 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/flybyMin: 10 flybys for science |
| **Capillary electrophoresis**  | 192 kbits/flybyMin: 10 flyby |
| **Ion selective electrodes (ISE)** | 348 bits/flybyMin: 10 flyby |
| **Altimeter** | 1130 bits/sRequires 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 electrophoresisIon selective electrodes (ISE) (Orbiter) | 8 | PISCESWCL 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 |