# 13.5 COMMUNICATIONS

The communications subsystem provides ODIN with reliable two-way radio frequency links between the spacecraft and Earth-based ground stations throughout all phases of the heliocentric mission. The subsystem is responsible for three core functions: telemetry downlink of spacecraft housekeeping data and Solar Orbiter inspection science data, telecommand uplink from ground operators, and radio tracking for orbit determination. The subsystem architecture is derived from the Solar Orbiter and BepiColombo communications heritage [17], [18], both of which operate in comparable heliocentric environments and use the same X-band deep space frequency allocation [17], [24].

The primary design drivers for ODIN's communications subsystem are the variable Earth–spacecraft range across the heliocentric orbit, the occurrence of solar conjunction blackout periods during which no communication is possible, the need to downlink compressed inspection imagery at operationally useful data rates, and compatibility with the European Space Tracking Network (ESTRACK) and NASA Deep Space Network (DSN) X-band ground infrastructure [11], [15], [24]. The subsystem is composed of two redundant X-band transponders, two traveling wave tube amplifier assemblies, an RF distribution assembly, a high-gain antenna with two-axis pointing mechanism, and two fixed low-gain antennas providing omnidirectional safe mode coverage.

## 13.5.1 COMMUNICATIONS SUBSYSTEM REQUIREMENTS

The communications requirements for ODIN are established at two levels. System-level requirements define the spacecraft-level obligations for maintaining ground contact, transmitting mission data, receiving commands, and supporting autonomous operations. Subsystem-level requirements flow down from these to define specific constraints on frequency, link margin, data content, and command handling applicable to the communications and command and data handling subsystems respectively.

**Table 13.5.1: Communications Subsystem-Level Requirements**

| SSR-ID | Requirement Type | Description | Verified by | Rationale for requirement | Traces to |
|---|---|---|---|---|---|
| **SSR-COMM-01** | Constraint | The ODIN communication system shall transmit | Analysis (A) & Test (T) | X-band provides the range performance required for heliocentric deep-space | SYS-4-1, SYS-4-2 |

| | | | | | |
|---|---|---|---|---|---|
| | | telemetry and payload data using X-band frequency (7.17 GHz uplink / 8.42 GHz downlink). | | communication and is compatible with ESTRACK 35 m DSAs and the L3Harris UST. | |
| **SSR-COMM-02** | Constraint | The ground system shall be equipped to receive and process X-band telemetry from ODIN at 7.17 GHz uplink / 8.40 GHz downlink. | Review (R) | Ground station antennas and receivers must be compatible with X-band to close the communication link. | SYS-4-2 |
| **SSR-COMM-03** | Performance | The link budget shall maintain ≥6 dB margin at all Earth–spacecraft ranges from 0.7 AU to 2.0 AU across all mission phases. | Analysis (A) | A 6 dB margin ensures robust link closure accounting for pointing losses, atmospheric effects, and range variation during heliocentric orbit. | SYS-4-2 |
| **SSR-COMM-04** | Operational | ODIN shall downlink inspection payload data (imagery, proximity sensor readings) at a rate sufficient to clear each inspection cycle within the available daily ESTRACK contact window. | Analysis (A), Test (T) | Primary mission objective requires transmission of Solar Orbiter inspection data to support mission extension engineering assessment. | SYS-4-1, SYS-4-3 |
| **SSR-COMM-05** | Operational | The ODIN communication system shall downlink spacecraft housekeeping telemetry including temperatures, voltages, | Test (T) | Housekeeping data enables ground operators to monitor spacecraft health and diagnose anomalies throughout the mission. The acceleration data from the ASTRIX200 IMU is required to monitor thruster performance, | SYS-4-2 |

| | | | | | |
|---|---|---|---|---|---|
| | | currents, attitude, and acceleration data sampled at ≥ 10 Hz, 32-bit resolution per axis. | | detect anomalous disturbances during proximity operations, and support post-event fault reconstruction. The ≥10 Hz, 32-bit-per-axis rate gives the requirement a measurable acceptance criterion. | |
| **SSR-COMM-06** | Operational | The ODIN communication system shall receive, decode, and route uplink commands from ground stations to the appropriate onboard subsystems. | Test (T) | Uplink capability is required for mission planning, proximity operations approval, and contingency response. | SYS-2-5, SYS-4-2 |

## 13.5.2 COMMUNICATIONS FUNCTIONAL ANALYSIS

**Table 13.5.1: Communications High-Level Functional Analysis**

| No. | Function Name | Description | Inputs | Outputs |
|---|---|---|---|---|
| 1 | Science/Payload Data Downlink | Transmit inspection imagery, sensor readings, and proximity measurements to ESTRACK via X-band HGA at 85–89 kbps during inspection windows | Compressed imagery (ONC-W, LORRI, IR), LA range data from SSMM | Downlinked science data frames to ground station |
| 2 | Housekeeping Telemetry Downlink | Continuously downlink 5,888 bps of spacecraft health parameters via HGA or LGA to allow ground operators to monitor spacecraft health across all mission phases | HK telemetry stream from C&DH (all subsystems) | HK TM frames delivered to MOC |
| 3 | Command Uplink Reception | Receive, demodulate, decode, and route uplinked commands from ESTRACK to the appropriate onboard subsystems via the MIL-STD-1553B bus | 7.17 GHz BPSK uplink signal from ground station | Authenticated command packets routed to C&DH |
| 4 | Onboard Data Storage | Store all payload and housekeeping | Continuous data | Data retained in |

| | | | | |
|---|---|---|---|---|
| | During Blackout | data in the SSMM without loss during solar conjunction blackouts and between contact windows | stream from C&DH during blackout | SSMM; available for downlink post-blackout |
| 5 | Data Processing and Formatting | Packetize all downlink data per CCSDS TM Space Data Link Protocol; apply image compression (PNG, ratio 1.83) before storage and transmission | Raw imagery and HK from payload and subsystems | CCSDS-compliant telemetry frames queued for downlink |
| 6 | Emergency/Contingency Link | Provide omnidirectional LGA beacon and low-rate TT&C independent of HGA during safe mode, HGA deployment failure, or anomalous conditions | LGA chain output from UST/TWTA at 40 W RF | Beacon signal and HK TM at safe-mode data rate (5 bps / 20 bps) |

## 13.5.3 COMPONENT SELECTION AND DESIGN (COMMS)

The ODIN communications subsystem hardware was selected to provide deep space X-band telemetry and telecommand capability compatible with ESTRACK and DSN ground infrastructure, while minimizing mass and power consistent with a Solar Orbiter-class spacecraft. Component selection prioritized flight heritage on comparable heliocentric missions, particularly Solar Orbiter and BepiColombo, to reduce development risk and establish credible performance baselines for the preliminary design review [11], [15], [17], [18].

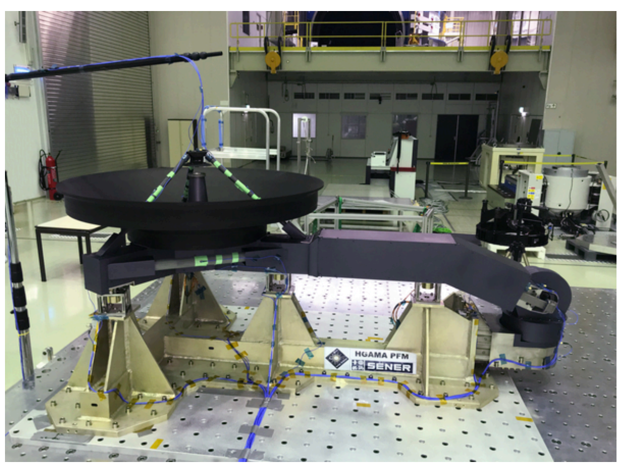


**Figure 13.5.1: Solar Orbiter's High Gain Antenna Subsystem**

### 13.5.3.1 ANTENNA SIZING

The selection of antenna aperture size is driven by the requirement to close the X-band downlink link budget with a minimum 6 dB margin at the worst-case Earth–ODIN distance occurring during the inspection phase. Sizing of High Gain Antenna (HGA) and Low Gain Antenna (LGA) are inherited from Solar Orbiter's antennas [17], [18]. Antenna scales with aperture area and operating frequency according to the relationship Equation 13.5.4. For the X-band downlink frequency of 8.4 GHz, a 1.1 m class aperture with a typical aperture efficiency of 0.55 yields a gain of approximately 36.4 dBi, consistent with the values derived from the antenna pattern analysis shown in the figures below.

#### 13.5.3.1.1 HIGH GAIN ANTENNA

Shown in Figure 13.5.4, defining a diameter of the parabolic antenna as 1.1m, which is the diameter of the Solar Orbiter's HGA, the aperture diameter of 1.1m gives a base gain of 37.1236, which was obtained by the equation:

$$G = \eta \times (\frac{\pi D}{\lambda})^2 \quad (13.5.3)$$

where G is the antenna gain (linear), η is the aperture efficiency (dimensionless, typically 0.55–0.60), D is the aperture diameter (m), and λ = c/f is the operating wavelength (m) at carrier frequency f. Equation # can equivalently be expressed in terms of effective aperture area $A = \pi \times (\frac{D}{2})^2$:

$$G = \eta \times (\frac{4\pi A}{\lambda})^2 \quad (13.5.4)$$

Expressing gain in dBi by taking $10\log_{10}$ of Equation 13.5.4.:

$$G_{dBi} = 10log_{10}(\eta) + 20log_{10}(\frac{\pi D}{\lambda}) \quad (13.5.5)$$

For the ODIN HGA with D = 1.1 m, η = 0.55, and downlink frequency f = 8.4 GHz (λ = 0.0357 m), the gain values for uplink and downlink come out to be:

**Table 13.5.3: Gain for HGA**

| Uplink | Downlink |
|---|---|
| 35.09 dBi | 36.42 dBi |

These values are confirmed by Figure 13.5.3.4, which plots antenna gain as a function of aperture diameter for C, X, Ku, Ka, and Q band frequencies. At D = 1.1 m in X-band, the figure yields approximately 37 dBi, consistent with Equation # to within the rounding of the graphical read.

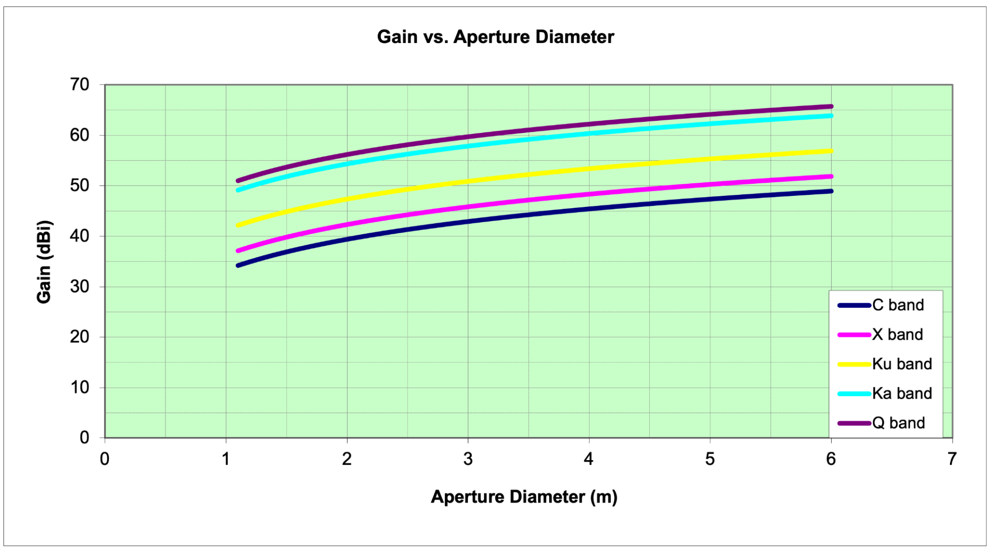


**Figure 13.5.2: Gain vs. Aperture diameter, plotted for operating frequencies common to satellite communication systems [26]**

The half-power beamwidth (HPBW) of a parabolic reflector, which is HGA in ODIN's comms subsystem, determines angular coverage area, which also determines the accuracy requirement placed on the APME gimbal, which is approximated by:

$$\theta_{HPBW} = \frac{21}{fD} \qquad 13.5.6$$

As shown in Figure 13.5.2, for HGA, the beamwidths come out to be:

**Table 13.5.4: HPBW for HGA**

| Uplink | Downlink |
|---|---|

| | |
|---|---|
| 2.652 degrees | 2.274 degrees |

The corresponding solid angle coverage area, approximated as the square of the half-power beamwidth, is:

$$\Omega_{HPBW} = (\theta_{HPBW})^2 \qquad 13.5.7$$

**Table 13.5.5: Coverage Area for HGA**

| Uplink | Downlink |
|---|---|
| $7.033\ degrees^2$ | $5.171\ degrees^2$ |

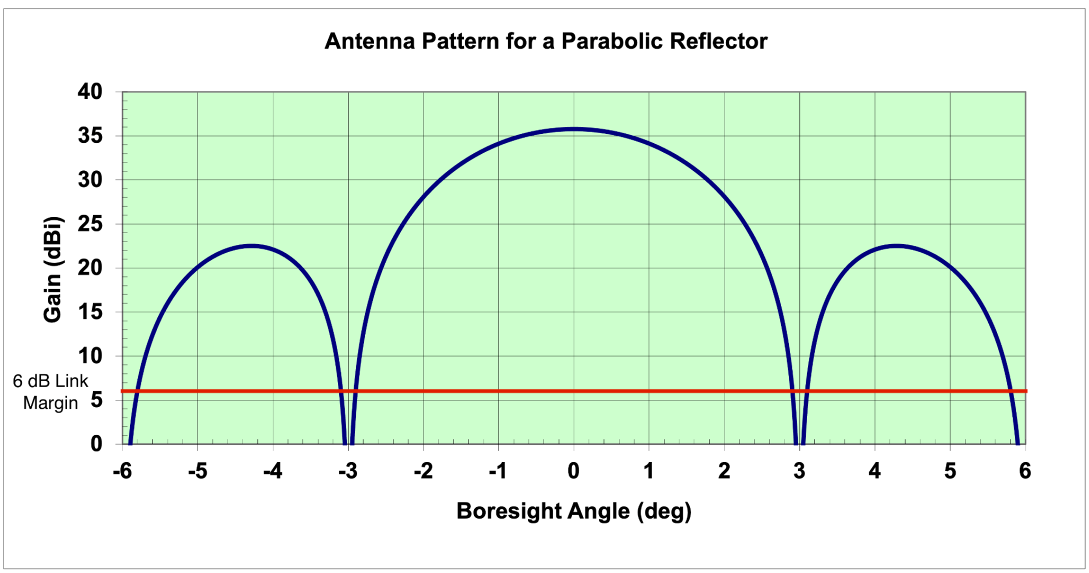


**Figure 13.5.5: Antenna pattern for a 1.1m parabolic reflector with uniform illumination operated at 8.4 GHz (Uplink) [26]**

The same method was used to calculate the HPBW and coverage area of the 35m antenna. As Table 13.5.7 shows, the HPBW angle is significantly narrower than the ODIN's HGA antenna due to the ground station's high gain, which supports the significance of gimbaled HGA.

Table 13.5.6: HPBW for Ground Station

| Uplink | Downlink |
|---|---|
| 0.083 degrees | 0.071 degrees |

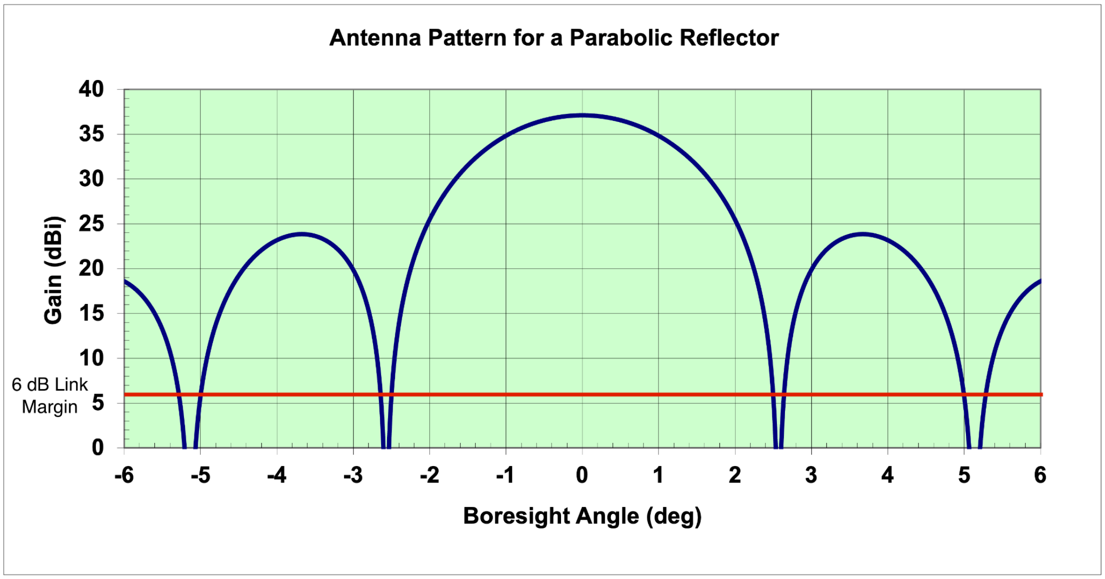


Figure 13.5.6: Antenna pattern for a 1.1m parabolic reflector with uniform illumination operated at 8.4 GHz (Downlink) [26]

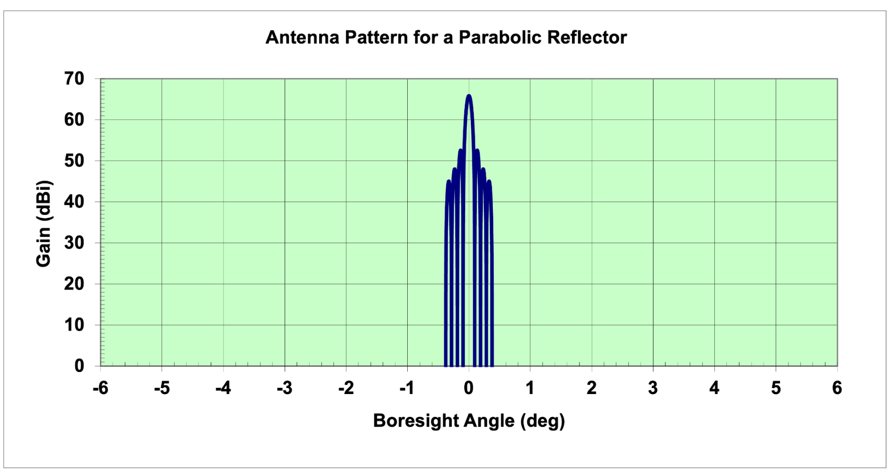


Figure 13.5.7: Antenna pattern for a 35 m parabolic reflector with uniform illumination operated at 8.4 GHz (Uplink) [26]

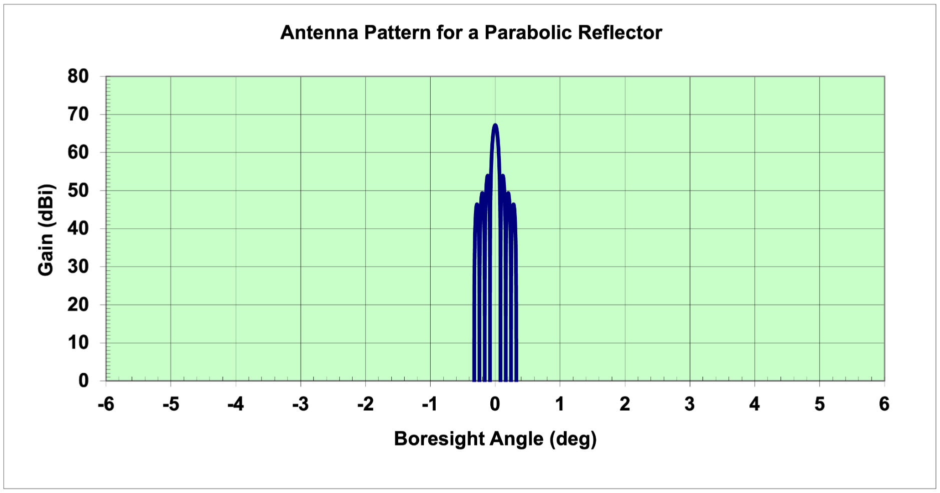


**Figure 13.5.8: Antenna pattern for a 35m parabolic reflector with uniform illumination operated at 8.4 GHz (Downlink) [26]**

### 13.5.3.1.2 LOW GAIN ANTENNA

The ODIN LGA is a helical antenna treated as a near-omnidirectional antenna providing broad angular coverage for contingency, safe-mode, housekeeping, and low-rate TT&C. Because the LGA is not intended to form a narrow, high-gain beam, its gain is estimated from the angular extent of its required coverage rather than from an aperture diameter.

Coverage is specified as a half-cone angle θ measured from the antenna boresight — the angle out to which the LGA maintains useful gain. For PDR, ODIN assumes θ = 50° (a 100° full beamwidth about boresight). This broad cone — roughly one-third of the forward hemisphere by solid angle — is consistent with deep-space low-gain antenna heritage; for comparison, Juno's LGAs operate over a ±40° beamwidth [25].

The coverage solid angle of a cone of half-angle θ, in square degrees, is

$$A_{deg^2} = 20626.5 \times (1 - cos\theta) \tag{13.5.8}$$

where 20626.5 $deg^2$ is the solid angle of one hemisphere. For θ = 50°

$$A_{deg^2} = 20626.5 \times (1 - cos\,50°) = 7,368\,deg^2$$

This coverage area is the value carried into the link budget as the LGA directivity input.

The LGA gain is then estimated by treating the antenna as an ideal radiator that distributes its power uniformly over the coverage solid angle, derated by a radiation efficiency η:

$$G_{dBi} = 10log_{10}(\eta \times \frac{41,253}{A_{deg}}) \quad 13.5.9$$

**Table 13.5.7: Gain for LGA**

| Uplink | Downlink |
|---|---|
| 3.90 dBi | 4.90dBi |

## 13.5.3.3 COMMUNICATIONS SYSTEM ARCHITECTURE

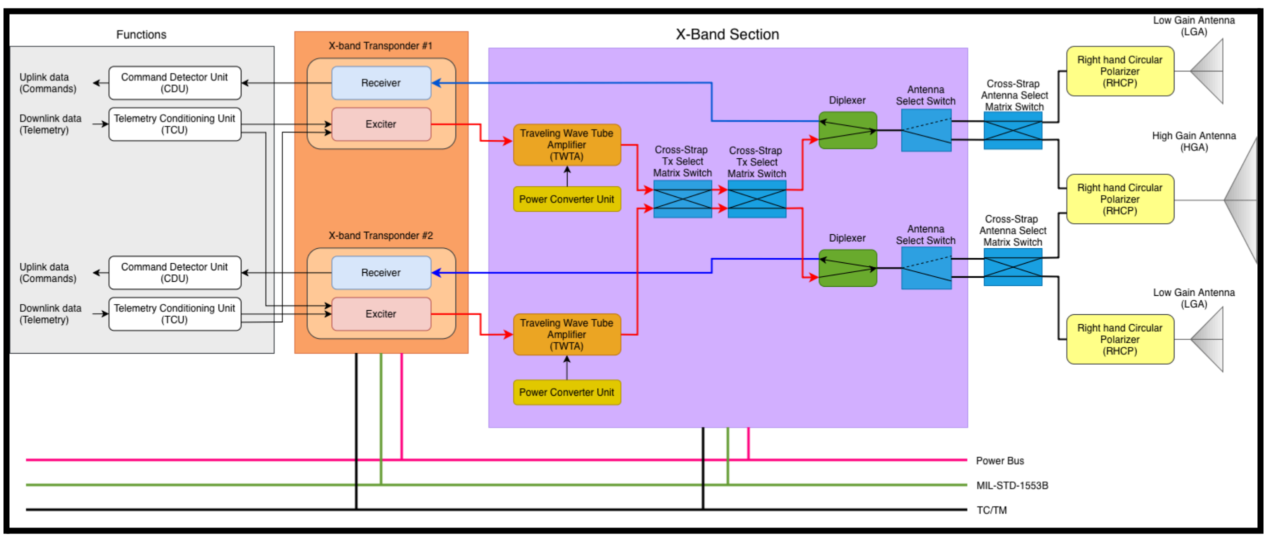


**Figure 13.5.9: ODIN Communication Subsystem Block Diagram**

The ODIN communications subsystem implements a fully redundant X-band RF chain, illustrated in Figure 13.5.9. The architecture follows the Solar Orbiter and BepiColombo heritage design philosophy [17], [18], where every active component in the transmit and receive chain has a cold or hot redundant counterpart, and cross-strap switching at every stage ensures that any single hardware failure does not prevent communication with the ground.

For transponder redundancy, two L3Harris Universal Space Transponders (UST) are baselined. The UST was selected over the retired General Dynamics Small Deep Space

Transponder (SDST), which was the heritage unit flown on Solar Orbiter's BepiColombo-derived design. The UST is the current production successor and the baseline transponder for NASA planetary missions including Mars Sample Return, providing equivalent or superior capability in the same spacecraft class [26].

UST #1 operates as the active unit throughout nominal operations. Its receiver is maintained in hot redundancy, meaning both the UST #1 and UST #2 receivers are powered and listening at all times. This ensures that uplink commands from the ground are never missed due to a receiver failure — a single event upset or component failure in UST #1's receiver does not require a switchover command from the ground before command reception is restored, because UST #2 is already tracking the uplink carrier. The transmitter, by contrast, operates in cold redundancy: only one transmitter is active at any time to avoid RF interference between the two chains, and UST #2's transmitter is brought online only in the event of a confirmed UST #1 transmitter failure.

For TWTA redundancy, two Thales TH4704C X-band traveling wave tube amplifier assemblies are baselined, one for each transponder chain, with one active and one cold spare at any time. The TH4704C was selected because it is the unit flown on Solar Orbiter, providing the strongest possible flight heritage argument for a mission operating in a comparable heliocentric thermal and radiation environment. The TH4704C provides 70 W RF output in HGA science downlink mode, backed off to approximately 40 W in LGA safe mode, via the Electronic Power Conditioner (EPC) which controls the operating point of the tube without switching the unit off [17].

The cross-strap architecture of the two TWTA chains is managed by a series of passive RF switches as shown in Figure #. Two Cross-Strap Tx Select Matrix Switches route the exciter output from either transponder to either TWTA, ensuring that a failure of TWTA #1 does not prevent the use of UST #1's transmitter — the matrix switch can route UST #1's exciter signal to TWTA #2 instead.

For redundancy of diplexers, two X-band diplexers separate the transmit path at 8.4 GHz from the receive path at 7.2 GHz on the shared antenna feed, one per antenna chain. The diplexer is a passive waveguide component that eliminates the need for a separate receive antenna or a transmit/receive switch, allowing the same antenna feed to be used simultaneously for transmission and reception.

For redundancy of antenna select switches, beyond the TWTA cross-strap, the architecture provides a second level of switching at the antenna port level. Each diplexer chain is followed by an antenna select switch that routes the RF signal to either the HGA feed or the

LGA port. In addition, two cross-strap antenna select matrix switches provide a final cross-strap layer at the antenna feed, ensuring that either diplexer chain can drive either antenna port. This means that even if a switch fails in the wrong position, the redundant chain's matrix switch can still route a signal to the required antenna.

**Table 13.5.9: Communication Subsystem Payload Elements**

| Element | HGA | LGA |
|---|---|---|
| **Antenna** | Single mechanically steered parabolic reflector, X-band, 1.1 m class. 2-axis APME gimbal. X-band RHCP feed at focus. 65 kg including APME electronics. | Two fixed body-mounted helix antennas, X-band, RHCP, opposite circular polarizations (LHCP/RHCP pair). Omnidirectional coverage. |
| **Antenna Gain** | 36.42 dBi (downlink 8.4 GHz)<br>35.09 dBi (uplink 7.2 GHz) | 4.90 dBi (downlink)<br>3.90 dBi (uplink). |
| **Coverage Area** | 5.17 $deg^2$ (downlink)<br>7.0 $deg^2$ (uplink). | 7,336 $deg^2$ (downlink)<br>9,234 $deg^2$ (uplink). |
| **Repeater Type** | L3Harris Universal Space Transponder (UST). Software-defined radio (SDR); in-flight reprogrammable. Coherent Doppler turnaround ratio 880/749. DSN and ESTRACK X-band compatible. UST #1 active (hot redundant RX, cold redundant TX); UST #2 cold spare. | Same UST chain routed via RF switching network to LGA port. Coherent TT&C mode. Both LGA receivers are simultaneously active (hot redundant RX). |
| **Power Amplifier** | Thales TH4704C X-band TWTA. 70 W RF output. 140 W DC bus at ~50% efficiency. One active, one cold spare. | Thales TH4704C TWTA backed off to ~40 W RF output. ~80 W DC bus. Routed via switch. |
| **Payload Topology** | Single HGA communicating with selected ESTRACK 35-m deep space stations (Malargüe, Cebreros, New Norcia). | Same ESTRACK network. Omnidirectional — no pointing required. |
| **Modulation / Coding** | Downlink: QPSK, code rate 1/3<br><br>Uplink: BPSK | Safe mode / TT&C: BPSK |
| **Channel Bandwidth** | 1.5 MHz allocated; ~0.18 MHz used at 89 kbps peak (~0.10 MHz at 49 kbps nominal). | 1.5 MHz used at 89 kbps peak (~0.10 MHz at 49 kbps nominal).1.5 MHz allocated; <0.001 MHz used at 5–20 bps. |
| **Primary Function** | High-rate science image downlink and primary TT&C during scheduled ground contacts when Earth-pointing geometry is satisfied. | Emergency telecommand uplink, safe-mode housekeeping telemetry, spacecraft acquisition during LEOP, Doppler ranging, and attitude-independent health monitoring. |

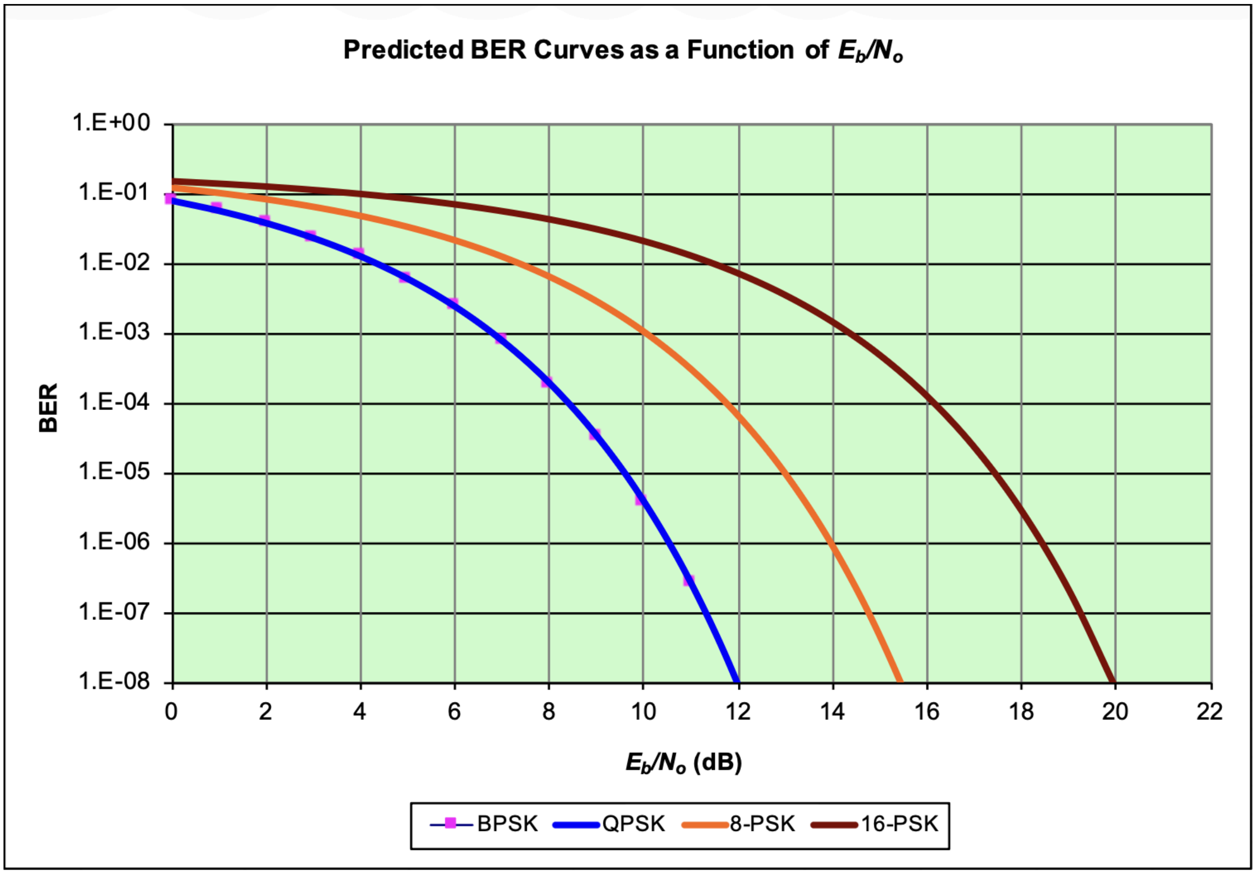


**Figure 13.5.10: Predicted BER curves as a function of Eb/No [26]**

The $1\times10^{-6}$ BER target is not an arbitrary number — it is what makes the inspection imagery scientifically usable and the command link safe. At the frame level, bit errors compound: a 16,384-bit transfer frame survives intact only if every bit survives, so the probability a frame is delivered error-free is approximately $(1 - \text{BER})^{16384}$. At BER = $1\times10^{-6}$ roughly 1.6% of frames carry at least one error and are dropped for retransmission, which is the basis of the ~1.6% overhead already budgeted; at BER = $1\times10^{-4}$ that frame-loss rate climbs to roughly 80%, and the link spends more time retransmitting than delivering new data. The BER target therefore sets the boundary between a downlink that clears each cycle and one that never catches up — it is a throughput requirement as much as a quality one. On the uplink the same target protects command integrity: an undetected bit flip in a command frame could execute the wrong sequence during proximity operations, which is why command reception is verified end-to-end rather than assumed.

Reaching that BER at the available signal strength is precisely what the rate-1/3 channel code buys. Without coding, a $1\times10^{-6}$ BER on an uncoded BPSK/QPSK link requires an $E_b/N_0$ of roughly 10.5 dB according to Figure 13.5.10; the CCSDS rate-1/3 code delivers the same BER at a coded threshold near 0.5 dB, a coding gain of about 10 dB. That gain is the entire reason the link closes — ODIN's operating $Eb/N_0$ of ~8.6 dB would sit ~2 dB *short* of the uncoded requirement at the worst-case range, but sits comfortably ~6 dB *above* the coded threshold. The cost is bandwidth: rate-1/3 means three transmitted channel symbols per information bit, tripling occupied bandwidth relative to the uncoded rate, which is why the channel-bandwidth allocation in the link budget is sized to the coded symbol rate rather than the information rate [22]. ODIN accepts that bandwidth penalty deliberately, because at deep-space ranges the link is power-limited, not bandwidth-limited — spectrum is plentiful, received power is scarce, and trading bandwidth for ~10 dB of coding gain is the favorable exchange. Choosing CCSDS 132.0-B specifically (rather than a custom code of equal strength) also means ESTRACK's 35 m DSAs decode it natively with no mission-unique ground hardware, which is what SSR-CDH-02 codifies.

**Table 13.5.10: Communications System Architecture**

| ODIN | Names | Details | Mass / Size | Power |
|---|---|---|---|---|
| **TT&C** | X-Band | Solar Orbiter HGAMA (65 kg inc. APME).<br><br>Low Noise Amplifier (LNA) | HGA: 65 kg including APME Antenna Pointing Mechanism Electronics)<br><br>LGA: 0.9 kg | 0 W (Passive Antenna)<br><br>Actuator (Solar Orbiter): Standby 6.8 W / Hold 34 W / Steer 51 W. |
| **Payload downlink** | X-Band payload downlink using QPSK. | Main science image data path<br><br>The HGA provides the needed antenna gain for downlink from Solar-Orbiter-like distances. | Included in HGA/TT&C mass above | Peak Tx mode: ~182 W total (42 W transponder + 140 W TWTA for 70 W RF out) |
| **Solid-State Mass Memory (SSMM)** | Airbus Defence and Space SSMM | 96 GiB raw capacity (3 × 32 GiB SDRAM modules). Full redundancy throughout. SpaceWire interface. Reed-Solomon ECC. CCSDS TC/TM packet management. To be procured as part of the spacecraft prime contract. | ~ 10 –15 kg | ~ 15 W (active read/write)<br><br>~ 5 W (standby) |
| **Transponder** | L3Harris Universal Space Transponder | Features an in-flight reprogrammable digital | 6 kg x 2 = 12 kg | Standby: 26 W |

| | | | | |
|---|---|---|---|---|
| | (UST) | processing core with modular hardware architecture.<br><br>Supports coherent Doppler turnaround (X-band turnaround ratio 880/749) for precision ranging and radio science. | 21.0 cm W x<br>27.0 cm D x<br>16.0 cm H | Rx only: 32 W<br><br>Rx & Tx: 42 W |
| **Power Amplifier** | Thales TH4704C X-band TWTA | X-band traveling wave tube amplifier (7.25–8.50 GHz) following the UST transponder.<br><br>Same unit flown on Solar Orbiter. | 3.5 kg x 2<br>= 7.0 kg | HGA (70 W RF**)**: ~140 W DC bus at ~50% efficiency.<br><br>LGA (40 W RF**)**: ~80 W DC bus. |
| **RF Switch / Diplexer** | X-Band diplexer | Routes the transponder output to either HGA or LGA.<br><br>Also separates transmit and receive paths if using the same antenna system. Enables fallback from HGA to LGA during safe mode. | 0.6 kg x 2<br>= 1.2 kg | 0 W (Passive) |
| **Command / housekeeping bus** | MIL-STD-1553B | Low-rate command, configuration, and housekeeping traffic between the OBC and transponder subsystem. | Negligible | Included in transponder power |
| **Science / TM data bus** | SpaceWire (SpW) | High-rate science and telemetry data transfer between payload instruments, SSMM, and transfer frame generators. Supports up to 400 Mbps per link. | Negligible | Included in SSMM power |
| **Timing Reference** | AccuBeat Ultra Stable Oscillator (USO) | Provides stable 57.51852 MHz frequency reference for OBC timekeeping and UST coherent X-band turnaround. ADEV $5\times10^{-13}$ (1–1000 s). | 2 kg, 132.6×120×105 mm | 6.5 W (steady state), 8 W (warm-up) |

| | | | | |
|---|---|---|---|---|
| **Ground Segment** | Cebreros, Malargue, or New Norcia | The spacecraft should select the station with visibility and best link geometry during the downlink pass. | N/A | 20,000 W |

## 13.5.5 COMMUNICATION POWER AND MASS BUDGET

The power and mass budget for the ODIN deep space TT&C subsystem is presented in Tables 13.5.11 and 13.5.12. The budget covers all components from the transponder input to the antenna feed, including the RF distribution assembly, switching network, cabling, and both antenna systems.

**Table 13.5.11: Power and Mass Summary for ODIN's Deep Space TT&C Subsystem**

| Unit | Qty | DC Bus Power (W) | Total Power (W) | Unit Mass (kg) | Total Mass (kg) | Notes |
|---|---|---|---|---|---|---|
| **X-Band Transponder** | 2 | 42 | 42 | 6.0 | 12.0 | L3Harris UST. Two units for redundancy.<br><br>One active, one cold spare. Rx+Tx mode 42 W.<br><br>DSN/ESTRACK-compatible X-band. |
| **X-Band TWTA** | 2 | 140 | 140 | 3.5 | 7.0 | Thales TH4704C. 70 W RF out at ~50% efficiency.<br><br>One active, one cold spare. |
| **X-Band Diplexer** | 2 | 0 | 0 | 0.6 | 1.2 | Separates 7.2 GHz uplink / 8.40 GHz downlink on HGA feed |
| **Cross-Strap Tx Select Matrix Switch** | 2 | 0 | 0 | 0.3 | 0.6 | Routes TWTA outputs between chains before diplexers. Enables either TWTA to feed either antenna chain. |
| **Antenna** | 2 | 0 | 0 | 0.2 | 0.4 | Selects HGA or LGA |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Select Switch** | | | | | | output per diplexer chain. |
| **Cross-Strap Antenna Select Matrix Switch** | 2 | 0 | 0 | 0.3 | 0.6 | Final cross-strap stage at antenna ports. Full redundancy at antenna selection level. |
| **X-Band Cables** | - | 0 | 0 | - | 5.0 | Coaxial cables |
| **Subtotal (Active Electronics)** | | ~ 182 | ~ 182 | | ~ 26.8 | One transponder + one TWTA active at any time. |
| **X-Band LGA** | 2 | 0 | 0 | 0.9 | 1.8 | Helix type<br>9234 $deg^2$ uplink,<br>7336 $deg^2$ downlink |
| **X-Band HGA** | 1 | 0 | 0 | 65 | 65 | 1.1 m class parabolic reflector + 2-axis APME gimbal |
| **AccuBeat USO** | 1 | 6.5 | 6.5 | 2 | 2 | Ultra-stable oscillator, steady-state 6.5 W |
| **HGA APME Gimbal** | 1 | ~ 50 | ~ 50 | Included in HGA | Included in HGA | 2-axis Antenna Pointing Mechanism. Stand-by 6.8 W / Hold 34 W / Steer ~ 50 W. |
| **Total** | | **~ 238.5** | **~ 238.5** | | **~ 95.6** | Worst-case peak: UST 42 W + TWTA 140 W + APE ~ 50 W + USO 6.5 W. |

Table 13.5.12 presents the three defined power modes for the ODIN communications subsystem. These modes correspond to distinct phases of spacecraft operation and drive different requirements on the spacecraft power subsystem.

**Table 13.5.12: Comms Power Mode Summary**

| Component | Standby (W) | LGA transmit (W) (safe mode) | HGA transmit (W) (inspection) |
|---|---|---|---|
| Transponder | 26 | 32 | 42 |
| TWTA | ~ 5 | ~80 | ~140 |

| | | | |
|---|---|---|---|
| Gimbal | 6.8 | 0 | ~ 50 |
| USO | 6.5 | 6.5 | 6.5 |
| **Total** | **~ 44.3** | **~ 118.5** | **~ 238.5** |

Standby mode applies during cruise phase between contact windows, when the spacecraft is maintaining its attitude and the communications subsystem is ready to receive commands but not transmitting. The 26 W transponder standby draw plus the approximately 5 W TWTA warm standby draw plus the 6.8 W APME standby power for maintaining gimbal position gives a total of approximately 38 W. This is the baseline continuous power demand of the communications subsystem throughout the mission.

LGA transmit mode applies when the spacecraft has entered safe mode and is transmitting housekeeping telemetry through the LGA at low data rate. The transponder draws 32 W in Rx & Tx mode at LGA data rates, the TWTA draws approximately 80 W backed off to 40 W RF output, and the APME draws 0 W as the LGA provides omnidirectional coverage that does not require pointing. The total of approximately 112 W represents the safe mode communications power budget, which must be available from the spacecraft EPS even in degraded power conditions, since the ability to communicate in safe mode is a survival-critical function.

HGA transmit mode applies during scheduled inspection/downlink passes when science imagery is being transmitted through the HGA. The transponder draws 42 W in full duplex mode, the TWTA draws 140 W at 70 W RF output, and the APME draws approximately 50 W in active steering mode as it continuously tracks Earth during the pass. The total peak communications power draw of approximately 238.5 W is the highest power mode of the subsystem and represents a significant fraction of the spacecraft total power budget. This peak draw occurs only during the scheduled inspection/downlink pass — approximately 8 hours per inspection cycle — and not continuously.

## 13.5.6 LINK BUDGET

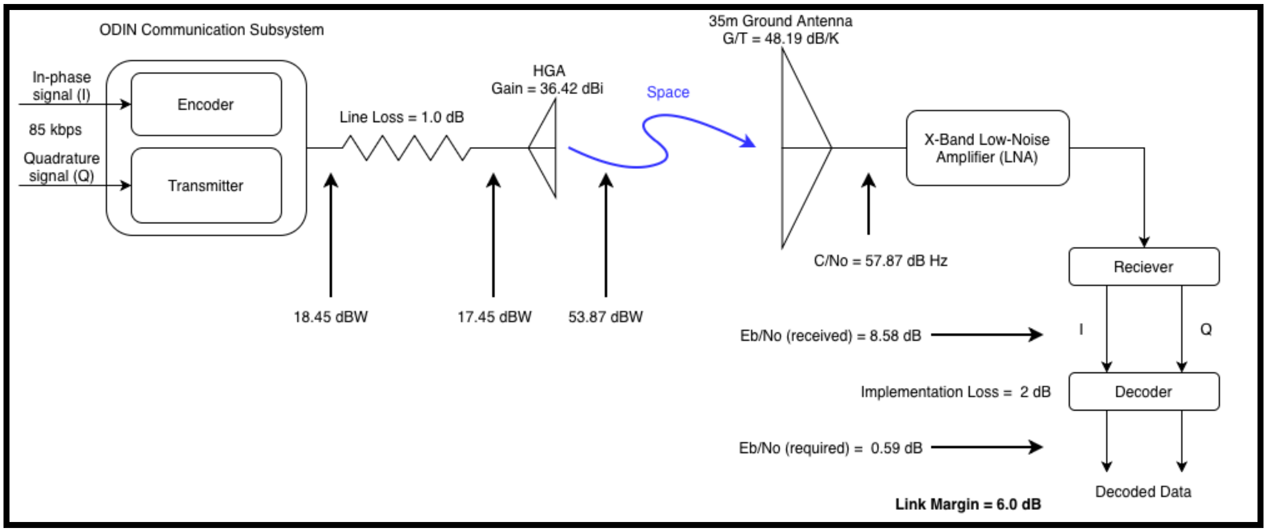


**Figure 13.5.11: Link Budget Diagram for HGA Downlink at Inspection #1**

The link budget is the accounting of all power gains and losses experienced by a RF signal as it travels from the transmitter, through the RF chain, across free space, and through the ground station receive chain to the decoder. For ODIN, the link budget determines whether the communications subsystem can deliver a signal of sufficient quality to the ESTRACK ground station receiver to support reliable demodulation and decoding of the science telemetry (images of Solar Orbiter) and housekeeping data at the required data rate, with a minimum margin of 3 dB above the threshold for error-free reception.

The link budget must be evaluated separately for each mission geometry of interest. In ODIN's case, the two inspection opportunities at different Earth–spacecraft ranges, the furthest cruise geometry at 2.0 AU, and the nominal geometry at 1.0 AU. As Solar Orbiter's HGA was designed to close the link margin as far as 2.0 AU for a great margin of Rx & Tx, ODIN's link budget is analyzed at the distances that are further/closer than the expected orbit.

### 13.5.6.1 LINK BUDGET ANALYSIS

The full link budget is evaluated at two bounding mission geometries: the worst-case geometry at 2.0 AU Earth–spacecraft range, which represents the maximum operational distance within the ODIN mission profile, and the best-case geometry at 0.73 AU, the closest inspection range. The complete results are presented in Table 13.5.13.

For the worst-case scenario at 2.0 AU, the uplink chain closes with a received carrier power at the spacecraft of −136.84 dBW and a receiver $C/N_0$ of 72.76 dB·Hz. The available uplink $Eb/N_0$ at the 12.2 kbps command rate (40.86 dB·Hz) is 31.90 dB, which is substantially above the threshold required for reliable telemetry and command reception, confirming that the ground station can command ODIN at any point in the 2.0 AU worst-case geometry without difficulty.

The spacecraft transmit chain Effective Isotropic Radiated Power (EIRP) is computed from $P_t = 70\,W = 18.45\,dBW$, $G_t = 36.42\,dBi$, and $L_l = 1.0\,dB$.

$$EIRP_{HGA} = P_t + G_t - L_l = 53.87\,dBW \qquad 13.5.10$$

The free-space path loss is computed from:

$$L_{fs} = 20log_{10}(\frac{4\pi Rf}{c}) \qquad 13.5.11$$

The available $Eb/N_0$ at the ground station decoder input is computed from Equation 13.5.12 at each geometry, with assumptions of atmospheric loss $L_a$ = 0.5 dB, ground station line loss $L_r$ = 0.2 dB, and ground station G/T = 48.19 dB/K:

$$(\frac{Eb}{N_o})_{available} = EIRP - L_{fs} - L_a - L_r + G/T + 228.6 - 10log_{10}(R_b) \qquad 13.5.12$$

$$(\frac{Eb}{N_o})_{required} = (\frac{Eb}{No})_{min} + L_{impl} + Margin\,floor \qquad 13.5.13$$

where the minimum $Eb/N_0$ of 0.59 dB is the theoretical minimum for QPSK (code rate 1/3) at BER = $10^{-5}$ read from Figure 13.5.10, $L_{impl}$ = 2.0 dB is the assumed modem implementation loss, and Margin_floor = 6.0 dB is the minimum design margin required by SSR-COMM-03. The residual link margin from Equation 13.5.14 at each geometry is:

$$Link\,Margin = (\frac{Eb}{N_o})_{available} - (\frac{Eb}{N_o})_{required} \qquad 13.5.14$$

which leaves 0.15 dB of slack above the 6 dB floor at the furthest case.

Table 13.5.13: ODIN Component Data Budget Characterization

| Parameter | Units | HGA Far-Range Case | HGA Nominal Case | Inspection Case 1 | Inspection Case 2 | LGA Far-Range Case | LGA Nominal Case |
|---|---|---|---|---|---|---|---|
| Mission Mode | | Reduced-rate HGA downlink | Nominal HGA downlink | Inspection image downlink | Inspection image downlink | Safe-mode TT&C only | Safe-mode TT&C only |
| Earth-ODIN Range | km | 299,195,741.4 | 149,597,870.7 | 114,000,000 | 109,370,000 | 299,195,741.4 | 149,597,870.7 |
| Approximated Range | AU | 2.0 | 1.0 | 0.76 | 0.73 | 2.0 | 1.0 |
| Uplink Parameter | | | | | | | |
| Uplink Frequency | GHz | 7.17 | 7.17 | 7.17 | 7.17 | 7.17 | 7.17 |
| Ground Antenna Type | | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish |
| Ground Antenna Gain | dBi | 65.80 | 65.80 | 65.80 | 65.80 | 65.80 | 65.80 |
| Ground Transmit Power | W | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 |
| Ground EIRP | dBW | 108.66 | 108.66 | 108.66 | 108.66 | 108.66 | 108.66 |
| ODIN Receive Antenna | | HGA | HGA | HGA | HGA | LGA | LGA |
| ODIN Receive Gain | dBi | 35.09 | 35.09 | 35.09 | 35.09 | 3.90 | 3.90 |
| Uplink Free-Space Path Loss | dB | -279.08 | -273.06 | -270.70 | -270.34 | -279.08 | -273.06 |
| Uplink Net Path Loss | dBW | -279.58 | -273.56 | -270.20 | -270.84 | -279.58 | -273.56 |
| Uplink Received | dBW | -136.84 | -130.82 | -128.46 | -128.10 | -168.02 | -162.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Carrier Power | | | | | | | |
| Uplink Receiver $C/N_0$ | dB-Hz | 72.76 | 78.78 | 81.14 | 81.50 | 41.58 | 47.60 |
| Available Uplink $Eb/N_0$ | dB | 31.90 | 31.88 | 31.83 | 32.01 | 34.59 | 34.59 |
| Downlink Parameter | | | | | | | |
| Downlink Frequency | GHz | 8.42 | 8.42 | 8.42 | 8.42 | 8.42 | 8.42 |
| Ground Antenna Type | | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish | 35 m tracking dish |
| Ground Antenna Gain | dBi | 67.19 | 67.19 | 67.19 | 67.19 | 67.19 | 67.19 |
| ODIN Transmit Power | W | 70 | 70 | 70 | 70 | 40 | 40 |
| ODIN EIRP | dBW | 53.87 | 53.87 | 53.87 | 53.87 | 19.92 | 19.92 |
| ODIN Transmit Antenna | | HGA | HGA | HGA | HGA | LGA | LGA |
| ODIN Transmit Gain | dBi | 36.42 | 36.42 | 36.42 | 36.42 | 4.90 | 4.90 |
| Downlink Free-Space Path Loss | dB | -280.48 | -274.45 | -272.09 | -271.73 | -280.48 | -274.45 |
| Downlink Net Path Loss | dBW | -280.98 | -274.95 | -272.59 | -272.23 | -280.98 | -274.95 |
| Downlink Received Carrier Power | dBW | -160.11 | -154.09 | -151.73 | -151.37 | -194.06 | -188.04 |
| Downlink Receiver | dB-Hz | 49.49 | 55.51 | 57.87 | 58.23 | 15.54 | 21.56 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $C/N_0$ | | | | | | | |
| Available Downlink $Eb/N_0$ | dB | 8.63 | 8.61 | 8.58 | 8.74 | 8.55 | 8.55 |
| Implementation Loss | dB | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Final Link Margin | dB | 6.0 | 6.0 | 6.0 | 6.1 | 6.0 | 6.0 |
| Data Rate and Bandwidth | | | | | | | |
| Channel Bandwidth | MHz | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| Number of Channels | | 1 | 1 | 1 | 1 | 1 | 1 |
| Code Rate | | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| Single-User Data Rate | Mbps | 0.0122 | 0.0490 | 0.085 | 0.089 | 0.000005 | 0.000020 |
| Single-User Data Rate | bps | 12,200 | 49,000 | 85,000 | 89,000 | 5 | 20 |
| **Total Capacity** | **kbps** | **12.2** | **49.0** | **85.0** | **89.0** | **5.0** | **20.0** |

As shown in Table 13.5.11, each mode satisfies the ≥6 dB requirement of SSR-COMM-03, with the data rate at each geometry selected to hold that margin. [11], [15], [22], [24]

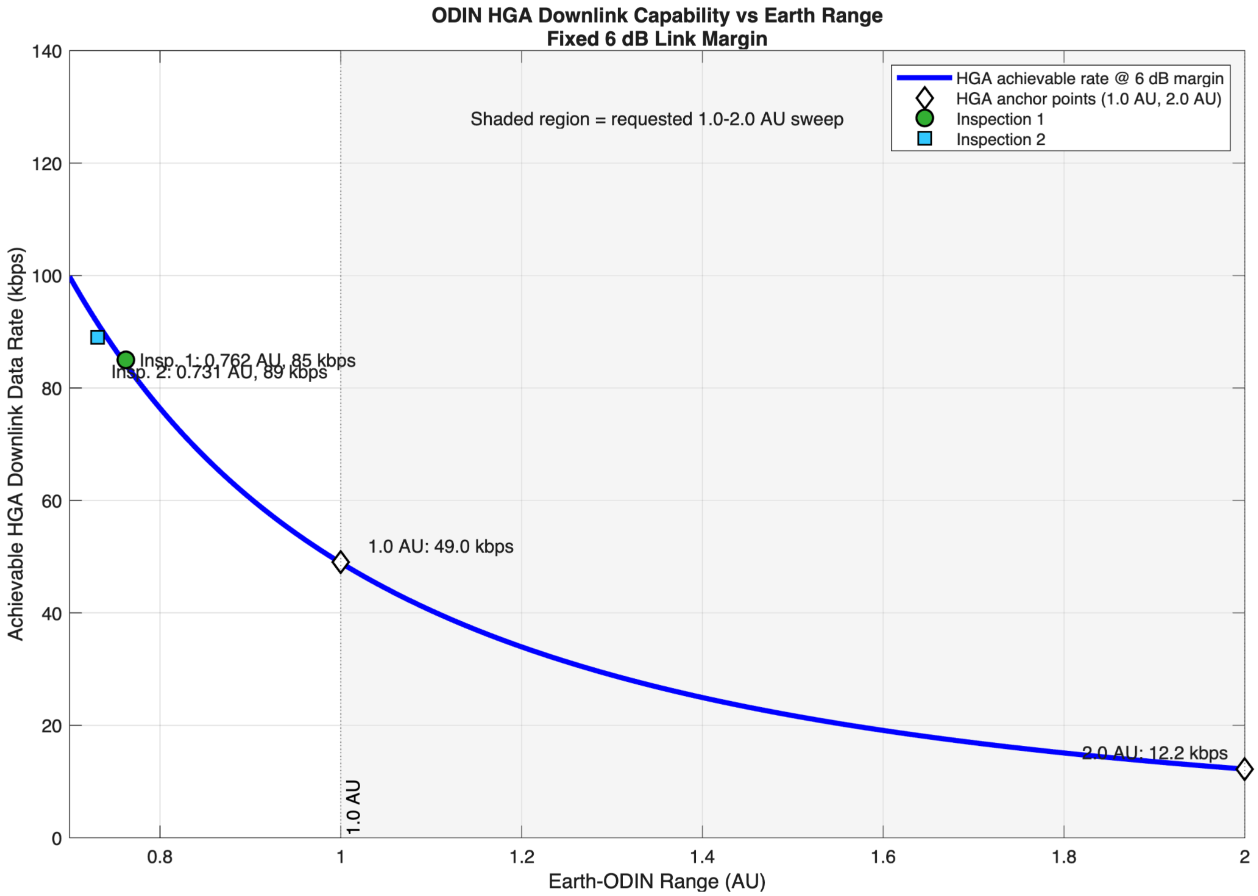


**Figure 13.5.12: Link Budget Summary**

## 13.5.7 DATA BUDGET ANALYSIS

The data budget analysis characterizes the volume and timing of data that ODIN's avionics must generate, process, store, and downlink across the mission, and confirms that the onboard data architecture (OBC, SSMM, and data bus) together with the X-band downlink can accommodate the worst-case load. The analysis proceeds from a qualitative characterization of each component's demands, through the mode-dependent load on the flight computer, to a quantitative housekeeping budget and a per-mode activity breakdown. The governing case is the inspection mode, in which simultaneous high-rate imaging drives the peak data-generation rate well above the available downlink capacity [22], [23], [14].

Table 13.5.14 characterizes each onboard component against the parameters that size the data system: throughput, CPU utilization, non-volatile and volatile memory, update frequency, and timing accuracy. The dominant data sources are the ONC-W, LORRI, and

IR imagers and the on-board computer, which rate High across nearly every category, with the SSMM and data bus carrying the corresponding high throughput and storage demands. The remaining bus housekeeping sources — thermal, power, and propulsion — are individually low-rate but require regular sampling at strict timing where they support closed-loop control. This ranking establishes which components the quantitative budgets must capture in detail.

**Table 13.5.14: ODIN Communication Link Budget Summary**

| Subsystem | Component | Throughput Estimation | CPU Utilization | Non-volatile Memory | Volatile Processor Memory | Update Frequency | Timing Accuracy |
|---|---|---|---|---|---|---|---|
| Payload | Cameras (ONC-W, LORRI) | High | High | High | High | High | Strict |
| | IR Camera (MDA IR Camera/ ) | High | High | High | High | High | Strict |
| | Laser Altimeter | Low | Low | Low | N/A | Low | Strict |
| Structures and Mechanism | HGA Antenna Pointing Mechanism(AMPE) | Low | Medium | Low | Low | Medium | Strict |
| | Solar Array Deployment Mechanism | Low | Low | Low | N/A | Low | Strict |
| Thermal Control | Heat Shield Temp Sensors | Low | Low | Low | N/A | Medium | Medium |
| | Bus Temp Sensors | Low | Low | Low | N/A | Low | Low |
| | Heaters | Low | Low | Low | N/A | Low | Low |
| Power | Battery | Low | Medium | Low | Low | Medium | Medium |
| | Solar Arrays | Low | Low | Low | N/A | Low | Low |
| | PCDU | Low | Low | Low | Low | Medium | Medium |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Telemetry and Control | Receiver | Low | Low | Low | Low | Low | Strict |
| | Transmitter | High | Medium | Medium | Medium | Medium | Strict |
| Command and Data Handling | On-Board Computer (OBC) | High | High | High | High | High | Strict |
| | Solid-State Mass Memory | High | Medium | High | Medium | High | Strict |
| | Data Bus | High | Medium | Low | Low | High | Strict |
| | AccuBeat USO | Low | Low | Low | N/A | Low | Strict |
| Attitude and Determination Control | Star Tracker | Low | Low | Low | Low | Medium | Strict |
| | Fine Sun Sensor | Low | Low | Low | N/A | Medium | Medium |
| | IMU | Medium | Medium | Low | Medium | High | Strict |
| | Reaction Wheels | Low | Low | Low | Low | Medium | Medium |
| Propulsion | R-4D-11 Main Engine | Low | Low | Low | Low | Medium | Strict |
| | MR-106L RCS Thrusters | Low | Low | Low | Low | High | Strict |
| | Moog Solenoid Valves | Low | Low | Low | Low | High | Strict |

Table 13.6. maps the flight computer's resource demands onto the seven ODIN mission modes. Science Operation places the heaviest load across throughput, memory, and update frequency, with the Radio Pointing / Downlink mode close behind; Safe Mode is intentionally minimal. This confirms that the OBC and SSMM must be sized to the Science Operation / Inspection case, and that the timing-critical modes (deployment, downlink, stationkeeping) impose the strict synchronization met by the AccuBeat USO.

Table 13.5.15: ODIN Computer Characteristics by Mission Mode

| Computer Characteristics | Initial Checkouts | Initial Deployment | Science Operation | Radio Pointing / Data Uplink and Downlink | Sun Pointing / Spacecraft Charging | Stationkeeping / Orbit Adjustment | Safe Mode |
|---|---|---|---|---|---|---|---|
| Throughput Estimation | Low | N/A | High | High | Low | Low | Low |
| CPU Utilization | Medium | Low | High | Medium | Medium | Medium | Low |
| Non-volatile Memory | Low | N/A | High | High | Low | Low | Low |
| Volatile Processor Memory | Low | N/A | High | High | Medium | Medium | Low |
| Update Frequency | Low | Low | High | Medium | High | Medium | Medium |
| Timing Accuracy | Low | Strict | High | Strict | Medium | Strict | Low |

Table 13.6.16 resolves the continuous housekeeping telemetry budget to the sensor level, totaling 5,888 bps of health and status data across all subsystems. The ASTRIX200 IMU dominates at 3,840 bps (three-axis rate and acceleration sampled at 10 Hz), with the remaining ~2,000 bps distributed across power, thermal, propulsion, ADCS, payload, and comms housekeeping. This stream is downlinked continuously via the HGA or LGA in every mission phase and represents the floor of the data budget.

The continuous housekeeping data rate of each on-board component is determined from its sampling logic rather than assumed. For component *i*, the rate is the product of the word size, the number of distinct values sampled per unit, the sampling frequency, and the number of units of that type:

$$R_i = b_i n_{words,i} f_i N_i \qquad 13.5.15$$

where:

- $b_i$ = resolution, in bits per value
- $n_{words,\,i}$ = number of measured values per unit (e.g. a quaternion is four values; a 3-axis rate plus 3-axis acceleration is six)
- $f_i$ = sampling frequency, in Hz
- $N_i$ = number of identical units sampled
- $R_i$ = component data rate, in bits/s

In Table 13.5.16 these map to the *Resolution*, *Rate*, and *Quantity* columns. Where a component reports more than one value per sample, the per-unit word count is carried in the resolution entry using the notation $b * n_{words}$ (for example, "32 × 6" denotes a 32-bit word sampled across six axes). For single-value sensors, $n_{words,\,i} = 1$ and the resolution entry is the word size alone.

As a low-rate example, the bus thermistors are sampled at 0.1 Hz with 12-bit resolution across 40 units, giving a single temperature value per unit at 48 bps.

The dominant contributor is the ASTRIX-200 IMU, which reports three-axis rate and three-axis acceleration — six values per unit — at 32-bit resolution and 10 Hz, across two redundant units at 3.840 bps.

This single component accounts for roughly two-thirds of the housekeeping budget, a direct consequence of its high sampling frequency relative to the rest of the bus, which is sampled at 1 Hz or below.

The total continuous housekeeping rate is the sum over all sampled components, with fractional results rounded to the nearest bit per second

**Table 13.5.16: ODIN Data Rates for On-Board Components**

| Sensor | Subsystem | Measurements | Resolution (bits) | Rate (Hz) | Quantity | Data Rate (bps) |
|---|---|---|---|---|---|---|
| AccuBeat USO | Time Keeping | Relative time (ms) | 32 | 1 | 1 | 32 |
| Thermister | Thermal | Component temperature | 12 | 0.1 | 40 | 48 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Heat Shield Thermocouple | | Front shield temperature | 16 | 1 | 8 | 128 |
| Heater Status | | On/Off State | 1 | 1 | 20 | 20 |
| Solar Array RTD | | Solar array panel Temperature | 12 | 1 | 4 | 48 |
| Bus Voltage Sensor | Power | 28 V bus | 16 | 1 | 4 | 64 |
| Battery Cell Voltage | | Per-cell voltage | 12 | 0.1 | 50 | 60 |
| Bus Current Sensor | | Branch current | 16 | 1 | 8 | 128 |
| Battery Temp | | State of charge | 16 | 0.1 | 2 | 3 |
| MPPT Regulator | | Voltage, current, power per channel | 16 | 1 | 3 | 144 |
| ASTRIX200 IMU | ADCS | 3-axis rate + 3-axis acceleration | 32 x 6 | 10 | 2 | 3840 |
| Leonardo A-STAR | | Attitude quaternion | 32 x 4 | 1 | 2 | 256 |
| Jena-Optronik FSS | | Sun angle | 16 x 2 | 1 | 2 | 64 |
| Reaction Wheel | | Speed, torque, current | 16 x 3 | 1 | 4 | 192 |
| Phoenix Flight Computer | C&DH | CPU, memory, FDIR | 32 | 1 | 2 | 64 |
| SSMM | | Utilization, ECC errors | 32 x 2 | 1 | 1 | 64 |
| Rocketdyne R-4D-11 | Propulsion | Chamber pressure, valve status, propellant flow | 16 | 1 | 6 | 96 |

| | | | | | | |
|---|---|---|---|---|---|---|
| MR-106L RCS Thrusters | | Pulse count, energy | 16 | 1 | 16 | 256 |
| Fuel Tank | | Pressure, temperature | 16 x 2 | 0.1 | 4 | 13 |
| Propellant Flow | | Mass flow rate | 16 | 1 | 1 | 16 |
| ONC-W Camera HK | Payload | Status, temperature, exposure | 16 | 1 | 1 | 16 |
| LORRI Camera HK | | Status, temperature, exposure | 16 | 1 | 1 | 16 |
| IR Camera | | Status, temperature, exposure | 16 | 1 | 1 | 16 |
| Laser Altimeter | | Range | 16 | 1 | 1 | 16 |
| L3Harris UST Transponder | Comms | RF Status, AGC, PLL lock | 16 | 1 | 8 | 128 |
| Thales TH47TWTA | | Helix current, anode voltage, temperature | 16 | 1 | 6 | 96 |
| APME Gimbal | | Position, current, status | 16 | 1 | 4 | 64 |
| **Total HK** | | | | | | **5888 bps** |

Table 13.6.4 combines the per-component data rates with their on/off state in each mode to give the total data-generation rate per mode. The rate climbs from 1.38 kbps in Standby to a peak of 694.5 kbps during Inspection, when all three imagers, the laser altimeter, and the full sensor suite operate simultaneously. Pre-Inspection and Approach follow at ~242 kbps each (single-camera imaging), and Safe and Conjunction modes fall back to the ~5–6 kbps housekeeping floor.

**Table 13.5.16: Component Activity Across ODIN Mission Modes**

| Component | Data | Standby | Cruise | Pre-Inspec | Approach | Inspection | Downlink | Safe | Conju |
|---|---|---|---|---|---|---|---|---|---|

| | Rate (kbps) | | | tion | | | | | nction |
|---|---|---|---|---|---|---|---|---|---|
| Comms | | | | | | | | | |
| HGA Imagery Downlink | 85 - 89 | OFF | OFF | OFF | OFF | OFF | ON | OFF | OFF |
| HGA Cruise Downlink | 50 | OFF | ON | OFF | OFF | OFF | OFF | OFF | OFF |
| LGA Telemetry | 0.35 | OFF | OFF | OFF | OFF | OFF | OFF | ON | OFF |
| UST Receiver (Uplink) | 0.5 | ON | ON | ON | ON | ON | ON | ON | OFF |
| Thales TWTA | 0.096 | OFF | ON | OFF | OFF | OFF | ON | ON | OFF |
| APME Gimbal | 0.064 | ON | ON | ON | ON | ON | ON | OFF | OFF |
| C&DH | | | | | | | | | |
| Phoenix Flight Computer | 0.064 | ON | ON | ON | ON | ON | ON | ON | ON |
| SSMM | 0.032 | ON | ON | ON | ON | ON | ON | ON | ON |
| AccuBeat USO | 0.032 | ON | ON | ON | ON | ON | ON | ON | ON |
| Power | | | | | | | | | |
| Bus Voltage | 0.064 | ON | ON | ON | ON | ON | ON | ON | ON |
| Bus Current | 0.128 | ON | ON | ON | ON | ON | ON | ON | ON |
| Battery Cells | 0.060 | ON | ON | ON | ON | ON | ON | ON | ON |
| MPPT Regulator | 0.144 | ON | ON | ON | ON | ON | ON | ON | ON |
| Solar array temperature | 0.048 | ON | ON | ON | ON | ON | ON | ON | ON |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Battery Temp | 0.003 | ON | ON | ON | ON | ON | ON | ON | ON |
| Thermal | | | | | | | | | |
| Thermistors (x40) | 0.048 | ON | ON | ON | ON | ON | ON | ON | ON |
| Heat shield TCs | 0.128 | ON | ON | ON | ON | ON | ON | ON | ON |
| Heater status | 0.020 | ON | ON | ON | ON | ON | ON | ON | ON |
| ADCS/GNC | | | | | | | | | |
| ASTRIX200 IMU | 3.840 | OFF | ON | ON | ON | ON | ON | ON | ON |
| A-STAR Star Tracker | 0.256 | OFF | ON | ON | ON | ON | ON | OFF | ON |
| Jena FSS | 0.064 | OFF | ON | ON | ON | ON | ON | ON | ON |
| Reaction Wheel | 0.192 | OFF | ON | ON | ON | ON | ON | ON | ON |
| Propulsion | | | | | | | | | |
| Rocketdyne R-4D-11 | 0.096 | OFF | ON | OFF | ON | ON | OFF | OFF | OFF |
| MR-106L RCS Thrusters | 0.256 | OFF | OFF | OFF | ON | ON | OFF | OFF | OFF |
| Fuel Tank P/T | 0.013 | ON | ON | ON | ON | ON | ON | ON | ON |
| Propellant Flow | 0.016 | OFF | ON | OFF | ON | ON | OFF | OFF | OFF |
| Payload | | | | | | | | | |
| ONC-W HK | 0.016 | OFF | OFF | ON | ON | ON | OFF | OFF | OFF |
| LORRI HK | 0.016 | OFF | OFF | OFF | OFF | ON | OFF | OFF | OFF |
| IR Camera HK | 0.016 | OFF | OFF | ON | ON | ON | OFF | OFF | OFF |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ONC-W Imagery | 236.1 | OFF | OFF | ON | ON | ON | OFF | OFF | OFF |
| LORRI Imagery | 228.1 | OFF | OFF | OFF | OFF | ON | OFF | OFF | OFF |
| IR Camera Imagery | 224.0 | OFF | OFF | OFF | OFF | ON | OFF | OFF | OFF |
| Laser Altimeter | 0.16 | OFF | OFF | OFF | OFF | ON | OFF | OFF | OFF |
| **Total (kbps)** | | **1.38** | **55.94** | **241.86** | **242.23** | **694.50** | **90.83 – 94.83** | **5.86** | **5.17** |

The defining result of the data budget is the gap between peak generation and downlink capacity. During inspection ODIN generates ~694.5 kbps, while the X-band HGA closes the link at only 12.2–89 kbps depending on Earth–spacecraft range. The spacecraft therefore cannot downlink imagery in real time; all payload and sensor data are written to the SSMM and cleared over subsequent scheduled ESTRACK contacts. This storage-and-forward requirement is what sizes the SSMM capacity and sets the contact-window cadence treated in the link budget and ConOps analysis, and it confirms that the data architecture is buffer-driven rather than real-time.

### 13.5.8 COMMS CONCEPT OF OPERATIONS

This section describes how the communications subsystem is operated across the inspection campaign — when each link is active, what it carries, and how the subsystem responds to off-nominal conditions. The concept of operations is organized around the campaign timeline of Figure 13.5.13, which traces ODIN from window preconditions through approach, the human-in-the-loop GO/NO-GO gate, the autonomous six-face inspection, and departure.

Two communications regimes run through this timeline. The nominal regime, shown in the yellow flow, carries all command uplink and high-rate data downlink on the X-band HGA during scheduled ESTRACK contacts. The gate/anomaly regime, shown in red, falls back to the omnidirectional LGA for attitude-independent safe-mode TT&C whenever the spacecraft cannot point or an anomaly forces a safe-hold. A continuous housekeeping telemetry stream underlies both regimes in every mission phase, allowing ground operators to monitor spacecraft health regardless of which link is active.

The operating principle that shapes the entire concept is the imbalance between data generation and downlink capacity. During inspection ODIN produces data far faster than the link can return it — roughly 694 kbps peak against an 85–89 kbps HGA downlink at inspection range — so the subsystem operates store-and-forward: payload and sensor data are buffered to the SSMM as they are produced and cleared over subsequent passes rather than transmitted in real time. This single constraint governs the contact cadence, the SSMM sizing, and the rhythm of inspection-then-downlink cycles described below.

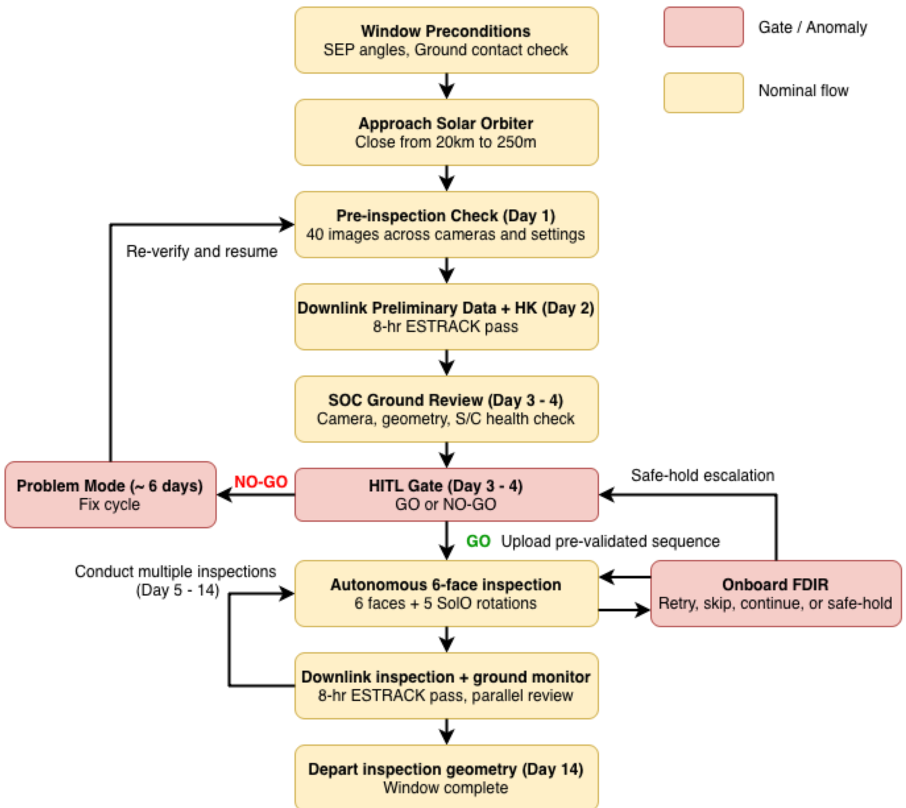


**Figure 13.5.13: Link Budget Summary**

The campaign opens with the window preconditions check, which for communications confirms two things: that the Sun–Earth–Probe geometry places the X-band link outside the solar-conjunction exclusion zone for the duration of the window, and that ESTRACK contact is scheduled. During approach, as ODIN closes from 20 km to 250 m, the HGA maintains the nominal TT&C link; the UST receiver remains powered and tracking the uplink carrier so that approach commands and aborts are received without interruption.

Data generation begins at the pre-inspection check on Day 1, where the 40 calibration images and their housekeeping are captured and buffered in the SSMM — none of this is downlinked in real time. The first scheduled return occurs on Day 2, when the preliminary data and housekeeping downlink clears the buffered Day-1 data to the ground over a single 8-hour ESTRACK pass using the HGA in QPSK, code rate 1/3. This downlink feeds the SOC ground review on Days 3–4, during which the link is primarily quiescent on the downlink side and carries planning traffic on the uplink.

The HITL gate is the pivot between the two regimes. On a GO decision, the ground uplinks the pre-validated autonomous inspection sequence — a BPSK command load at 7.17 GHz — and the campaign proceeds into the autonomous phase. On a NO-GO, the spacecraft enters Problem Mode; communications continue on the HGA at reduced housekeeping activity through the fix cycle until the sequence is re-verified and the flow resumes at the pre-inspection check.

During the autonomous 6-face inspection (Days 5–14), the spacecraft executes its pre-loaded sequence with the comms subsystem in pure store-and-forward: peak data generation is buffered to the SSMM while onboard FDIR handles execution anomalies locally (retry, skip, or continue) without ground intervention. The buffered imagery is cleared on the inspection downlink passes — one 8-hour ESTRACK contact per day, reviewed in parallel on the ground — which size the SSMM capacity and contact cadence, since each pass downlinks only a fraction of what an inspection cycle produces. This downlink/inspection loop repeats across the campaign.

The gate/anomaly path defines the off-nominal communications behavior. If FDIR cannot resolve an anomaly locally, it escalates to a safe-hold, on which the spacecraft autonomously transitions to LGA-based safe-mode communications independent of the HGA. The LGA provides omnidirectional coverage requiring no attitude control, downlinking a reduced critical-housekeeping beacon and accepting emergency telecommand uplink at safe-mode rates (5–20 bps over the air). This re-routes the campaign back through the HITL gate, where ground operators diagnose the condition and issue a recovery sequence before any return to autonomous operation.

The campaign closes when ODIN departs the inspection geometry on Day 14. Communications revert to the cruise configuration, with the HGA downlinking at the reduced rates appropriate to the increasing Earth–spacecraft range (down to 12.2 kbps near 2.0 AU) and the housekeeping stream continuing uninterrupted.

## 13.5.9 CONTACT WINDOW

The contact window analysis establishes the time each inspection cycle requires, the data volume it generates, whether that volume can be cleared against the available ESTRACK contact, and how the imaging, rotation, margin, and downlink phases partition the 24-hour inspection day. The analysis is bounded by four inputs established earlier in the report: the 8-hour daily ESTRACK downlink cap; the inspection-geometry data rates of 85 kbps at Inspection 1 (0.762 AU) and 89 kbps at Inspection 2 (0.731 AU) from the link budget of Table 13.5.13; the per-image compressed volumes of the three-camera payload (ONC-W 0.8853 MB, LORRI 1.1531 MB, LWIR 0.8400 MB); and the Solar Orbiter rotation rate of ω = 0.15 deg/s. The analysis is evaluated at the two inspection epochs and confirms that neither contact capacity nor onboard storage is the limiting resource — the binding constraint on the inspection day is the contiguous off-Sun pointing interval [11], [15], [20].

### 13.5.9.1 DATA VOLUME ANALYSIS

As defined by Payload subteam, each inspection cycle covers six faces of Solar Orbiter, with every face imaged by all three cameras: 6 ONC-W, 6 LORRI, and 44 LWIR exposures, for 56 images per face and 336 images per cycle. The compressed data volume per face is the sum over the three cameras of image count times per-image size:

$$D_{face} = \Sigma N_{images} S_{per\ image} \tag{13.5.16}$$

**Table 13.5.17: Image PLan and Data Volume per Face**

| Camera | Image/face | Size/face (MB) | Data/fave (MB) |
|---|---|---|---|
| ONC-W | 6 | 0.8553 | 5.31 |
| LORRI | 6 | 1.1532 | 6.92 |
| LWIR | 44 | 0.8400 | 36.96 |
| **Total** | **56** | **-** | **49.19** |

Over six faces the camera data totals 295.14 MB; adding the background housekeeping generated during imaging, margin, and rotation phases brings the queued volume per cycle to 311.04 MB. The middle panel of Figures 13.5.14a–b resolves this per timeline segment — six ~49 MB imaging blocks plus background housekeeping — and the lower panel shows the resulting single-day SSMM fill peaking at 303.7 MB before the downlink pass clears it.

$$D_{cycle} = N_{faces} D_{face} + D_{HK,bg} = 311.04\, MB$$

The single-pass downlink capacity is the data rate times the 8-hour contact: 306 MB at 85 kbps and 320.4 MB at 89 kbps. Comparing the two:

**Table 13.5.18: Data Volume per Cycle vs. Single-Pass Capacity**

| | Inspection 1 (85 kbps) | Inspection 2 (89 kbps) |
|---|---:|---:|
| Camera data per cycle | 311.04 MB | 311.04 MB |
| 8-hr pass capacity | 306.0 MB | 320.4 MB |
| Margin (camera only) | +5.0 MB | -9.4 MB |
| Contacts to clear one cycle | 2 | 1 |

Figures 13.5.14a (Inspection 1, 85 kbps) and 13.5.14b (Inspection 2, 89 kbps) contrast the two cases directly: in the per-segment panel the downlink-capacity bar falls just short of the cycle total at 85 kbps and exceeds it at 89 kbps, which is the +5.0 / −9.4 MB residual of the table.

At Inspection 2 a single pass clears the cycle with 9.4 MB of margin. At Inspection 1 the cycle exceeds single-pass capacity by 5.0 MB, so each cycle leaves a small residual that is carried into the following pass. Across the nine-cycle campaign this accumulates to roughly 45 MB of carried backlog — bounded, monotonic, and cleared on the final passes of the window. The end-of-window SSMM occupancy is 712.9 MB at Inspection 1 and 583.3 MB at Inspection 2, both dominated by the Day-14 departure data rather than the per-cycle imaging residual. Figures 13.5.15a–b (14-day window) show this campaign-level behavior: the cumulative-downlink trace trails generation by a fixed offset that retires on the final passes, while the SSMM trace stays below 0.8 GB against the 64 GB limit — confirming storage is never the constraint.

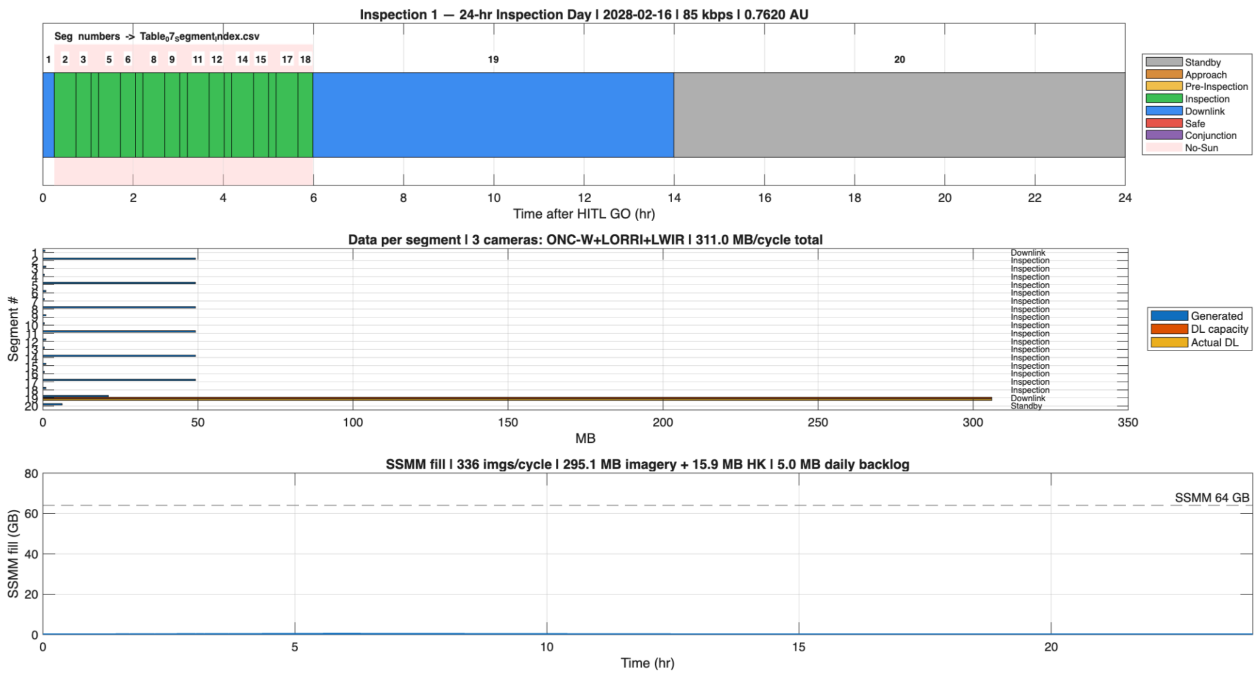


**Figure 13.5.14a: MATLAB Simulation Result of Inspection 1 single inspection day (2028-02-16, 0.762 AU, 85 kbps): operating-mode timeline, per-segment data volume vs. downlink capacity, and 24-h SSMM fill.**

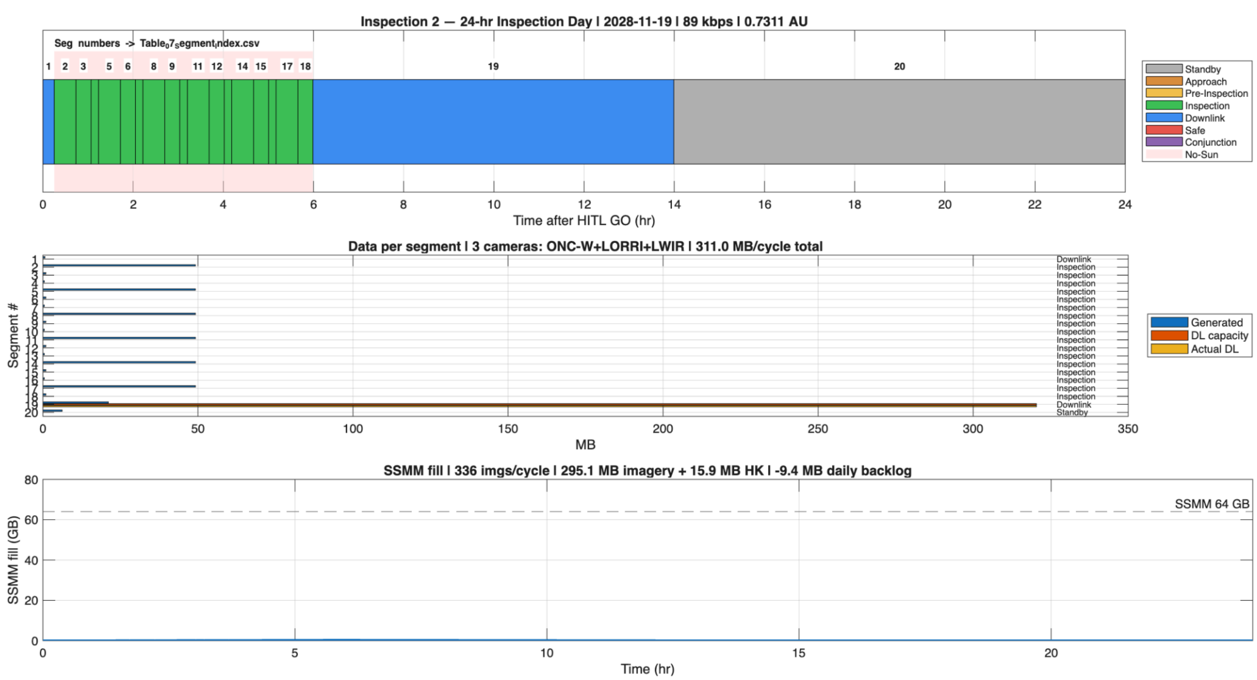

Figure 13.5.14b: MATLAB Simulation Result of Inspection 2 single inspection day (2028-11-19, 0.731 AU, 89 kbps): same panels as 13.5.17a.

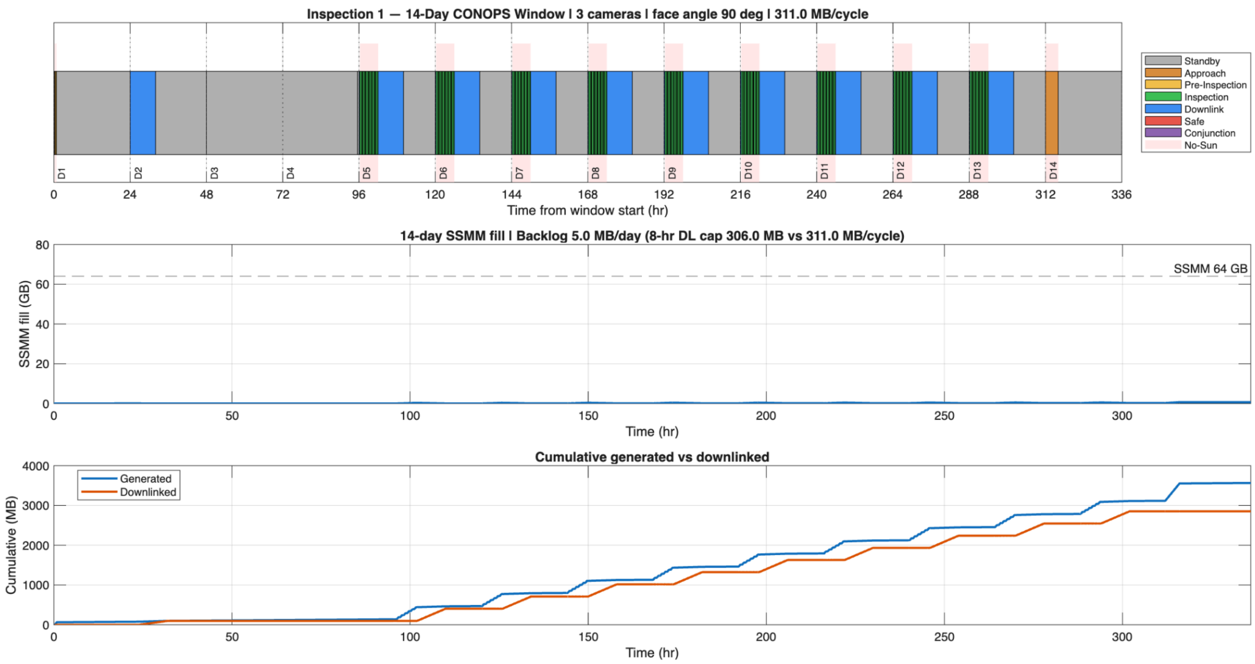


Figure 13.5515a: MATLAB Simulation Result of Inspection 1 14-day CONOPS window: mode timeline, SSMM fill, and cumulative generated vs. downlinked.

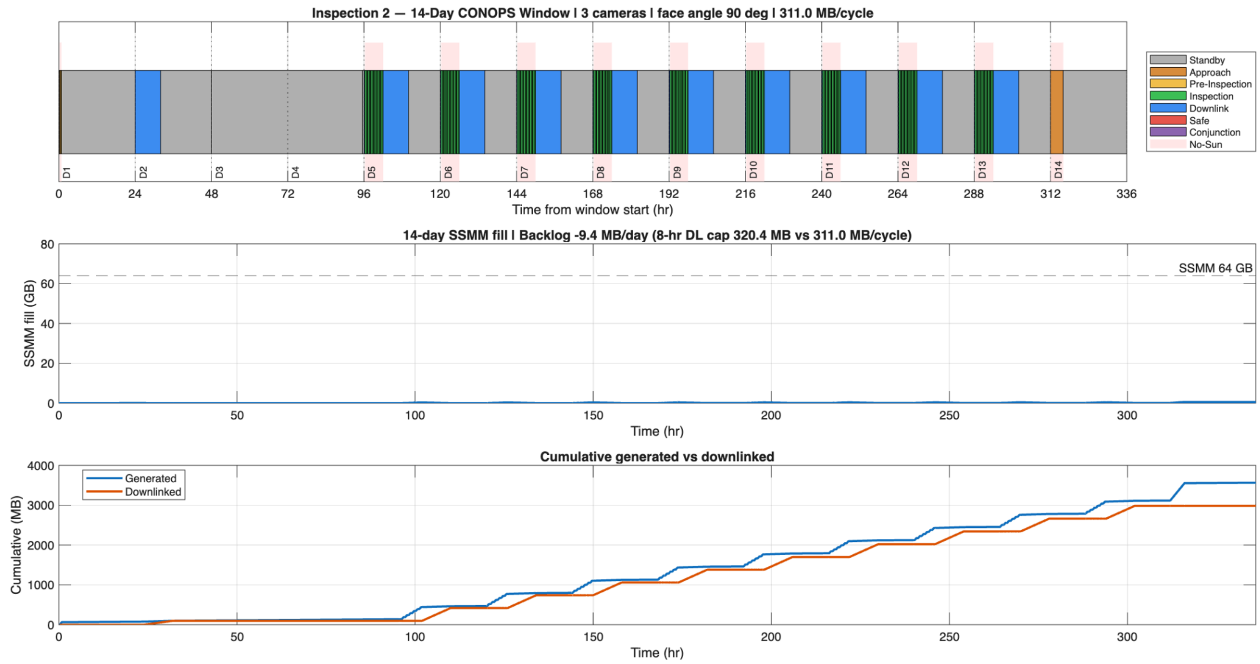


**Figure 13.5.15b: MATLAB Simulation Result of Inspection 2 14-day CONOPS window: same panels as 13.5.18a.**

## 13.5.9.2 DUTY CYCLE ANALYSIS

The 24-hour inspection day partitions into four operating modes, shown in Figure 13.5.20: a 0.25-hour sequence upload, the 5.74-hour off-Sun inspection interval, the 8.00-hour downlink and ground-monitor pass, and 10.01 hours of Sun-pointing standby. The inspection interval itself decomposes into imaging, inter-face rotation, and operational margin:

$$t_{cycle} = N_{faces}\,(t_{image} + t_{margin}) + N_{rot}\,t_{rot} \qquad 13.5.17$$

The per-camera imaging cadence follows from the Table 13.5.16 data rates and the compressed image sizes, $t_{cycle} = 8\,S_c / R_c$, giving 30.0 s for ONC-W and LWIR and 40.4 s for LORRI; with 56 sequential exposures this yields 29.04 min of imaging per face. Each face adds a 20-min margin (3 min attitude settle + 2 min onboard validation + 15 min ground reserve), and the five inter-face transitions take 10 min each (90° cube rotation at 0.15 deg/s = 600 s):

$$t_{cycle} = 6\,(29.4 + 20) + 5(10) = 344\,min = 5.74\,h$$

**Table 13.5.19: Inspection-Day Duty Fractions**

| Activity | Duration (h) | % of 24-hr day |
|---|---:|---:|
| Sequence upload | 0.25 | 1.0 % |
| Imaging | 2.90 | 12.1 % |
| Rotation | 0.83 | 3.5 % |
| Margin / validation | 2.00 | 8.3 % |
| Downlink / ground monitor | 8.00 | 33.3 % |
| Standby / Sun-pointing | 10.01 | 41.7 % |
| **Inspection (off-Sun) subtotal** | **5.74** | **23.9 %** |

The downlink pass (33.3%) and standby (41.7%) together occupy three-quarters of the day, leaving ample schedule margin: the spacecraft spends more time in the downlink and Sun-pointing states than in active inspection, which is the desired posture for thermal and power management.

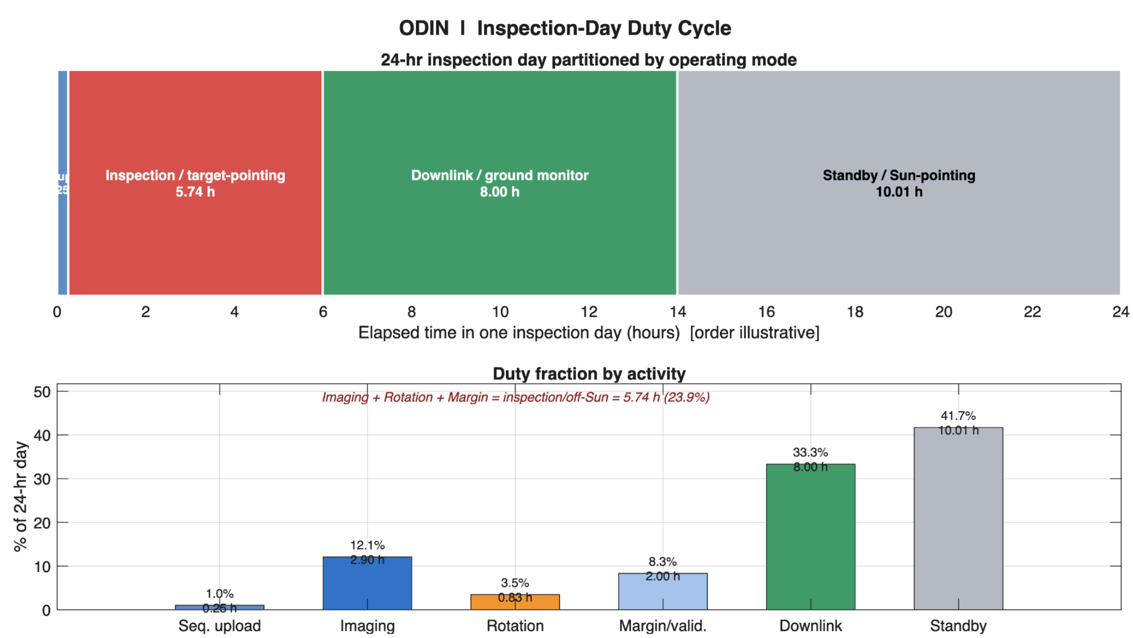

Figure 13.5.16: MATLAB Simulation Result of Inspection Duty Cycle

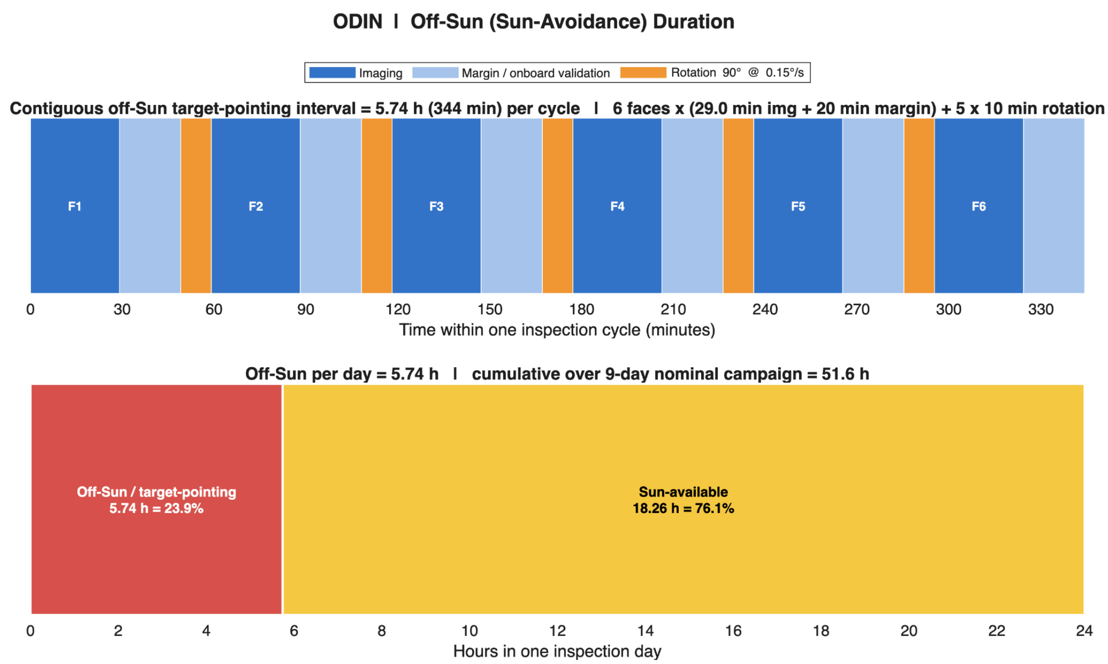


Figure 13.5.17: MATLAB Simulation Result of Inspection Duty Cycle

## 13.5.10 COMMS FAILURE MODES

The communications failure modes were assessed using a four-level severity scale, defined below, that ranks each mode by its consequence to mission success rather than by the affected component. Severity 4 modes represent complete loss of ground contact and drive the redundancy architecture; severity 2–3 modes are tolerated through degraded-mode operation. As a reminder, ODIN's mission failure modes are following:

Table 13.5.20: ODIN Failure Modes

| Code | Name | Description |
|---|---|---|
| 1 | Non-Critical | If this error occurs, the primary mission could still be accompanied without additional need for redundancy. |
| 2 | Reduced Capability | If this error cannot be mitigated, the mission is still a success, but further |

| | | |
|---|---|---|
| | | research is needed to extend mission lifetime in future missions. |
| 3 | Reduced Lifetime | If this error cannot be mitigated, the mission is still a success, but further research is needed to provide increased capability. |
| 4 | Mission Failure | If this error cannot be mitigated, the mission will be a failure - no communications to the ground station. |

Applying this scale to the communications chain yields the failure modes below, organized by part. Every severity-4 mode is covered by hot or cold redundancy with autonomous switchover, so that no single hardware failure severs the link.

**Table 13.5.21: ODIN Comms Failure Modes**

| Part | Failure | Code | Effect | Mitigation |
|---|---|---|---|---|
| L3Harris UST Transponder | Power failure | 4 | Complete loss of uplink and downlink; no | Redundant transceiver (hot spare). Automatic switchover upon loss-of-signal |
| | Firmware crash | 3 | Transceiver unresponsive; uplink commands not received | MCU watching resets transceiver. Backup firmware image stored in protected memory |
| | Oscillator frequency drift | 2 | Frequency offset; ground station must re-acquire signal | UST internal AFC (automatic frequency control) compensates for drift. Ground station commanded re-acquisition if AFC range exceeded. |
| Thales TH47 TWTA | Overheating | 3 | TWTA shutdown; loss of high-power downlink; reduced data throughput | Phoenix monitors TWTA temperature via telemetry. Duty cycle limited and transmit power reduced if thermal threshold exceeded. LGA used for housekeeping downlink during recovery. |
| | High-voltage power supply failure | 3 | No RF amplification; downlink signal loss | Fallback to UST direct low-power output via LGA. Housekeeping and beacon downlink maintained at reduced data rate. |
| | TWTA cathode degradation (end of life) | 2 | Gradual output power reduction; reduced link margin. | Link budget carries margin for expected cathode lifetime degradation. Reduced data rate mode commanded if margin drops below threshold. |

| | | | | |
|---|---|---|---|---|
| HGA | Deployment failure | 4 | No high-gain RF link; mission-critical data downlink unavailable | Redundant burn wire deployment mechanism. Secondary deployment attempt from ground. LGA maintains an emergency communications link. |
| | Pointing error | 3 | Degraded link margin; reduced science data downlink rate | ADCS re-points spacecraft to compensate. Ground recalculates pointing solution and uplinks corrected ephemeris. |
| LGA | Chip failure | 2 | Loss of omnidirectional emergency link; reduced redundancy | HGA used for all communication in degraded mode. Mission success preserved. Emergency recovery capability reduced. Design review to assess single-point risk. |

The redundancy and recovery paths identified above define what the verification program must demonstrate: that each mitigation actually performs as claimed. These are carried into the V&V plan in Section 13.5.11.

## 13.5.11 COMMS VERIFICATION & VALIDATION PLAN

The communications V&V plan verifies each subsystem requirement (SSR-COMM-01 through -06) through the appropriate method — analysis for link-budget and ConOps closure, test for hardware-in-the-loop functional behavior, and review for ground-segment compatibility. Each entry traces to its governing requirement and assigns a verification level and type, summarized below.

**Table 13.5.22: ODIN Comms V & V Plan**

| Verification Name | Req. ID | Purpose | Method | Description | Level | V&V Type |
|---|---|---|---|---|---|---|
| X-Band Link Performance (HGA, inspection) | SSR-COMM-01, SSR-COMM-03, SSR-COMM-04 | Verify 6 dB minimum link margin at achievable data rate at both inspection geometries. | Analysis (A) | Inspection link budget evaluated at Inspection 1 (0.76 AU, 85 kbps) and Inspection 2 (0.73 AU, 89 kbps). QPSK rate ⅓ | Subsystem | Performance |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | downlink. Includes atmospheric and pointing loss contributions. Results: 6.0 and 6.1 dB margins. | | |
| X-Band Link Performance (HGA, Cruise) | SSR-COMM-01, SSR-COMM-03 | Verify 6 dB minimum link margin at worst case range (2.0AU) using HGA. | Analysis (A) | Analytical free-space link budget evaluated at 2.0 AU using EIRP = 53.87 dBW and ESTRACK 35-m G/T = 48.19 dB/K. | Subsystem | Performance |
| LGA Safe Mode Link | SSR-COMM-01, SSR-COMM-03 | Verify LGA provides positive link margin for housekeeping TT&C at worst-case and nominal range. | Analysis (A) | LGA link budget evaluated at 2.0 AU and 1.0 AU with TWTA backed off 40 W RF output. BPSK, low data rate. LGA gain; 4.9 dBi downlink, 3.9 dBi uplink. Confirms full-safe mode TT&C independent of HGA. | Subsystem | Performance |
| Solar Conjunction Blackout Verification | SSR-COMM-01, SSR-CDH-01 | Confirm no planned inspection windows overlap with solar conjunction X-band exclusion zone, and that SSMM stores all data accumulated during the blackout. | Analysis (A) | SSMM utilization during 14-day conjunction blackout verified against storage capacity via RF ConOps simulation. Post-conjunction recovery pass count calculated. | System | Functional |
| Contact Window Scheduling | SSR-COMM-01, SSR-COMM-04, SSR-COMM-05 | Verify ESTRACK handover timing across Malargüe, Cebreros, and New Norcia provides sufficient daily contact time to clear | Analysis (A) | MATLAB contact window analysis accounts for maintenance blackouts and inspection cycle timelines. | Subsystem | Functional |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | inspection data volumes. | | Verified against 8-hour daily downlink cap. | | |
| Uplink Command Reception Test | SSR-COMM-06 | Confirm UST transponder receives, | Test (T) | Bench test: simulated ESTRACK 7.17 GHz BPSK uplink signal injected at UST RF input. Commanded data rates exercised across the full UST range. OBC 1553B bus activity monitored to confirm command routing on both Bus-A and Bus-B. | Subsystem | Functional |
| Payload Data Downlink Functional Test | SSR-COMM-04 | Verify end-to-end science image downlink from SSMM through UST and TWTA to ground receiver. | Test (T) | SSMM loaded with representative compressed imagery (0.858 MB/image). Downlink test through UST (42 W Rx + Tx) and TWTA (70 W RF) to ground RF front end. QPSK rate ⅓ at 85 and 89 kbps. BER and data rate measured. | Subsystem | Functional |
| HGA Gimbal Pointing Functional Test | SSR-COMM-01, SSR-COMM-03 | Verify the APME two-axis gimbal achieves Earth-pointing accuracy sufficient to stay within the 0.5 dB pointing loss allocation in the link budget. | Test (T) | APME gimbal exercised through full azimuth and elevation operational range in ground test fixtures. Pointing error measured at multiple commanded positions and | Component | Performance |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | compared against 0.5 dB link budget allocation. | | |
| RF Switch Matrix Cross-Strap Test | SSR-COMM-01 | Verify all RF cross-strap switching configurations correctly route signals, ensuring no single component failure breaks the communication link. | Test (T), Inspection (I) | RF distribution assembly bench test cycles valid switch states: UST-1 → TWTA-1 → HGA, UST-1 → TWTA-2 → HGA, UST-2 → TWTA-1 → HGA, UST-2 → TWTA-2 → HGA, and both LGA chains. Diplexer isolation, insertion loss, and antenna select switch routing verified per state. | Subsystem | Functional |
| Safe Mode Communications Test | SSR-COMM-01, SSR-COMM-05, SSR-COMM-06 | Verify the spacecraft autonomously transitions to LGA-based safe mode communications on HGA failure, maintaining housekeeping downlink and emergency uplink. | Test (T) | Safe mode transition triggered by simulated HGA deployment failure. Autonomous routing of UST through LGA chain confirmed. LGA uplink and downlink exercised at safe mode TT&C data rates. Beacon transmission monitored. | System | Functional |
| ESTRACK X-Band Ground Segment Compatibility Review | SSR-COMM-02 | Confirm that the designated ESTRACK deep-space ground stations (Malargüe, Cebreros, New | Review (R) | Review of ESA ESTRACK network specifications confirming 35m DSA stations | System | Functional |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Norcia) are equipped with X-band uplink/downlink capability compatible with ODIN's 7.17 GHz uplink and 8.40 GHz downlink frequencies. | | operate X-band and that the station G/T = 48.19 dB/K is consistent with published ESTRACK capability. Compatibility confirmed by cross-reference against the ODIN link budget input assumptions. | | |

Together these activities close every communications requirement: the analysis cases confirm link margin and data-volume feasibility, the bench and system tests confirm command reception, downlink, cross-strap switching, and autonomous safe-mode transition, and the ground-segment review confirms ESTRACK compatibility. The failure modes these tests exercise are carried into the risk assessment in Section 13.5.12.

## 13.5.12 COMMS RISK MANAGEMENT

The communications failure modes are placed on a 5×5 likelihood–consequence matrix to prioritize residual risk after mitigation. Each lettered item corresponds to a failure mode from Section 13.5.10; its position reflects the post-mitigation likelihood and the severity of its effect, so that items remaining in the upper-right region would warrant further design attention.

**Table 13.5.22: ODIN Comms Risk Management**

| | | | | | |
|---|---|---|---|---|---|
| **Certain** >80% | | | | | |
| **Likely** 60% - 70% | | F | | | |
| **Possible** 40% - 59% | | | H | | |
| **Unlikely** 20% - 39% | | C | D | | |
| **Rare** | | I | B, E | | A, G |

| | | | | | |
|---|---|---|---|---|---|
| < 20% | | | | | |
| | 1<br>Insignificant | 2<br>Minor | 3<br>Moderate | 4<br>Major | 5<br>Severe |

The lettered entries are defined below, with the effect and mitigation that justify each placement:

**Table 13.5.23: ODIN Comms Failure Mode Groups**

| Code | Failure Name | Effect | Mitigation |
|---|---|---|---|
| A | Transponder power failure | Complete loss of uplink and downlink; no ground contact possible. | Redundant transceiver on hot standby; automatic switchover upon loss-of-signal detection. |
| B | Transponder firmware crash | Transceiver unresponsive; uplink commands not received. | OBC watchdog resets transceiver. Backup firmware image stored in protected memory. |
| C | Oscillator frequency drift | Frequency offset; ground station must re-acquire signal. | UST internal AFC compensates for drift. Ground station commanded re-acquisition if AFC range exceeded. |
| D | TWTA overheating | TWTA shutdown; loss of high-power downlink; reduced data throughput. | Phoenix monitors TWTA temperature via telemetry. Duty cycle limited and transmit power reduced if thermal threshold exceeded. LGA used for housekeeping downlink during recovery. |
| E | TWTA high-voltage power supply failure | No RF amplification; downlink signal loss. | Fallback to UST direct low-power output via LGA. Housekeeping and beacon downlink maintained at reduced data rate. |
| F | TWTA cathode degradation (end of life) | Gradual output power reduction; reduced link margin over mission lifetime. | Link budget carries margin for expected cathode degradation. Reduced data rate mode commanded if margin drops below threshold. |

| | | | |
|---|---|---|---|
| G | HGA deployment failure | No high-gain RF link; mission-critical data downlink unavailable. | Redundant burn wire deployment mechanism. Secondary deployment attempt from ground. LGA maintains emergency communications link. |
| H | HGA pointing error | Degraded link margin; reduced science data downlink rate. | ADCS re-points spacecraft to compensate. Ground recalculates pointing solution and uplinks corrected ephemeris. |
| I | LGA chip failure | Loss of omnidirectional emergency link; reduced redundancy. | HGA used for all communication in degraded mode. Mission success preserved. Emergency recovery capability reduced. Design review to assess single-point risk. |

All communications failure modes fall in the rare-to-unlikely likelihood band after mitigation, with no item in the high-likelihood/high-consequence region. The two mission-critical modes — transponder power failure (A) and HGA deployment failure (G) — are held at *rare* likelihood by hot-spare redundancy and redundant deployment respectively, so that no single credible failure results in loss of mission. This closes the communications subsystem analysis.

## 13.5.13 COMMAND & DATA HANDLING SUBSYSTEM REQUIREMENTS

**Table 13.5.24: ODIN C&DH Subsystem-level Requirements**

| SSR-ID | Requirement Type | Description | Verified by | Rationale for requirement | Traces to |
|---|---|---|---|---|---|
| **SSR-CDH-01** | Constraint | The CD&H shall store payload data and HK telemetry onboard during blackout periods, with capacity for a minimum of 30 days of continuous HK accumulation. | Analysis (A) & Test (T) | Heliocentric orbit produces communication blackouts; onboard storage ensures no mission-critical data is lost between contact windows. 30 days provides margin over the worst-case ~ 14 - 22 day solar-conjunction blackout and | SYS-5-1 |

| | | | | | |
|---|---|---|---|---|---|
| | | | | bonds SSMM sizing. | |
| **SSR-CDH-02** | Operational | The CD&H shall packetize and format all telemetry per CCSDS TM Space Data Link Protocol (CCSDS 132.0-B) and Space Packet Protocol (CCSDS 133.0-B). | Analysis (A) & Test (T) | CCSDS compliance ensures compatibility with ESTRACK decommutation chains and DSN cross-support, and enables efficient use of the 1.5 MHz channel bandwidth. | SYS-5-1, SYS-5-2 |
| **SSR-CDH-03** | Operational | The CD&H shall receive, authenticate, decode, and route uplink commands via MIL-STD-1553B on both Bus-A and Bus-B | Test (T) | Reliable command handling is required for ground operator control of ODIN, including proximity operations and contingency response. | SYS-5-2 |
| **SSR-CDH-04** | Operational | The CD&H shall autonomously initiate FDIR responses within 60 seconds of anomaly detection. | Analysis (A) & Test (T) | 60-second response time is derived from the attitude divergence rate budget (SSR-ADCS-02/03). Ground response is not possible during blackouts or at inspection-geometry light-time delays (~8–10 min). | SYS-5-1, SYS-5-2 |
| **SSR-CDH-05** | Operational | The CD&H shall maintain mission time synchronization using the ultra-stable oscillator (USO), achieving a max time drift of ±10 μs over any 24-hour period without ground correction, and a synchronization accuracy of ±1 μs following UST coherent ranging at each ground contact. | Analysis (A) & Test (T) | The AccuBeat USO aging spec ($<7\times10^{-11}$/day) limits free-running drift to ~6 μs/day, providing ample margin on the ±10 μs floor and maintaining sub-ms timing accuracy throughout the worst-case 30-day conjunction blackout without ground correction. The ±1 μs post-ranging value supports multi-sensor HK data correlation and inspection image timestamping. | SYS-5-1, SYS-5-3 |

## 13.5.14 COMMAND & DATA HANDLING FUNCTIONAL ANALYSIS

**Table 13.5.25: ODIN C&DH High-Level Functional Analysis**

| No. | Function Name | Description | Inputs | Outputs |
|---|---|---|---|---|
| 1 | Command Receipt | Receive commands decoded by the | Decoded command | Authenticated, |

| | | | | |
|---|---|---|---|---|
| | and Routing | UST transponder, authenticate via CCSDS telecommand protocol, and route to the correct subsystem over MIL-STD-1553B Bus-A or Bus-B | packets from UST over 1553B | routed commands to ADCS, payload, propulsion, COMMS |
| 2 | Telemetry Collection and Packetization | Collect 5,888 bps of health and status data from all subsystems at defined rates; packetize in CCSDS Space Packet format and queue for downlink | Raw sensor readings from all subsystems | CCSDS-compliant HK telemetry frames queued in SSMM for downlink |
| 3 | Onboard Data Storage Management | Manage the 96 GiB SSMM — store payload imagery and HK during blackout periods, track memory allocation, and flag corrupted blocks via Reed-Solomon ECC before downlink | Payload imagery from SpaceWire bus, HK from 1553B | Data stored in SSMM with ECC; utilisation telemetry reported to ground |
| 4 | Autonomous Fault Detection and Response | Monitor spacecraft health continuously and autonomously initiate FDIR responses — watchdog resets, safe mode entry, subsystem switchovers — within 60 seconds of anomaly detection | Health parameters from all subsystems; FDIR fault tree | FDIR response commands; safe mode transition; fault telemetry |
| 5 | Data Processing and Distribution | Apply onboard image compression to payload imagery and distribute formatted science data to COMMS for downlink; distribute processed data to other onboard systems as required | Raw imagery from ONC-W, LORRI, IR Camera via SpaceWire | Compressed imagery in SSMM; formatted data stream to UST for downlink |
| 6 | Time Management | ±10 μs over any 24-hour period using the AccuBeat USO as the primary frequency reference; re-synchronise to ±1 μs via UST coherent ranging at each ground contact | AccuBeat USO 57.51852 MHz reference; UST ranging signal at each ESTRACK contact | Synchronised mission clock; time-stamped telemetry and command sequencing |

## 13.5.16 TIME SYNCHRONIZATION ANALYSIS

The C&DH subsystem requires an onboard time reference accurate enough to timestamp inspection imagery, correlate multi-sensor housekeeping, and sequence autonomous operations during the proximity campaign. Because ODIN operates autonomously across an 8–10 minute one-way light time, the clock must hold its accuracy through a full contact cycle without continuous ground correction. This section identifies the governing timing requirement, shows that the UST internal oscillator cannot meet it, and establishes that the AccuBeat ultra-stable oscillator (USO) satisfies it with margin — motivating its selection as the dedicated timing reference. [21], [26]

### 13.5.16.1 OPERATIONAL TIMING NEEDS

The required clock accuracy is set by the tightest of the subsystem's timing needs. Each need and its basis is given below.

**Table 13.5.26: ODIN C&DH Operation Timing Needs**

| Operational Need | Required Accuracy | Basis |
|---|---|---|
| STRACK contact-window acquisition | ±30 min | 8-hr windows; coarse pointing/scheduling only |
| Autonomous inspection sequence execution | ±30 s | Absorbed by the 20-min per-face operational margin |
| HK multi-sensor correlation (IMU at 10 Hz) | ±50 ms | Half the 100-ms IMU sample interval (Nyquist correlation) |
| Inspection image timestamping (science) | ±1 ms | Sub-sample tie of each exposure to the attitude/ephemeris state |

The binding requirement is the **±1 ms** image-timestamping accuracy: every inspection image must be associated with the spacecraft attitude and position at the instant of exposure so the imagery can be georeferenced to Solar Orbiter's geometry. All other needs are looser by three or more orders of magnitude, so a reference that meets ±1 ms satisfies the full set.

### 13.5.16.2 UST

ODIN's UST internal oscillator has a frequency stability of ±5 ppm. For a fractional frequency offset $\Delta f/f$, the accumulated time error grows linearly with elapsed time:

$$\Delta t = (\Delta f / f)t = (5 \times 10^{-6})\, t \qquad 13.5.18$$

Setting Δt = 1 ms gives t ≈ 200 s — the ±1 ms threshold is exceeded in roughly 3.3 minutes. Holding ±1 ms from the UST oscillator alone would require a ground time-correction uplink every few minutes, which is incompatible with autonomous inspection operations and the 8–10 minute one-way light time. The UST internal oscillator is therefore insufficient as the sole timing reference.

The AccuBeat USO has a frequency aging of $<7\times10^{-11}$ per 24 hours. Taking the worst-case daily aging as a bounding constant fractional frequency offset between ranging updates gives a conservative linear drift:

$$\Delta t = (7 \times 10^{-6})\, t \qquad 13.5.19$$

**Table 13.5.27: Time Drift**

| Elapsed Time | USO Drift |
|---|---|
| 24 hr (one contact cycle) | ~ 6 μs |
| 30 days (conjunction) | ~ 181 μs |
| 167 days | ~ 1 ms |

The USO holds ±10 μs across any single 24-hour contact cycle and does not reach the ±1 ms threshold for over five months of free-running operation. This exceeds every identified timing need — including the 30-day conjunction blackout, during which no ground correction is possible — with substantial margin, and is the basis for selecting the AccuBeat USO as ODIN's dedicated timing reference.

## 13.5.16 COMPONENT SELECTION AND DESIGN (C&DH)

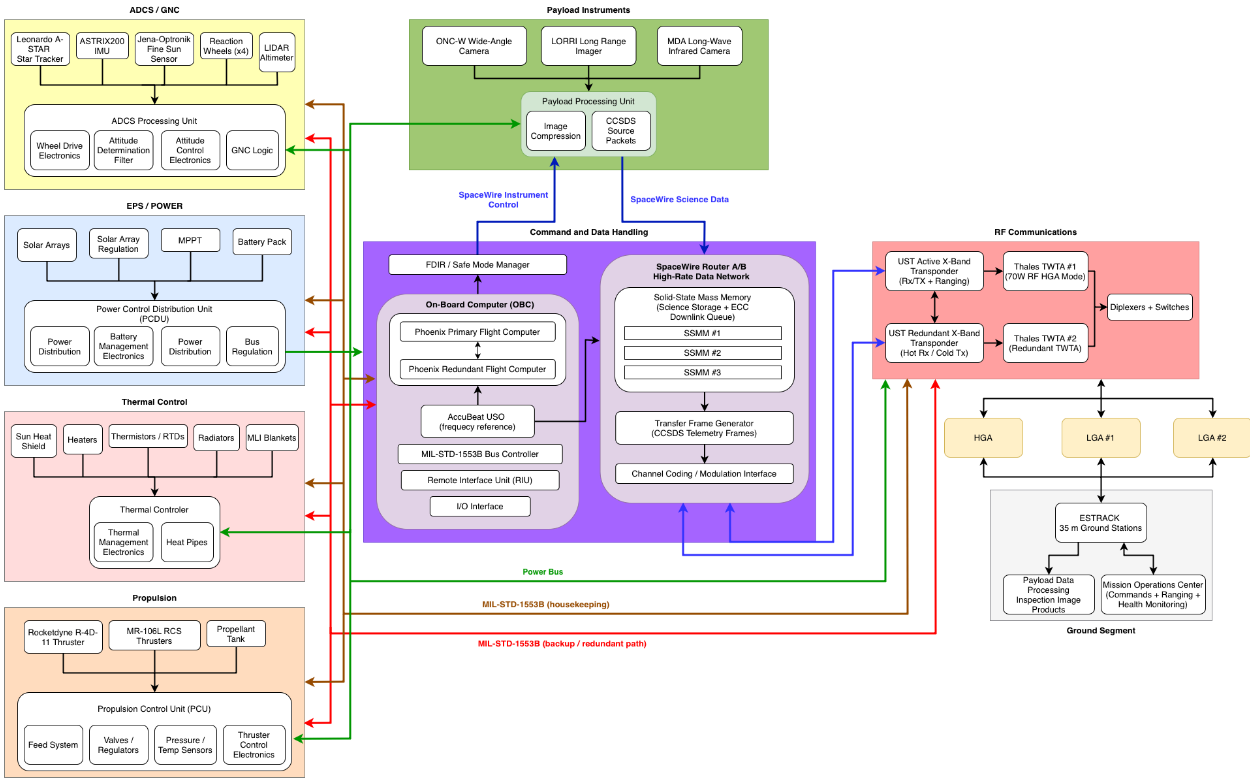


**Figure 13.5.18: ODIN Command and Data Handling Subsystem Block Diagram**

The ODIN Command and Data Handling (C&DH) subsystem provides all onboard data processing, storage, routing, command management, time synchronization, and fault detection functions for the spacecraft. The architecture is derived directly from the Solar Orbiter data handling subsystem heritage, which has demonstrated the dual-bus, SpaceWire-plus-1553B topology across a deep-space science mission in a comparable thermal and radiation environment. [17], [13], [14]

The defining feature of the architecture is the physical separation of high-rate science traffic from low-rate command and housekeeping traffic onto independent buses. Science imagery from the three payload instruments flows over SpaceWire, a high-throughput point-to-point network sized for the ~694 kbps peak inspection generation rate, while commands, telemetry, and housekeeping move over dual MIL-STD-1553B buses. This separation means a fault on the bulk-data path cannot disable command and control, and conversely that science data volume never competes with safety-critical telemetry for bus bandwidth. The two domains meet only at the OBC, which routes between them.

The OBC hosts the Central Software (CSW), which handles all spacecraft functions including attitude and orbit control, thermal control, power management, payload data routing, fault detection isolation and recovery (FDIR), and time synchronization. It is built around redundant Phoenix flight computers in a primary/backup configuration: the primary executes the CSW while the redundant unit is available for failover on a detected processor fault, so that no single computer failure halts spacecraft operations. The OBC provides two independent MIL-STD-1553B bus interfaces to the spacecraft subsystems through a bus controller and remote interface unit (RIU). A failure of either complete bus degrades but does not eliminate spacecraft controllability, because each subsystem remains reachable on the surviving bus. ODIN runs on MIL-STD-1553B because it has been extremely robust in flight, with no anomalies related to lost data or inability to communicate with any unit; the dual-redundant arrangement (primary and backup/redundant path) carries that heritage into a single-fault-tolerant command and housekeeping network.

Science data is handled on a dedicated chain that keeps bulk imagery off the command bus entirely. The three instruments — the ONC-W wide-angle camera, the LORRI long-range imager, and the MDA long-wave infrared camera — deliver raw imagery to the Payload Processing Unit, which performs onboard image compression and formats the output into CCSDS source packets. These packets cross the SpaceWire Science Data link to the SpaceWire Router A/B network in the C&DH subsystem, while instrument configuration and tasking return over a separate SpaceWire Instrument Control link. The redundant A/B router fabric provides a second independent routing path so that a single router or link failure does not sever the science chain.

Because imaging and downlink are sequential — the spacecraft generates data far faster than the link can return it — the Solid-State Mass Memory (SSMM) is the buffer that makes the data budget close. Compressed imagery and housekeeping are written to the SSMM as the science storage and ECC downlink queue, retained with error-correcting protection, and held until the ground confirms receipt rather than being overwritten in place. This makes the SSMM the loss-recovery buffer for the downlink: any frame dropped or failing CRC is retransmitted on a later ESTRACK pass, and at the per-cycle volumes of the inspection campaign the memory operates at a small fraction of its capacity, leaving ample margin to retain unacknowledged data across multiple passes and through the conjunction blackout.

Data leaving the SSMM passes through a fixed CCSDS pipeline before it reaches the radio. The Transfer Frame Generator assembles the queued source packets into CCSDS telemetry transfer frames, and the Channel Coding / Modulation Interface applies the rate-1/3 channel coding and frame error control that the link budget margins are computed against. This pipeline hands formatted, coded frames to the RF subsystem's UST transponders, and is the onboard half of the end-to-end coding-and-detection chain that protects downlink integrity. Housekeeping and low-latency telemetry are multiplexed ahead of bulk imagery in this queue, so a shortened contact never costs critical telemetry.

The FDIR / Safe Mode Manager continuously monitors subsystem health over the housekeeping bus and autonomously commands a transition to safe mode on a detected fault, consistent with the 8–10 minute one-way light time that precludes real-time ground intervention during proximity operations. On a communications fault this includes autonomous reconfiguration to the LGA-based safe-mode link; more broadly, FDIR isolates the failed unit and switches to its redundant counterpart — primary-to-redundant flight computer, A/B router, either 1553B bus, or the cross-strapped RF chain — so that the single-fault tolerance designed into each block is actually realized in operation.

## 13.5.17 C&DH FAILURE MODES

The C&DH failure modes are assessed against the same four-level severity scale used for the communications subsystem, ranking each mode by its consequence to mission success. The dominant concern is the flight computer, whose loss would end onboard control, followed by the SSMM, whose degradation costs science return but not spacecraft safety. The failure modes and their mitigations are listed below. The codes are defined in Table 13.5.20.

**Table 13.5.28: ODIN C&DH Failure Modes**

| Part | Failure | Code | Effect | Mitigation |
|---|---|---|---|---|
| Phoenix Flight Computer | Software memory error / bit flip | 3 | Flight computer malfunctions; incorrect commanding | Dual Phoenix MCUs monitor each other via watchdog. Faulted MCU is reset and reprogrammed by healthy unit. EDAC enabled on internal flash. |
| | Processor lockup / hang | 3 | No command execution; satellite unresponsive | Hardware watchdog timer triggers autonomous reset. Safe mode entered; beacon continues transmitting for ground recovery. |
| | Chip / hardware failure | 4 | Loss of primary flight computer; potential mission failure | Redundant (secondary) Phoenix unit on hot standby. Automatic switchover upon detection of primary failure. |
| SSMM (Solid State | Single bit error | 2 | Stored payload data | TRM data scrubbing, at a TBD |

| | | | | |
|---|---|---|---|---|
| Mass Memory) | | | inaccurate or corrupted | interval.EDAC corrects single-bit errors automatically. |
| | Chip failure | 2 | Mass memory unavailable; no payload data storage | Phoenix MCUs fall back to internal flash for housekeeping and beacon data. Payload data storage unavailable; primary mission communications unaffected. |
| | Multi-bit / uncorrectable error | 3 | Payload data block lost; partial science data loss | Corrupted blocks flagged and excluded from downlink. Mission success preserved; reduced science return. Re-observation planned if timeline permits. |

Each mitigation above — dual-MCU watchdog recovery, EDAC (Error Detection And Correction) and scrubbing, redundant-unit switchover, and corrupted-block exclusion — represents a behavior the verification program must demonstrate rather than assume. These are carried into the V&V plan below.

## 13.5.18 C&DH VERIFICATION & VALIDATION PLAN

The C&DH V&V plan verifies each subsystem requirement (SSR-CDH-01 through -05) and closes the integrated Comms–C&DH chain through the end-to-end test. Storage capacity, packetization, command routing, fault response, time accuracy, and SpaceWire throughput are each verified independently before the full pipeline is validated as a system. Each entry traces to its governing requirement with an assigned method, level, and type.

**Table 13.5.29: ODIN C&DH V & V Plan**

| Verification Name | Req. ID | Purpose | Method | Description | Level | V&V Type |
|---|---|---|---|---|---|---|
| SSMM Capacity Acceptance Test | SSR-CDH -01 | Verify SSMM provides enough raw storage capacity with full Reed-Solomon ECC protection across all SDRAM | Test (T) | Full write/read-back across all three SDRAM modules; inject single- and multi-bit errors to confirm ECC correction and flagging. | Component | Functional |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | modules. | | | | |
| SSMM Store-and-Forward Test | SSR-CDH-01 | Verify SSMM stores all mission data accumulated during a 30-day solar conjunction blackout. | Test (T) | SSMM loaded with 30 days of simulated housekeeping data at 5888 bps continuous rate. Data integrity verified post-storage via checksum comparison. Post-conjunction dump exercised through UST at cruise downlink rate. SSMM utilization tracked against 96 GiB capacity. | Subsystem | Functional |
| Telemetry Packetization and Protocol Test | SSR-CDH-02 | Verify OBC correctly packetizes all telemetry sources into CCSDS-compliant packets for X-band downlink. | Test (T), Analysis (A) | OBC software generates telemetry packets from simulated subsystem data inputs. Packet structure inspected against CCSDS packet standard: primary header, secondary header, application data. All 5888 bps housekeeping channels are verified across all mission modes. | Subsystem | Functional |
| Command Receive, Authenticate, and Route | SSR-CDH-03 | Verify OBC receives, authenticates, decodes, and routes uplink commands to correct subsystems over both MIL-STD-1553B Bus-A and Bus-B. | Test (T) | Ground support equipment generates CCSDS telecommand frames over 1553B bus. Full command set exercised across all subsystem bus addresses. Both buses tested independently. Invalid and unauthenticated commands injected to verify rejection with appropriate fault flag. | Subsystem | Functional |
| FDIR Fault Injection Test | SSR-CDH-04 | Verify OBC autonomously detects hardware anomalies and initiates correct fault responses without ground intervention. | Test (T) | Fault injection suite covers: primary flight computer lockup (watchdog timer), SSMM single-bit error (ECC scrubbing), UST transponder failure (auto-switchover), and power over-limit condition. Each fault is injected independently with an OBC response monitored against the defined fault tree. | Subsystem | Functional |
| Time Synchronizat | SSR-CDH-05 | Verify OBC maintains | Test (T), | OBC time maintained over a simulated 14-day period | Subsystem | Performance |

| | | | | | | |
|---|---|---|---|---|---|---|
| ion Accuracy Test | | mission time accurate enough for contact window scheduling and proximity operations sequencing across a full 14-day blackout period. | Analysis (A) | without ground correction. Drift measured against reference clock at the end of accumulation. Ground time-correction uplink command tested to verify re-synchronization within one execution cycle. | | |
| OBC Redundancy Switchover Test | SSR-CDH-04 | Verify automatic switchover from primary to redundant Phoenix flight computer on primary failure, with mission operations recovered within the defined response time. | Test (T) | Primary Phoenix MCU disabled via simulated chip failure. Hot-standby secondary unit monitored for autonomous switchover. SSMM state, 1553B bus addressing, and process continuity verified post-switchover . Full commanding and telemetry confirmed on redundant units. | Subsystem | Performance |
| SpaceWire Bus Peak Throughput Test | SSR-CDH-02 | Verify SpaceWire router sustains required throughput between payloads, cameras, SSMM, and telemetry frame generator during peak inspection imaging. | Test (T) | SpaceWire network loaded at peak inspection data rate: all three camera interfaces simultaneously transfer imagery to SSMM. Router switching latency and buffer utilization monitored. No data loss permitted at peak load. | Subsystem | Performance |
| End-to-End Integration | SSR-COMM-01, | Validate the complete | Test (T) | Full end-to-end test: uplink command from GSE → UST | System | Validation |

| | | | | | | |
|---|---|---|---|---|---|---|
| Test | SSR-COMM-04, SSR-COMM-05, SSR-COMM-06, SSR-CDH-01, SSR-CDH-02, SSR-CDH-03 | integrated Comms and C&DH chain from command uplink through OBC routing, SSMM, and science data downlink to ground. | | → OBC routing → confirmed in HK telemetry downlink. Science pipeline: payload imagery → SSMM → OBC packetization → UST/TWTA/HGA → ground. 14-day simulated mission timeline including conjunction blackout and safe mode transition executed in compressed form. | | |

The component and subsystem tests confirm each C&DH function in isolation — storage integrity, CCSDS packetization, authenticated command routing on both buses, autonomous fault response, time-base drift, and peak SpaceWire throughput — and the End-to-End Integration Test validates them together across a compressed 14-day mission including conjunction blackout and a safe-mode transition. The failure modes these tests exercise are carried into the risk assessment below.

## 13.5.19 C&DH RISK MANAGEMENT

The C&DH failure modes are placed on the 5×5 likelihood–consequence matrix to prioritize residual risk after mitigation. Each lettered item corresponds to a failure mode from Section 13.5.16; its placement reflects post-mitigation likelihood against the severity of its effect.

**Table 13.5.30: ODIN C&DH RISK MANAGEMENT**

| | | | | | |
|---|---|---|---|---|---|
| **Certain**<br>>80% | | | | | |
| **Likely**<br>60% - 70% | | | | | |
| **Possible**<br>40% - 59% | | D | A, B | | |
| **Unlikely**<br>20% - 39% | | | F | | |
| **Rare**<br>< 20% | | E | | | C |

| | 1<br>Insignificant | 2<br>Minor | 3<br>Moderate | 4<br>Major | 5<br>Severe |
|---|---|---|---|---|---|

The lettered entries are defined below with the effect and mitigation that justify each placement:

**Table 13.5.31: ODIN C&DH Failure Mode Groups**

| Code | Failure Name | Effect | Mitigation |
|---|---|---|---|
| A | Software memory error / bit flip | Flight computer malfunctions; incorrect commanding. | Dual Phoenix MCUs monitor each other via a watchdog. Faulted MCU is reset and reprogrammed by a healthy unit. EDAC enabled on internal flash. |
| B | Processor lockup / hang | No command execution; satellite unresponsive. | Hardware watchdog timer triggers autonomous reset. Safe mode entered; beacon continues transmitting for ground recovery. |
| C | Chip / hardware failure | Loss of primary flight computer; potential mission failure. | Redundant secondary Phoenix unit on hot standby. Automatic switchover upon detection of primary failure. |
| D | Single bit error | Stored payload data inaccurate or corrupted. | TRM data scrubbing at a 24-hr interval. EDAC corrects single-bit errors automatically. |
| E | SSMM chip failure | Mass memory unavailable; no payload data storage. | Phoenix MCUs fall back to internal flash for housekeeping and beacon data. Primary mission communications unaffected. |
| F | Multi-bit / uncorrectable error | Payload data block lost; partial science data loss. | Corrupted blocks flagged and excluded from downlink. Mission success preserved; reduced science return. Re-observation planned if timeline permits. |

After mitigation, every C&DH failure mode falls in the possible-to-rare likelihood band, with no item in the high-likelihood/high-consequence region. The one mission-critical mode — flight-computer chip failure (C) — is held at *rare* likelihood by the hot-standby redundant Phoenix unit with autonomous switchover, so that no single credible failure results in loss of vehicle control. This closes the C&DH subsystem analysis.

## 13.5.20 MISSION OPERATION SUBSYSTEM REQUIREMENTS

**Table 13.5.32: ODIN Mission Operation Subsystem-Level Requirements**

| SSR-ID | Requirement Type | Description | Verified by | Rationale for requirement | Traces to |
|---|---|---|---|---|---|
| **SSR-MC-01** | Constraint | The ODIN MOC shall use ESA ESTRACK (Malargüe, Cebreros, New Norcia 35 m DSAs) as the primary ground network. ESTRACK service fees shall be budgeted under a Mission Service Agreement. | Review (R) | ESTRACK selected over DSN for: (1) native X-band compatibility with Solar Orbiter heritage, (2) three-station longitudinal coverage, (3) reduced interface risk. | SYS-5-2 |
| **SSR-MC-02** | Constraint | The MOC shall schedule ≥1 contact per day: minimum 6 hr/day during cruise and 8 hr/day during inspection windows. | Analysis (A) | Regular contacts are required to track spacecraft state, uplink command loads, and react to anomalies in a timely manner during the Solar Orbiter inspection campaign. | SYS-5-2, SYS-5-1 |
| **SSR-MC-03** | Performance | The MOC shall process and distribute received telemetry to engineering and payload teams within 4 hours of end-of-pass. | Test (T) | 4-hour turnaround supports the Day 3–4 HITL gate, which requires ground review of calibration imagery before GO/NO-GO for the full inspection campaign. | SYS-5-1, SYS-5-3 |
| **SSR-MC-04** | Operational | The MOC shall generate, validate, and uplink command sequences for nominal ops, TCMs, and contingency response. All proximity operations loads shall be validated by an authorized engineer before uplink. | Test (T) | The spacecraft depends on ground-planned command loads for TCMs, payload activation, and Solar Orbiter inspection sequencing; on-board autonomy alone is insufficient. | SYS-5-2 |

| | | | | | |
|---|---|---|---|---|---|
| **SSR-MC-05** | Operational | The MOC shall archive all telemetry and payload data in a retrievable format for the mission duration plus ≥5 years post-mission. | Review (R) | 5-year retention supports post-mission Solar Orbiter condition analysis and lessons-learned for future heliocentric inspection missions, consistent with ESA science mission data policy. | SYS-5-1, SYS-5-3 |
| **SSR-MC-06** | Failure, Tolerance | The MOC shall maintain backup operations capability (NASA DSN or equivalent) such that loss of the primary facility does not interrupt commanding for more than 24 hours. | Analysis (A) | A single-point MOC failure during deep-space ops jeopardizes commanding with limited recovery windows. 24-hour RTO ensures ODIN can be commanded before any time-critical proximity window is missed. | SYS-5-2 |

## 13.5.21 MISSION OPERATION FUNCTIONAL ANALYSIS

**Table 13.5.32: ODIN Mission Operation High-Level Functional Analysis**

| No. | Function Name | Description | Inputs | Outputs |
|---|---|---|---|---|
| 1 | Contact Window Scheduling | Schedule daily ESTRACK passes (≥6 hr cruise, ≥8 hr inspection) across Malargüe, Cebreros, New Norcia | ESTRACK availability, spacecraft ephemeris | Daily contact schedule |
| 2 | Telemetry Processing and Distribution | Receive, decommutate, and distribute all downlinked housekeeping and payload data to engineering and SOC teams within 4 hours of end-of-pass | Raw telemetry frames (HK + imagery + LA range) | Processed HK, imagery products, SSMM utilisation report |
| 3 | Command Generation and Uplink | Generate, validate, and uplink command sequences for cruise ops, TCMs, inspection sequence arming, and contingency response; all proximity ops loads require authorised engineer sign-off | Flight rules, inspection CONOPS, SOC GO/NO-GO | Uplinked command load, execution confirmation via HK |
| 4 | HITL Gate Coordination | Review Day 1 calibration imagery and spacecraft health with SOC within 4-hour turnaround; issue GO or NO-GO for autonomous 6-face inspection campaign | Calibration images, S/C health TM, SOC assessment | GO/NO-GO decision, pre-validated sequence upload |
| 5 | Anomaly and Conjunction Management | Monitor FDIR events and safe mode entries during contact; plan post-conjunction recovery pass | FDIR telemetry, SSMM fill level, SEP angle predictions | Recovery pass plan, contingency command loads |

| | | | | |
|---|---|---|---|---|
| | | sequence to clear SSMM backlog after X-band blackout exit | | |
| 6 | Mission Data Archiving | Archive all telemetry, imagery, LA range history, and pointing metadata for mission lifetime plus ≥5 years post-mission | All received downlink data | Retrievable mission archive |

## 13.5.22 GROUND SEGMENT

The ODIN mission will utilize the European Space Agency's European Space Tracking Network, ESTRACK, as the primary ground infrastructure for nominal mission operations, with NASA's Deep Space Network, DSN, retained as a cross-support option for contingency or extended-coverage scenarios. ESTRACK's deep-space capability is built around 35-meter Deep Space Antennas located at New Norcia, Australia; Cebreros, Spain; and Malargüe, Argentina, with the newer DSA 4 antenna at New Norcia further increasing network capacity and redundancy. These stations primarily support X-band deep-space communications, which is compatible with the ODIN communications subsystem baseline.

Because ODIN operates in a heliocentric environment rather than low Earth orbit, the mission experiences none of the Earth-eclipse periods typical of LEO spacecraft. However, communications availability is still affected by Earth–spacecraft geometry, ground-station visibility, Sun-pointing constraints, and the solar-conjunction periods when the radio link passes near the Sun.

New Norcia (DSA 1) is designated as ODIN's primary Mission Operations Center for nominal mission operations, serving as the baseline single-station contact for routine command uplink, ranging, and health monitoring. New Norcia is selected for three reasons. First, it is the most capable of the three deep-space sites for ODIN's purposes: the co-located DSA 1 and newer DSA 4 antennas give the station two 35-meter apertures at one longitude, providing built-in station-level redundancy and the ability to extend a daily pass or run a backup antenna without a network handover. Second, its Southern-Hemisphere, Australian longitude complements the European (Cebreros) and South American (Malargüe) sites, so that as ODIN's heliocentric geometry shifts the three stations together provide near-continuous longitudinal coverage with New Norcia as the anchor. Third, concentrating routine operations at a single high-availability station simplifies scheduling and reduces inter-station handover overhead during the autonomous inspection campaign, where each cycle requires only one 8-hour pass to clear its data volume.

The remaining ESTRACK stations and DSN cross-support are retained as augmentation rather than baseline. Multi-station ESTRACK coverage across New Norcia, Cebreros, and Malargüe can be scheduled to increase total daily contact time, provide station redundancy during a New Norcia maintenance blackout, or support critical mission phases such as launch and early operations, the human-in-the-loop GO/NO-GO gate, and post-conjunction recovery. DSN cross-support provides a further independent network for contingency coverage if ESTRACK availability is constrained. Final pass-by-pass station assignment across the campaign will be confirmed once the ODIN trajectory and contact geometry are finalized, with New Norcia held as the primary operations site.


**Figure 13.5.19: ESA's ESTRACK ground stations and NASA's DSN ground stations [11], [15]**

**Figure 13.5.20: 35-m ESTRACK at New Norcia [11], [15]**

## 13.5.23 MISSION OPERATION FAILURE MODES

The mission operations failure modes are assessed against the same four-level severity scale used for the communications and C&DH subsystems, applied here to the ground segment, the MOC software and data systems, contact scheduling, and the human-in-the-loop command process. The two severity-4 modes — loss of the assigned ground station and an incorrect command sequence reaching the spacecraft during proximity operations — drive the cross-support and command-authorization mitigations respectively. The full set is listed below.

**Table 13.5.33: ODIN Mission Operation Failure Modes**

| Part | Failure | Code | Effect | Mitigation |
|---|---|---|---|---|
| ESTRACK ground segment | Ground station failure | 4 | Loss of contact from the assigned ESTRACK station; commanding and telemetry interrupted. | DSN cross-support within 24 hr (SSR-MC-06). Remaining ESTRACK stations cover the gap; 30-day onboard storage prevents data loss. |
| ESTRACK ground segment | Failure to establish ground link | 2 | Missed pass; delayed commanding and telemetry. | Re-acquisition next pass; reduced-rate LGA link if it persists. |
| Contact scheduling / flight dynamics | Communication scheduling conflict | 2 | Daily contact falls below minimum; SSMM backlog accumulates. | ESTRACK Mission Service Agreement gives inspection windows priority booking; DSN cross-support if unresolved within 24 hr. |
| MOC ground software & data | Ground software failure | 3 | MOC cannot process telemetry; ground commanding halted. | Redundant servers with automated failover. Spacecraft runs pre-loaded autonomous sequences during the outage. |
| Command generation & uplink | Incorrect command sequence uplinked | 4 | Unintended state change; collision risk with Solar Orbiter during proximity ops. | Flight-rule/constraint checks plus authorized-engineer sign-off (HITL) before uplink. OBC rejects out-of-bounds commands. |
| HITL / inspection operations | HITL gate missed or delayed | 2 | Inspection cycle delayed; science volume for the window reduced. | 2-day review buffer; reduced-scope inspection pre-approved; mission director may authorize go-ahead. |
| HITL / inspection | Post-conjunction | 2 | First | Recovery procedure pre-scripted and |

| | | | | |
|---|---|---|---|---|
| operations | recovery plan not ready | | post-conjunction pass spent on planning; backlog clears one pass later. | stored before conjunction entry; rehearsed in simulation. |
| MOC ground software & data | Data archive corruption or loss | 3 | Science/HK records partially or fully lost; re-observation if timeline permits. | Redundant servers, daily offsite backup; CCSDS checksums at ingest; corrupted segments isolated. |
| Contact scheduling / flight dynamics | Ephemeris error in contact schedule | 2 | Predicted window offset from actual geometry; pass partially missed. | Ephemeris cross-checked from two sources; acquisition scan window widened; missed pass rescheduled. |

Each mitigation above — DSN cross-support, priority contact booking, redundant MOC servers, flight-rule checks with authorized sign-off, and pre-scripted conjunction recovery — defines an operational capability the verification program must demonstrate. These are carried into the V&V plan below.

### 13.5.24 MISSION OPERATION VERIFICATION & VALIDATION PLAN

The mission operations V&V plan verifies each requirement (SSR-MC-01 through -06) through the method appropriate to it — review for network compatibility and archive policy, analysis for contact-window coverage, and operational test for telemetry turnaround, command authorization, and backup/recovery behavior. Several entries combine methods where a requirement spans both an analytical coverage claim and a demonstrated operational workflow. Each entry traces to its governing requirement with an assigned level and type.

**Table 13.5.34: ODIN Mission Operation V &V Plan**

| Verification Name | Req. ID | Purpose | Method | Description | Level | V&V Type |
|---|---|---|---|---|---|---|
| ESTRACK network compatibility review | SSR-MC-01 | Confirm ESTRACK station set satisfies X-band interface and longitudinal coverage | Review (R) | Review ESTRACK station interface documentation against ODIN X-band UST specs and Mission Service Agreement scope. Verify three-station longitude separation provides adequate heliocentric orbit coverage. | Subsystem | Compliance |

| Verification Name | Req. ID | Purpose | Method | Description | Level | V&V Type |
|---|---|---|---|---|---|---|
| | | needs | | Cross-reference with FreeFlyer contact window outputs. | | |
| Contact window schedule analysis | SSR-MC-02 | Verify MOC achieves >=1 contact/day: >=6 hr/day cruise, >=8 hr/day during inspection windows. | Analysis (A) | MATLAB/FreeFlyer propagation of ODIN's trajectory vs. ESTRACK stations. Confirm daily contact totals at both inspection geometries and across cruise arc. Simulate single-station outage; verify DSN cross-support restores compliance within 24 hr. Pass: >=6 hr/day cruise (95% of days), >=8 hr/day all 14 inspection days. | System | Performance |
| Telemetry processing and HITL turnaround test | SSR-MC-03 | Verify telemetry is processed and distributed to teams within 4 hr of end-of-pass, supporting the Day 3-4 HITL GO/NO-GO gate. | Test (T) | Inject a recorded inspection-pass downlink (HK + imagery, 85/89 kbps). Measure time from end-of-pass to: (1) HK available in displays, (2) imagery delivered to SOC. Conduct tabletop HITL review and issue GO/NO-GO with command sequence queued. Pass: all events within 4 hr. | Subsystem | Functional, Timing |
| Command generation, validation, and uplink authorization test | SSR-MC-04 | Verify MOC generates, validates, and uplinks command sequences for cruise, TCM, and proximity ops; proximity ops loads require authorized sign-off. | Test (T) | Conduct a mission rehearsal in which operators generate a prox ops command load, step through the validation checklist and flight rule checks, obtain authorized engineer sign-off, and uplink to the spacecraft simulator. Observe end-to-end workflow under expected operating conditions. Pass: sequence executes correctly on simulator, sign-off document in audit trail. | System | Functional, Safety |
| Mission archive | SSR-MC-05 | Confirm all telemetry and | Review (R) | Review data management plan for archive format | Subsystem | Compliance |

| Verification Name | Req. ID | Purpose | Method | Description | Level | V&V Type |
|---|---|---|---|---|---|---|
| completeness review | | payload data are stored in a retrievable format for mission lifetime plus >=5 years post-mission. | | (CCSDS-compliant or equivalent), storage redundancy, and retention schedule. Verify coverage of: HK frames, imagery products, LiDAR range history, pointing metadata, command records, SSMM utilization logs. Pass: all data types covered, retention policy documented consistent with ESA science data policy. | | |
| Backup operations and post-conjunction recovery test | SSR-MC-06 | Verify primary MOC loss does not interrupt commanding >24 hr; verify post-conjunction SSMM backlog is cleared on first recovery pass. | Test (T), Analysis (A) | Analysis: compute earliest DSN contact window within 24 hr of ESTRACK primary outage for all mission phases; confirm >=6 dB link margin at X-band. Test: simulate 30-day solar conjunction (HK-only accumulation); execute MOC recovery sequence on first post-conjunction pass and confirm SSMM backlog cleared within 2 passes. Pass: DSN contact available within 24 hr; backlog cleared within 2 passes. | System | Fault tolerance |

Together these activities close every mission operations requirement: the reviews confirm ESTRACK compatibility and archive retention, the contact-window analysis confirms the daily coverage that the data budget depends on, and the operational tests confirm telemetry turnaround for the HITL gate, authorized command generation for proximity ops, and recovery from both a primary-MOC outage and a solar-conjunction blackout. The failure modes these activities exercise are carried into the risk assessment below.

## 13.5.25 MISSION OPERATION RISK MANAGEMENT

The mission operations failure modes are placed on the 5×5 likelihood–consequence matrix to prioritize residual risk after mitigation. Each lettered item corresponds to a failure mode from Section 13.5.19; its placement reflects the post-mitigation likelihood against the severity of its effect.

**Table 13.5.35: ODIN Mission Operation Risk Management**

| | | | | | |
|---|---|---|---|---|---|
| **Certain** >80% | | | | | |
| **Likely** 60% - 70% | | | | | |
| **Possible** 40% - 59% | | C | D | | |
| **Unlikely** 20% - 39% | | | B. F | | E |
| **Rare** < 20% | | H, I | G | | A |
| | **1** Insignificant | **2** Minor | **3** Moderate | **4** Major | **5** Severe |

**Table 13.5.36: ODIN Mission Operation Failure Mode Groups**

| Code | Failure Name | Effect | Mitigation |
|---|---|---|---|
| A | Ground station failure | Loss of ESTRACK contact. | Use remaining ESTRACK stations and activate DSN cross-support within 24 hr. |
| B | Failure to establish ground link | Missed pass; delayed commanding and telemetry retrieval. | Retry acquisition on next pass. Use a lower-rate LGA link if needed. |
| C | Scheduling conflict | Contact time reduced; SSMM backlog may grow. | Reserve priority inspection contacts. Use DSN cross-support if conflict persists. |
| D | Ground software failure | MOC cannot command or process telemetry. | Use redundant MOC servers with failover. Spacecraft continues pre-loaded commands. |

| | | | |
|---|---|---|---|
| E | Incorrect command uplinked | Unexpected spacecraft state change; possible proximity risk. | Validate commands against flight rules. Require HITL sign-off. OBC rejects unsafe commands. |
| F | HITL gate missed or delayed | Inspection delayed or reduced; backlog may increase. | Include 2-day review buffer. Use pre-approved reduced-scope inspection if needed. |
| G | Recovery plan not ready | Post-conjunction recovery delayed by at least one pass. | Finalize and rehearse recovery plan before conjunction. Pre-script first recovery pass. |
| H | Data archive corruption or loss | Science or housekeeping data may be lost. | Use redundant archives, daily offsite backup, and checksum verification at ingest. |
| I | Ephemeris error in contact schedule | Contact window missed or shortened. | Cross-check ephemeris sources, update predictions within 24 hr, and extend acquisition scan window. |

After mitigation, the mission operations failure modes fall in the possible-to-rare likelihood band, with no item in the high-likelihood/high-consequence region. The two mission-critical modes — ground-station loss (A) and an incorrect command uplink (E) — are held at *rare* likelihood by DSN cross-support with 30-day onboard storage and by flight-rule validation with mandatory HITL sign-off, respectively, so that no single operational failure results in loss of mission or of the inspection target. This closes the mission operations analysis and the communications, C&DH, and mission operations sections of the ODIN design.

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