- Ensure the following:
    - Your writing is **Arial**, **size 12 font, single spaced**
    - All sources are included at the bottom of the document
    - List and define all acronyms used at the bottom of the document
    - All figures and tables are included and captioned

Acronyms in this section

CDH - Command-and-Data-Handling
ECC - Error-Correcting Code
EGA - Evolved Gas Analyzer
EPS - Electrical-Power System
FSW - Flight Software
GSFC - Goddard Space Flight Center
GEVS - General Environmental Verification Standard
RF - Radio Frequency
RTEMS - Real-Time Executive for Multiprocessor Systems
RTOS - Real-Time Operating System
SBC - Single-Board Computer
SEU - Single-Event Upset
SSR - Solid-State Recorder
TID - Total Ionising Dose
TRL - Technology Readiness Level
UHF - Ultra-High Frequency

2.1.3 CDH Subsystem

2.1.3 CDH Subsystem Overview

The Command and Data Handling (CDH) subsystems serve as the central nervous system for the ODIN Rover, managing all data collection, processing, storage, and transmission functions. The subsystem must support the mission's primary science objectives, which include examining radiation effects on the Mars surface, characterizing the chemical properties of Mars soil, determining the composition of polar ice, and measuring the thermal conductivity of the subsurface materials. The CDH subsystem addresses these science objectives using a combination of the following components:

- **On-Board Computer:** This on-board computer, specifically the DDC SCS3740 Board, will serve as the brain for the ODIN Rover. It will gather data collected from other instruments and send commands to any instruments and subsystems.
- **RH3440 Solid-State Data Recorder:** This Solid-State Data Recorder will store any software used for the instruments and all the data that has been

gathered from other instruments, which will be used to send data back to Earth.

- **C/TT-505 UHF Transceiver:** This radio transceiver will capture or generate any RF command, telemetry, and data link between two spacecraft. Once captured, the transceiver processes the information and sends it to the onboard, which will use that information as intended.
- **RUHF Antenna:** The antenna will serve as the mouth and ears that send and capture signals. When signals are sent from the spacecraft, the antenna will capture that signal and send it to the radio transceiver in order to process, vice versa.
- **NaTeCam:** This camera will serve as the eyes for the ODIN rover. It will capture pictures and footage for the on-board computer to process and store on the SSDR and send it to the transceiver in order to process it and send to the spacecraft so it can be sent back to Earth.

The software for the CDH subsystem will be responsible for managing all the data that flows in and out, as well as the commands and communication; it serves as the consciousness for the rover. The data that will be gathered will vary in each instrument and subsystem. It will gather radiation data from the Liulin-MO, chemical properties from the TEGA.

2.1.3.1 CDH Subsystem Requirements.

The Command-and-Data-Handling (CDH) architecture must fit inside the rover's limited avionics vault, satisfy tight mass/power budgets, and reach Technology Readiness Level (TRL) 5 or higher by the Preliminary Design Review (PDR). Lower-level requirements were derived from four principal sources:

- **Mission science objectives.** Continuous radiation dosimetry, TEGA ice-chemistry assays, and NaTeCam imaging drive interface bandwidths and real-time processing needs.
- **Environmental envelopes.** The –55 °C to +85 °C electronics temperature span and the Martian dust-latch-up risk set hardware hardening thresholds.
- **Programmatic constraints.** The project schedule allots a 30-month build-to-launch window; GAO schedule guidance recommends a 25-% reserve, translating to a <12-month hardware lead time for long-pole items such as radiation-hardened FPGAs (U.S. Government Accountability Office, 2020).
- **Cost and maturity targets.** NASA's Cost Estimating Handbook indicates that avionics typically consume ~15

2.1.3.2 CDH Sub-Assembly Overview.

The CDH subsystem orchestrates every information pathway on the ODIN rover. It receives and decodes uplinked commands, schedules and synchronizes all payloads, stores high data science files, compresses and

packetizes data, and finally hands telemetry to the telecom subsystem for relay to Earth. Because the vehicle will operate for an entire Martian year in a region characterised by temperature swings of ≈200 K, pervasive dust, and steady flux of ionising radiation, every CDH element must be radiation-tolerant, low-power, and mechanically hardened against shock, vibration, and dust incursion (Calle 2011; NASA JPL 2022). For hardware-centric sub-assemblies, the on-board computer, solid-state recorder, radio/antenna chain, and the NaTeCam engineering camera are bound together by a layered flight-software stack. The least mature flight article is the SCS3740 single-board computer at TRL 5; therefore, the overall CDH subsystem maturity at PDR is TRL 5.

Table XX: Physical & Electrical Summary of CDH Subsystem

Instrument	Mass (kg)	Dimensions (m)			Power (W)	TRL
		L	W	H	(nom.)	
DDC SCS3740 SBC	0.55	0.16	0.10	0.025	12	5
RH3440 Solid-State Recorder	0.62	0.16	0.10	0.025	14	5
L3 Harris C/TT-505	0.17	0.13	0.09	0.05	60 (TX) / 6(RX)	5
RUHF Turnsite Antenna	0.10	0.115	0.115	0.31	passive	6
NaTeCam (Nav-Terrain Camera)	0.70	0.70	0.12	0.11	1.8	6

On-Board Computer Sub-assembly (TRL 5)
The computational core is a radiation-tolerant DDC SCS3740 single-board computer (SBC) built around a quad-core LEON-4 processor. The board delivers 1700 DMIPS per core, includes SpaceWire and UART/SPI buses, and implements hardware EDAC in both SDRAM and NOR flash banks. A deterministic RTEMS-based real-time operating system guarantees less than 0 µs in-terrupt latency required for timing-critical events such as LIBS-laser firing and NaTeCam frame synchronisation.

Environmental counter-measures

- 10 mm-Al equivalent TID shielding limits cumulative dose to < 20 krad for a two-year surface stay (Bramson et al. 2015).

- Conformal Parylene-C coating minimises dust bridging, an approach flown on InSight (Banerdt 2019).
- Al-Si heat spreaders couple the SBC to an isothermal plate held at 233–253 K by loop heat-pipes, preventing cold-latch-up events (NASA Astrobiology n.d.).

Data-Storage Sub-assembly (TRL 5)
Bulk science and housekeeping data are buffered in an RH3440 radiation-hardened solid-state recorder (SSR) that offers 440 GB non-volatile NAND plus Reed-Solomon scrubbing. Interfaces run at 100 Mbps SpaceWire; sustained throughput of 60 Mbps accommodated concurrent Liulin-MO logs, TEGA chroatograms, and NaTeCam panoramas.

Environmental counter-measures
- Periodic scrubbing corrects single-event upsets every 30 s, cadence scaled from MSL-RAD heritage (Hassler et al. 2014).
- Visco-elastic mounts are tuned to suppress the 125 Hz primary mode expected during drill-hammer operations.

Communications Sub-assembly

UHF Transceiver – L3Harris C/TT-505 (TRL 5)
Operates in the 435-455 MHz Mars Relay band, providing 8-256 kbps downlink and 2 kbps uplink while drawing 6 W in receive and ≤60 W during 5-min daily downlinks.

Antenna – RUHF Turnstile (TRL 6)
A fixed dual-dipole right-circular-polarised antenna, eliminating deployment risk and yielding a ≥15 dB link margin to orbiters at 30° elevation.

Environmental Counter-measures
- Radio and antenna are housed in a shallow CO2 vault at 40 mbar, mitigating dust deposition.
- GaAs pHEMT RF front-end is immune to displacement damage up to 1×1013 p $cm{-}2$
- (Jakosky 2015).

Imaging & Engineering Camera Sub-assembly – NaTeCam (TRL 6)
NaTeCam is a low-mass nav/terrain imager derived from the ESA Rosalind-Franklin ECAM-C. A 4k×3k Si/HgCdTe hybrid sensor offers 12-bit global-shutter readout at 5 fps, sufficient for stereo drive-planning and dust-opacity monitoring.

Environmental counter-measures

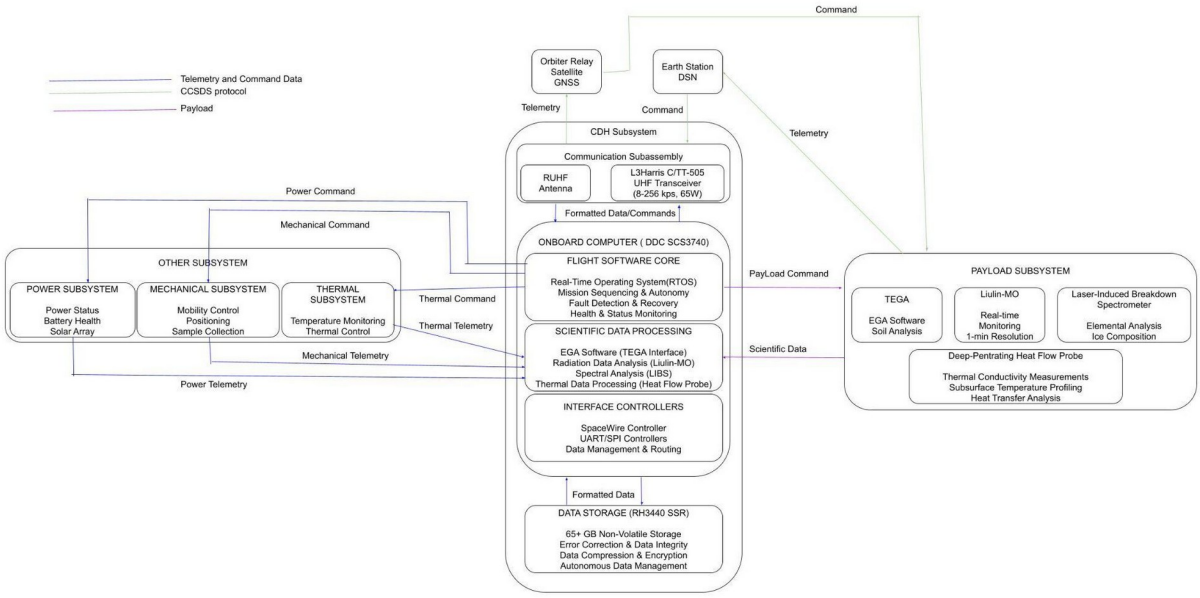
- Sol-gel AR coating baked at 110 °C prevents hydrophilic layers that trap electrostatic dust.
- Titanium flexures decouple the aluminium camera body ($\alpha = 23$ µm m-1 K-1) from the CFRP mast ($\alpha \approx 2$ µm m-1 K-1), surviving -120 °C night-time dips (Heavens 2017).

Flight-Software Architecture (TRL 5)

A three-layer RTEMS stack provides deterministic command execution, fault protection, and data throughput:

1. RTOS services, drivers, and board-support package.
2. Subsystem managers (CDH, EPS, Thermal, Mobility).
3. Payload applications: TEGA EGA control, LIBS sequencer, NaTeCam imaging pipeline.

Closed-loop autonomy during 8-h comm blackouts and rapid recovery from SEUs will be demonstrated in the FSW system-integration test-bed by CY 2026.



Environmental Factors & CDH Counter-Measures

- Dust-charged electrostatics can induce latch-up; ESD ground returns and conformal coating follow Pathfinder and InSight lessons (Calle 2011).
- Seasonal dust storms attenuate UHF links by ≤4 dB at $\lambda \approx 70$ cm; link-margin analysis assumes a worst-case 0.3 Np km-1 extinction coefficient (Hille 2015).
- Marsquakes up to M5 necessitate four-point silicone bushings rated to 30 gpk in the 10–500 Hz band (NASA JPL 2022).

- Thermal cycling between 180 K and 268 K is moderated by a thermostatically controlled 5 W Kapton heater during eclipse.

Subsystem TRL Roll-up
Because both the SCS3740 SBC and RH 3440 recorder are at TRL 5, the overall CDH subsystem maturity is TRL 5.

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans.

The Command and Data Handling (CDH) subsystem employs a strategic approach to redundancy that balances mission-critical reliability with mass and power constraints. Only two systems are single-point failures: the DDC SCS3740 and the RH3440, due to these systems having their own redundancy plans. The DDC SCS3740 onboard computer incorporates inherent redundancy through its quad-core LEON4 processor architecture, allowing computational failover in case one core fails. The processor's radiation-hardened design includes Single Event Upset (SEU) protection, providing additional fault tolerance in Mars' radiation environment (Data Device Corporation, 2020). The RH3440 solid-state recorder is also designed for fault-tolerance, maintaining reliable operation even if several individual NAND flash memory chips fail due to radiation effects or wear. Information redundancy is achieved through distributed storage across the onboard computer's memory and the dedicated data recorder, with automated creation of redundant copies of essential data, including flight software, calibration parameters, and critical scientific measurements ("440 GB 3U VPX Rad-Tolerant SSDR," n.d.).

The L3Harris C/TT-505 UHF transceiver remains the primary communications unit, supported by a secondary backup unit due to its compact form factor and low mass. The selected antenna, the Rover Ultra High Frequency (RUHF) QuadriFilar Helix (QFH) antenna, provides hemispherical coverage and circular polarization optimized for rover-to-orbiter relay links. This antenna has extensive Mars flight heritage, having been flown on the Mars Science Laboratory Curiosity rover, and has a Technology Readiness Level (TRL) of 9. Environmental qualification testing demonstrated durability through 2,010 simulated Martian thermal cycles—three times the expected mission duration—without measurable RF performance degradation (Kobayashi et al., 2013).

To optimize mass, integration complexity, and power budgets, the mission uses a single-frequency UHF system rather than multiple antennas across different frequency bands. This decision leverages the existing Mars relay infrastructure, where orbiters already support UHF rover communications. Using one high-heritage, high-TRL antenna minimizes hardware interfaces, reduces pointing requirements, and simplifies fault recovery procedures. Backup capability is provided by carrying a second identical RUHF antenna, which can be switched in electronically in case of primary antenna damage or degradation.

The software architecture implements comprehensive autonomous recovery procedures for common failure modes, including communication timeouts, instrument interface errors, and data corruption events. The Real-Time Operating System (RTOS) provides deterministic fault detection and recovery capabilities. In the event of a communication anomaly, the system automatically transitions to a safe mode that prioritizes restoring link integrity. For instrument interface errors, the CDH continuously monitors communication links for anomalies such as data inconsistencies or protocol mismatches, then isolates the faulty interface and switches to redundant pathways if available. Corrective actions such as command retries or alternate communication sequences are autonomously executed to maintain data flow. Information recovery is further supported by redundant storage pathways, ensuring preservation of essential mission data even during fault conditions. The combination of high-TRL hardware with proven Mars heritage, environmental robustness, and autonomous fault management ensures the CDH subsystem meets the mission's reliability and risk tolerance requirements within acceptable mass and power constraints.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans.

The Command-and-Data-Handling (CDH) chain comprises six flight articles: the DDC SCS3740 single-board computer, the Mercury RH3440 solid-state recorder, the L3Harris C/TT-505 UHF transceiver, a right-circular-polarised RUHF turnstile antenna, the NaTeCam nav/terrain imaging unit, and the 7075-T6 aluminium electronics-vault structure that houses all boards. Every component will be procured as contractor-supplied hardware; NASA in-house fabrication is avoided by NPD 1370.1, which discourages competition with the commercial industry (NASA 2019).

Supplier-Selection Rationale

Computer (SCS3740). Data Device Corp. was chosen because the board is radiation-hardened to 100 krad(Si), ships with a validated RTEMS BSP, and carries flight heritage on ESA PROBA-3 (DDC 2023). A secondary vendor, Artisan Technology Group, specialises in remanufactured rad-hard boards and maintains on-hand inventory, cutting lead time in half for contingency buys.

Data Storage (RH3440). Mercury Systems leads the market in NAND-based SSRs that include built-in BCH/RS scrubbing and EDAC (Mercury 2023). Avnet Silica is kept on contract as a distributor-integrator capable of rapid lot buys if supply-chain kinks appear.

Radio (C/TT-505). L3Harris provides the only COTS UHF transceiver with demonstrated Mars Relay Network interoperability (L3Harris 2022). Swapping to SatCatalog's brokered marketplace gives the project access to surplus units from terminated planetary programs.

Antenna (RUHF). The fixed turnstile antenna delivers 3 dB higher gain while eliminating deployment risk. Primary fabrication will be handled by Roccor LLC, whose carbon-fiber boom capability supports the 0.31 m mast. A backup is Mesa Microwave, a small business with ITAR-compliant machining for UHF helices.

NaTeCam. The camera is a derivative from payloads of Tranwen-1, China's first exploration to mission to Mars. (Tianwen-1, 2021). Surrey Satellite Tech. will build the flight unit under license because of the existing clean-room and planetary-optics pedigree; Malin Space Science Systems serves as backup and already holds a catalog of Mars-qualified optics (MSSS 2020).

Mechanical (Electronics Vault). Collins Aerospace will machine the vault from 7075-T6 plate using five-axis CNC, an approach that met ±50 µm tolerances on NASA VIPER avionics (Collins 2021). Alternate fabrication can be routed to Lockheed Martin's Space Systems Additive Manufacturing Center, which offers powder-bed fusion for complex ribbing without a schedule penalty.

Table XX: Lead-Time Summary

CDH Item	Primary Supplier	Backup Supplier	Lead Time (mo.)	Notes/Justification
SCS3740 SBC	Data Device Corp.	Artisan Technology	5–9 (2–4)	Radiation-hard ASICs gate the primary schedule; the refurb path halves time.
RH3440 SSR	Mercury Systems	Avnet Silica	4–7 (3–5)	Avnet stocks NAND die; only enclosure requalification required.
C/TT-505 Radio	L3Harris	SatCatalog Marketplace	6–12 (3–6)	Brokered units bypass the new rad-test campaign.
RUHF Antenna	Roccor LLC	Mesa Microwave	4–8 (3–5)	Both shops hold NASA-qualified UHF feedstock.
NaTeCam	Surrey Satellite Tech.	Malin Space Sci. Sys.	7–11 (6–9)	Detector procurement (12-µm pitch APS) is scheduled driver.
Electronics	Collins	LM Additive	3–6 (2–	5-axis CNC vs.

Vault	Aerospace	Mfg. Ctr.	4)	powder-bed fusion; either meets ±50 µm flatness.

Manufacturing Quality Control Approach

Electronics. All boards will undergo IPC J-STD-001 class 3 workmanship, with X-ray inspection of BGA packages and thermal-vac acceptance at –55 °C / +85 °C. Qualification includes per-lot total-ionizing-dose (TID) exposure to 50 krad(Si) to maintain 2× mission margin.

Antenna. The RUHF radiator and balun are machined from Ti-6Al-4V, then silver-plated to ≥5 µm for conductivity. Each unit is tuned in an anechoic chamber; gain must meet 4.1 dBi ±0.3 dB (NASA JPL, 2013).

Optics (NaTeCam). Surrey assembles the camera in ISO-5 clean-flow benches. Radiation-tolerant optical glass (Ohara E6) is bonded with NASA low-outgassing epoxy per ASTM E595.

Mechanical Vault. Collins uses rough-mill, stress-relief anneal, and precision-mill sequence to avoid warpage. Helicoil inserts are installed for every M3/M4 thread to survive 200 cycles of thermal swing (Calle 2011).

Schedule Integration

The longest single-item float is the NaTeCam optical path at 11 months. Procurement requests (PRs) will be released NLT L–30 months, ensuring all flight articles arrive before the system-integration thermal-vac (T/V-3) at L–18 months. Backup switches are viable until L–24 months without cascading slips, as modeled in the project integrated master schedule (IMS).

2.1.3.5 CDH Subsystem Verification Plans.

The verification strategy for the Command and Data Handling (CDH) subsystem was shaped by two complementary considerations: the nature of each requirement and the guidance in contemporary aerospace verification standards. NASA’s Systems Engineering Handbook defines certification as “proof of compliance obtained through test, analysis, inspection, or demonstration,” ranking those methods in order of increasing cost and schedule impact while emphasizing that the analyst should always select “the least cost, highest-confidence approach” that will still yield objective evidence of compliance (NASA, 2007). Following that guidance, every CDH requirement in the matrix was first mapped to an evidentiary attribute, quantitative performance, binary functionality, environmental robustness, or physical property, and only then was a verification method assigned.

Functional requirements that manifest as a single, easily observed behavior were assigned to demonstration. Collecting data from Liulin-MO, TEGA, and the ice-sampling assembly, for example, is fundamentally a matter of proving that the instruments and the onboard computer can communicate, ingest, and forward data without error. A top-tier demonstration using flight-representative cabling allows rapid iteration of instrument drivers while providing incontrovertible evidence that the data path is intact. The same logic applies to command responsiveness and UHF beacon operation. A scripted sequence from the ground emulator, observed in real time, confirms the behaviour unmistakably and avoids the expense of a full-up qualification test.

Where quantitative thresholds are specified, such as downlink rate, power draw, or thermal limits, a formal test was necessary. GSFC-STD-7000A directs that performance degradation under the environment be characterized with “sufficient margin to preclude the need for retest on flight article” (GSFC, 2013), so environmental tests were placed at the engineering qualification model stage. The thermal vacuum profile of –60 °C to +90 °C is slightly broader than the requirement to guarantee two degrees of analytical margin, and the six-hour simultaneous-data test captures long-cycle intermittent faults that a short demonstration might miss. For power consumption, connecting the CDH subsystem to a precision analyser during both standby and 30 W RF transmit modes yields time-correlated current and voltage data; that quantitative evidence, rather than a qualitative observation, is essential because any over-limit excursion would have direct implications for the power-system sizing analysis already baselined at the system level.

Analysis was selected whenever compliance could be proven more accurately, quickly, or safely through modelling or certificate review than through physical testing. The radiation-hardness requirement illustrates this point. The computer vendor already furnishes an independent test report showing a total ionizing dose tolerance of 30 krad(Si). Repeating that test would be high in cost and would subject scare flight-like hardware to unnecessary risk. Similarly, link-latency and interface bit-error-rate targets are best quantified with packet-capture tools and analytical extrapolation rather than by extended over-the-air tests, which would be vulnerable to facility noise or regulatory contains on continuous UHF transmission.

Inspection was reserved for purely physical attributes whose verification adds no information when exercised under operational conditions. Mass properties, storage-capacity readouts, and transceiver EEPROM configurations are deterministic; they either meet the specification or do not, and that can be established by reading a calibrated scale, issuing a capacity query, or scrolling through register maps. Inspection is therefore the lowest burden method and, as the NASA handbook notes, should be preferred “whenever a direct measurement alone proves compliance” (NASA, 2007).

Although each requirement was paired with a single primary method, cross-checks were embedded where complexity or mission criticality warranted additional confidence. The error-correction capability of the solid-state recorder, for instance, has an inspection of ECC logs with an analysis of a one-gigabyte write and read cycle; combining methods ensures that capacity, integrity, and endurance are all verified without having to allocate scarce thermal-vacuum chamber time.

Schedule integration was addressed by tying every verification activity to the hardware maturity level. Demonstrations that rely only on software and harnesses commence immediately after the engineering unit is brought up, allowing early fault discovery. High-risk environmental tests are deferred until the qualification model is available, but well before flight hardware is exposed. This staging not only protects critical path items but also satisfies the Systems Engineering Handbook recommendation that “verification be distributed throughout the life-cycle to maximize feedback” (NASA, 2007).

In summary, the preliminary verification plan adheres to accepted aerospace practices by matching each CDH requirement to the verification method that yields the most credible evidence with the least programmatic impact. Demonstrations validate discrete functions, test and quantify performance under stress, analyze explicit high-fidelity models or venor data, and perform inspections that confirm immutable attributes. By structuring the campaign around those principles, the team can be confident that, when the matric is executed, every requirement will be closed with objective evidence traceable to authoritative standards. At the same time, the mission’s cost and schedule envelope remains protected.

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