HARD LESSONS IN CISLUNAR COMMUNICATIONS INFRASTRUCTURE. D. V. Lantukh[1], [1]demyan@astroforge.io AstroForge, 1790 Apollo Ct, Seal Beach, CA 90740.

Introduction: AstroForge flew Odin, a 110 kg deep-space probe, on Feb 27, 2025. Odin was a rideshare on the Intuitive Machines Mission 2 (IM-2) launch to the moon. In addition to difficulties with the vehicle itself, the flight highlighted challenges faced by a nascent cislunar commercial industry. In particular, the limitations of ground stations and schedule contention on a few sites showed how infrastructure on the ground has not kept up with the ambitions of a cislunar economy. AstroForge shares some key lessons learned in consolidating and integrating across multiple stations, which is currently required by the lack of deep-space capable commercial ground sites.

Mission Overview: Odin was intended as an asteroid prospector, aiming to fly by 2022 OB5 in about a year and take detailed surface images. The vehicle was designed and built in 10 months using a mix of commercial off the shelf (COTS) and custom components. Here is Odin integrated onto the launch vehicle.

Odin uses a dual string architecture sharing a common propulsion system and core guidance, navigation, and control (GNC) components. Each string contains a separate radio fed to low-gain hemispherical antennas or a directional antenna for communication over longer distances, up to 20 million km. Radio selection and safe mode design were two key aspects of Odin that distinguish it as a deep-space vehicle.

Ground Segment Design: In addition to the vehicle itself, AstroForge built the mission operations system for Odin and integrated with multiple ground stations. As a fully private venture with no government payloads, AstroForge could not use the Deep Space Network (DSN) or other government-owned communication and navigation assets. As a result, AstroForge put together a network of multiple large-aperture ground sites. Since no pre-existing network exists which can meet the needs of Odin, ten dishes across six sites in six countries from five different ground station providers were ultimately integrated into the ground network. Sites were primarily chosen for compatibility with deep-space needs, but also to allow for a single model of baseband unit to be used throughout. Below is an image of AstroForge's Mission Operations Center during a ground station test event.

Each ground site had some unique features, including a distinct digitizer as well as a local or remote software-defined radio that required its own configuration. Some sites involved an intermediary to help coordinate and others were coordinated directly with the antenna owners. The complexity of this system meant that many parts were not thoroughly tested in the short timeline to get Odin operational.

Flight Issues: AstroForge encountered a series of issues in the Odin flight, starting with a long delay between separation and initial contact, as detailed in [1]. By the time of the first signal from Odin, it was clear the spacecraft was in a low-power state with minimal reserve power. Little additional data could be gathered over multiple days of attempts to contact Odin, ultimately leading to the early end of the mission. Although no root cause of the vehicle failure could be determined, the preparation and flight of Odin highlight some of the unique challenges of flying in the cislunar domain today.

Challenges of Rideshare: Odin was one of four free-flying payloads on rocket for IM-2. Ultimately none of the payloads operated fully as expected or executed nominally. Though being a rideshare on that particular rocket is likely not the root cause of any of those challenges, it highlights how the domain of cislunar missions is still very difficult and success is not guaranteed, especially in the context of limited budgets and timelines for risk reduction. Attempting to debug and recover three spacecraft simultaneously on a lunar direct inject did complicate the issue, however, for all parties involved. All of these issues were exacerbated by the quickly-increasing distance to Earth – over 100,000 km away within a day, at the moon in 4.5 days, and out at 1,000,000 km in two weeks, heading further away. Increasing distance quickly reduces the number of ground antennas that can communicate with the spacecraft and the telescopes and radars that could aid in navigation. Further, having three vehicles in distress and with limited communication made discrimination between them with radar or optical tracking difficult and ambiguous.

Even without any kind of flight anomalies, the relatively small number of antennas suitable for communication to low-gain antennas on the spacecraft leads to an inevitable contention between ground support assets. Even if a spacecraft could potentially use smaller antennas, there is a desire to have larger antennas for contingencies, and further there is often a requirement to have multiple overlapping antennas for critical events. NASA has an internal process for working through this contention on the DSN, but commercial missions get little or no time on the DSN, instead relying on ad-hoc scheduling across multiple providers, each with different prioritization rules. Further, many of the suitable dishes are national assets for other nations – in Odin's case India, South Africa, and Germany – which makes commercial use inherently lower priority than national use.

Lessons on Ground Stations: The relatively low number of deep-space capable, commercially-accessible ground stations meant AstroForge was doing integration directly with multiple organizations, including providing hardware and conducting test campaigns in many cases. This is a relatively large endeavor for a small team and led to rushed and incomplete tests, as well as oversights due to the inexperience of the team.

Baseline integrated tests. All standard radio frequency compatibility tests (RFCT) should be evaluated for every use case, but AstroForge found a few simple integrated tests to be critical. Insist these tests be done on the operational network and configuration.

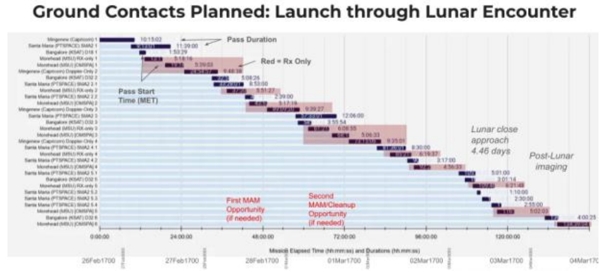
1) Long-loop tests or better yet over-the-air tests, Having all ground transmit and receive hardware in the chain, including antenna feeds. If possible, doing this with an engineering transponder is best since this fully validates uplink and downlink waveforms and phase noise, but using a test loop translator or equivalent is sufficient to validate uplink performance.
2) Live-sky receive from a similar asset. For Odin that would be any spacecraft in lunar orbit in S-band, such as the Lunar Reconnaissance Orbiter (LRO). There is no need to decode data, but the ability to verify that a signal can be received and demodulated in the right frequency and distance range validates receiver setup.

Make key data a requirement. Contracts should require key data products as prerequisite to paying for station integration: For example, an RF survey in the flight frequency and antenna geodetics in WGS84 coordinates – basics which were not by several stations even when expressly requested. A station should not be considered "integrated" if it cannot provide basic data required to properly utilize it.

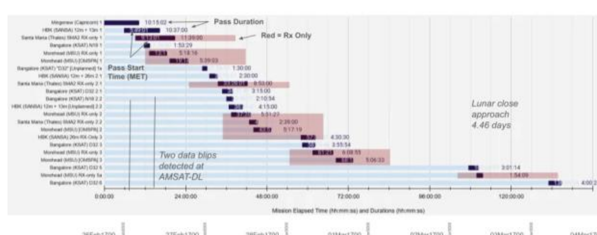
Additionally, having real telemetry from the stations and validation of key metrics helps debug issues in time-critical situations. In particular, live reading of antenna controller pointing angles and an independent verification of uplink frequency (e.g. via a sniffer antenna) should become standard for any critical pass. This may seem unnecessary on the DSN, but on commercial antennas that are switching between multiple customers and constantly reconfiguring, steps toward real-time validation of configuration are key.

Lessons on Schedule: It will change. AstroForge lost one ground station power amplifier the day of launch. The state of the spacecraft led to different antenna prioritization, leading to further changes including integration of an additional antenna. Below is the comparison of the first few days of ground contacts as planned before launch and as executed for Odin.

Ground Contacts Planned: Launch through Lunar Encounter



Ground Contacts Executed: Launch through Lunar Encounter



References:

[1] Snowden, C. (2025) *online:* AstroForge | Odin't: A Complete Debrief of Our Deep Space Mission