

Trials for a Flagship: The Unexpected Space Communications Experience of JWST Operations

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Abstract

The James Webb Space Telescope (JWST) is a valuable astronomical Observatory that is enabling unprecedented views into the cosmos, from redefining early galaxy formation models to probing exoplanet atmospheric chemistry. To maximize mission success, the spacecraft's RF communication subsystem was designed to be robust and simple. However, a unique set of circumstances presented themselves throughout the 6-month commissioning period that caused unexpected issues, high workloads, and threatened to delay commissioning and degrade mission science output in routine operations. Despite a low risk baseline and a world class operations team, at some point each of the spacecraft's 3 RF links had data delivery problems affecting the spacecraft- to the point the mission communications requirements needed to be amended. Through a combination of persistence, mitigation, collaboration, ops-con changes, software updates, and many late nights, the JWST mission operations team was able to overcome, eliminate, suppress, or workaround every issue that arose- enabling JWST to complete its commissioning on schedule and fulfill its mission with no impacts to success. However, the situation is ongoing- although the communications impacts are currently mitigated, there exists long term schedule implications extending into the future as additional missions utilizing DSN are launched- which will reduce the already slim availability to JWST and all current DSN users. This discussion reviews some of the undesired RF communications events and lessons learned that occurred within the JWST post-launch timeframe, covers the solutions that were developed to keep the packed commissioning timeline on schedule for 6 months to the release of the first images, and the impacts that should be considered in space mission designs for the future.

Keywords: NASA, JWST, RF, DSN

Acronyms/Abbreviations

Acquisition of Signal (AOS), Commissioning Activity Request (CAR), Consultative Committee for Space Data Systems (CCSDS), CCSDS File Delivery Protocol (CFDP), Commissioning Activity Sequence Timeline (CAST), Deep Space Network (DSN), Deep Space Operations Center (DSOC), Flight Dynamics Facility (FDF), Flight Operations Team (FOT), High Gain Antenna (HGA), James Webb Space Telescope (JWST), Jet Propulsion Laboratory (JPL), Medium Gain Antenna (MGA), Mission Operations Center (MOC), Mission Operations Team (MOT), NASA (National Aeronautics and Space Administration), Protocol Data Units (PDU), Radio Frequency (RF), Radio Frequency Communications [System/personnel] (RF-COMM), Sequence of Events (SOE), Space Network (SN) Solid State Recorder (SSR), Transiting Exoplanet Survey Satellite (TESS), Tracking and Data Relay Satellite System (TDRSS), Travelling Wave Tube Amplifier (TWTA).

1. Introduction

Approaching launch of the James Webb Space Telescope (JWST), the Flight Operations Team (FOT) expected that RF Communications (RF-COMM) during the launch, commissioning, and normal operations phases would be relatively uneventful and be a low workload to FOT and the greater Mission Operations Team (MOT). However reality was far from what the JWST MOT expected.

This work outlines the major obstacles that were encountered, how those obstacles were solved, and provides explanations for why they may have occurred and/or how they managed to remain hidden despite a 5-year pre-launch test and rehearsal campaign. The intent of this work is to provide a wealth of lessons learned that may inform future space missions in designing, testing, and commissioning RF-COMM systems of issues that may be encountered.

1.1 An Ambitious Concept

One of the major defining features of the JWST is that it is a very ambitious mission with very significant science goals that impact the science of astronomy as a whole. The mission, at launch, contained 344 single points of failure, the largest primary mirror launched into space, the largest sunshield, and would have to make 50 major motorized deployments in the L2 transfer orbit. To ensure success of this mission and mitigate risk, a major design driver was

robust, redundant, simple bus subsystems that would survive the launch environment and support the very delicate and precise payload for at least 5 years with a goal of 10. For this reason, the spacecraft bus architecture designed and hardware selected had few unique characteristics and long, proven heritage that would guarantee mission success.

1.2 Proven Ground Assets

The Deep Space Network (DSN) would be used for all JWST communications beyond day 1. NASA's DSN has a long history of supporting space missions that primarily reside outside at and beyond Lunar distances. The Deep Space Network was established under the United States Army in the late 1950's, and after transferring to NASA in 1969 supported the manned Apollo missions to the lunar surface using S-band communications. Between the Apollo era and the launch of the JWST, the DSN has supported dozens of missions both domestic and international, to various destinations all over the solar system, including to all 8 major planets. Utilizing the DSN for communications would be a proven method that would again lower risk through the use of heritage hardware and organizations.

To ensure contact during the critical phases of early flight, including spacecraft separation, solar array release, acquisition of signal, and mid-course correction maneuver planning, assets from NASA's Tracking and Data Relay Satellite System (TDRSS), and the European Space Agency's Malindi ground station were utilized for S-band capabilities on day 1 of the mission. This included TDRS-East for the first 45 minutes of the mission, and Malindi Station from that time until 2 hours after launch, and again from 4 to 6 hours after launch. After this period, slant range was high enough to allow the DSN antennas to track JWST continuously.

2. JWST RF-COMM Operations Overview

2.1 Overview

The JWST RF-COMM subsystem enables all communications with the Observatory and Earth. It consists of equipment utilizing both S-band and K-band [1]. S-band communications on JWST are 2-way and used for commanding and realtime engineering state-of-health telemetry, whereas K-band is downlink only and used for downlinking SSR files. S-band equipment transmits at all times whereas K-band is set to power off in safing instances as a method of load-shedding. It should be noted that in project documentation, the K-band signal is referred to as "K-band" despite the fact the carrier frequency is 25.9 GHz.

The DSN contained 18 antennas at the time of the JWST launch, but only 10 antennas would actually be allocated to communicate with it. This included the large 70-meter (70m) antennas for emergency use (DSS-14, DSS-43, and DSS-63), the "JWST nominal" 34m antennas (DSS-24, DSS-34, and DSS-54), the "JWST backup" 34m antennas (DSS-26, DSS-36, DSS-56), and one extra 34m antenna, DSS-65. Each antenna has varying capabilities which will be discussed in later sections of this work. After commissioning completed, the JWST was allocated 6 antennas: the 3 'primes' and the 3 'backups'.

2.2 Operations

JWST launch and commissioning operations were performed by the MOT. The MOT was comprised of subsystem-level teams representing each subsystem on the Observatory, as well as flight controllers, ground systems engineers, management, and anomaly support. The total count of this team at peak was about 550 persons. Each team contained representatives from factory (Northrop Grumman Space), FOT, NASA's Applied Engineering Directorate, and other subject matter experts / trade experts in some cases. JWST support was 24 hours a day, 7 days a week through the end of RF-COMM console staffing, which completed following the end of spacecraft commissioning on day 36 of the mission. JWST RF-COMM MOT was comprised of 6 factory Northrop Grumman engineers, 1 engineer from FOT, and 1 NASA Applied Engineering Directorate representative. After the end of spacecraft commissioning, the RF-COMM MOT was phased down to 2 factory engineers and 1 FOT engineer with primary focus on that system.

The RF-Communications operations concept has continuous transmission for both S-band and K-band, with S-band reconfiguring in safings whereas K-band equipment is powered off. The S-band transmitter 2 was powered on shortly after fairing separation during powered flight on the launch vehicle. K-band equipment was first powered on 25 days after launch. RF Communications with JWST would be near-continuous from launch through 120 days after launch, the completion of Optical Telescope Element commissioning. From 120 to 180 days after launch (science instrument commissioning) contact time was 16 hours per day, typically omitting the late night and early morning hours at the Mission Operations Center (MOC) in Baltimore, Maryland, USA (UTC-4 during daylight savings time). Once commissioning completed, it was expected that the JWST would transition to twice a day 4-hour long contacts spaced approximately 12 hours. However resource contention with other missions as well as stability of the K-band and ground network prevented this from being implemented. This will be discussed in section 4.6.

JWST commissioning was executed in a pre-planned timetable known as the Commissioning Activity Sequence Timeline (CAST). The CAST was populated with Commissioning Activity Requests (CARs). Each CAR was a series

of commands or actions that when correctly executed accomplish 1 complete commissioning objective (i.e. acquiring S-band command & control, deploying the high gain antenna, checking out a star tracker, etc).

The JWST MOT defined 18 RF-COMM CARs for the system to be fully commissioned (see Table 1).

Table 1. List of JWST RF-COMM Commissioning Activity Requests

CAR No.	CAR Title	Execution Time	Description	Result
275	Ascent Sequence	L+ 4 minutes	Verify ascent command sequence turns S-band transmitter 2 on.	SUCCESS
927	Establish Command and Control on TDRSS	Not Executed.	If the ascent command sequence is not nominal, establish uplink on TDRS-East.	UNEXECUTED Ascent was nominal.
027	Configure for 4K downlink and 2K uplink	L+ 1 hour	Establish command and control on Malindi. Increase downlink rate to 4kbps.	SUCCESS
011	Initiate ranging	L+ 1 hour 7 minutes	Start first ranging to enable planning of mid-course correction maneuvers.	SUCCESS
027	Configure for 4K downlink and 2K uplink	L+ 1 hour 16 minutes	Increase uplink rate to 2kbps.	SUCCESS
915	Disable Gimbaled Antenna Array Deadman Sequence	L+ 1 hour 40 minutes	If the omni antennas are healthy, cancel a scheduled automatic deploy and switch to the medium gain antenna.	SUCCESS
278	Transition to DSN Canberra & Configure for 40K downlink	L+ 2 hours 10 minutes	When DSN becomes visible, establish communications and raise downlink rate to 40kbps.	SUCCESS
874	Transition to Malindi & Configure for 4K downlink	L+ 4 hours 21 minutes	Prevent a COMM gap by returning to Malindi. Lower downlink rate to 4K to ensure adequate margins.	SUCCESS
888	Transition to DSN Madrid & Configure for 40K downlink	L+ 5 hours 50 minutes	When DSN Madrid is visible, establish communications and raise downlink rate to 40kbps.	SUCCESS
283	Configure for MGA Operations	L+ 1 day 5 hours	After the MGA is deployed and checked out, switch communications to transmitter 1 for MGA.	SUCCESS
031	COMM Reconfiguration	L+ 1 day 7 hours	At this range the telescope side omni antenna will only be facing away from Earth, so an RF switch	SUCCESS

			configures it out of the downlink path.	
885	COMM Reconfiguration prior to Inertial Reference Unit calibration	L+ 15 days 7 hours	This calibration requires the gimbaled antenna assembly to park, so communications need to be moved off the MGA back to the omni.	SUCCESS
886	COMM Reconfiguration after Inertial Reference Unit calibration	Not Executed.	Return communications to the MGA.	Not executed as intended, as JWST entered safe during the calibration. However a similar recovery procedure returned COMM to the MGA.
014	Ka-band Activation	L+ 25 days 2 hours	Power on the Ka-band modulator 1 and Travelling Wave Tube Amplifier 1.	SUCCESS, though the signal was unstable for the first few hours.
913	HGA Calibration	L+ 25 days 17 hours	Gimbal the HGA around to find the electrical boresight.	Unexpected results. Entered safe during activity. Results lowered the observed link margins, so the change was backed out. Link analysis showed ample margin with no need to retry.
050	Initial Ka-band Playback	L+ 27 days 15 hours	The Solid State Recorder has been storing data since launch. Downlink the data to clear the recorder.	FAILED first attempt, re-executed with success.
894	7M, 14M, 28M Ka-band Rate Characterization	L+ 30 days 15 hours	Characterize functionality and performance of all Ka-band selectable rates.	SUCCESS, though signal was unstable at times.
917	Nominal Flight Packet Lists & Filter Tables	Not executed.	Change the onboard data rates to normal operations.	Not executed due to earlier piecemeal executions placing JWST in the post CAR-917 state.

3. Subsystem Architecture

3.1 JWST COMM Subsystem Overview

As mentioned earlier, the JWST RF-COMM subsystem features both hardware for S-band and K-band. S-band is utilized for all ground commanding, ranging, and real-time engineering telemetry for health-and-safety. K-band supports a duplicate real-time stream that can be used to help diagnose S-band equipment problems, but only if the S-band downlink rate is 8kbps or greater. However the K-band is primarily used for downlinking of Solid State Recorder (SSR) files, comprised of either engineering telemetry or science image data.

3.1.1 JWST COMM Subsystem S-Band Equipment

The S-band hardware includes 2-for-1 redundant S-band transponders that transmit and receive. Hybrid couplers allow the receivers to receive RF from any functional antenna at all times. The receivers are always on. JWST contains 4 antennas: a High Gain Antenna (HGA) (Ka-band), a Medium Gain Antenna (MGA) (S-band), and 2 omnis. One of the omnis is mounted to the sun side spacecraft bus and coined the spacecraft omni. The other is located on the far end of the primary mirror (the optical telescope element omni marked OTE in Figure 1). This omni was added to allow downlink to be received in the first hour of the mission.

A switch allows either transmitter to be routed to either the MGA (used for S-band only), or the omnis. 2 switches in the omni path allow for the downlink to either be fully sent to the spacecraft omni, or split between it and the optical telescope element omni. Because the optical telescope omni is mounted on the far side of the telescope, which for thermal reasons must never be allowed to be exposed to the sun or Earth, it is only in view of mission assets for approximately the first 3 hours of the mission. For this reason, the switch was moved to route downlink only through the spacecraft omni on day 2 of the mission. It should be noted the optical telescope omni significantly overperformed expectations during its short operational life, providing early launch telemetry through periods expected to be out of view.

3.1.2 JWST COMM Subsystem K-Band Equipment

The K-band equipment includes 2-for-1 redundant K-band modulators. The clock is generated within the modulator and sent to the spacecraft avionics where the data is applied before being routed back through the modulator. This architecture resulted in numerous stability issues which will be evaluated in section 4.5 of this work. Downstream of the modulators is a hybrid coupler that allows the output of the modulators to be routed to 2 travelling wave tube amplifiers (TWTA). The output of 1 of the TWTAs is then routed through a circulator switch to the HGA. Only one modulator and 1 TWTA is operated at a time- to date, only modulator 1 and TWTA 1 have been powered on.

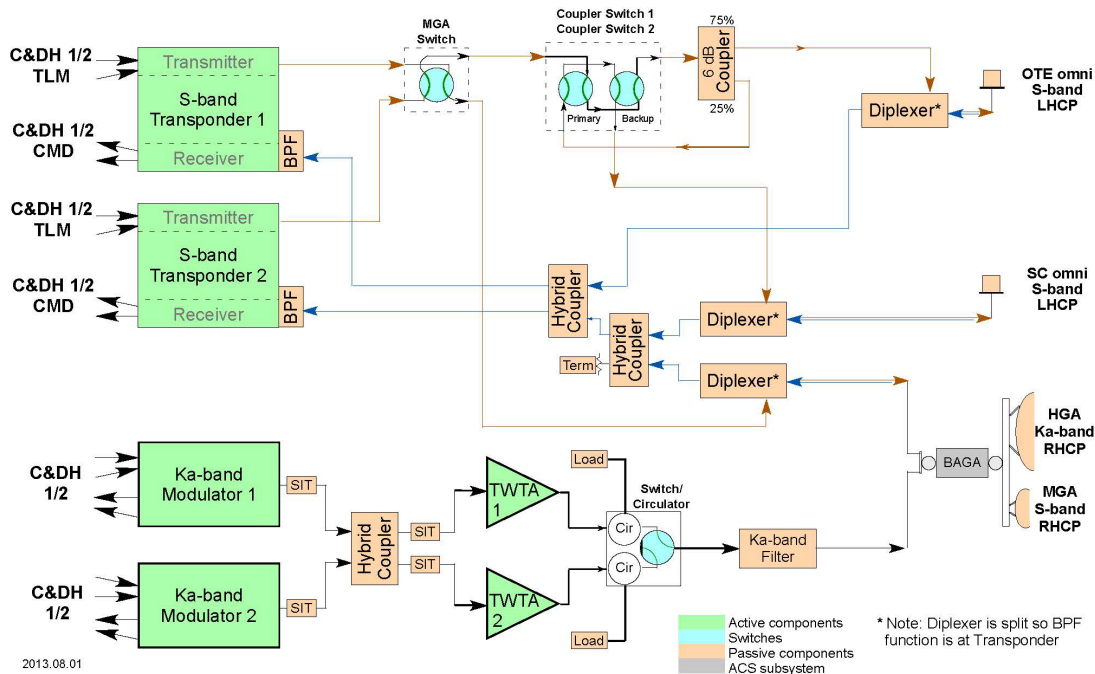


Fig. 1- JWST RF-COMM Subsystem Hardware Block Diagram [2]

3.2 DSN Antennas

As mentioned earlier 10 DSN antennas were allocated for JWST as seen in Table 2. When the JWST RF-COMM system was designed, JWST was to be allocated the 3 antennas marked as prime: DSS-24, DSS-34, and DSS-54. These antennas are typically used for deep space missions beyond the Earth vicinity, as the antennas are fitted with more powerful 20 kW transmitters [3] (see EIRP column of Table 2). The other 3 34m Beam Waveguide antennas (DSS-26, DSS-36, and DSS-56) did not have K/Ka-band functionality when subsystem design was taking place, so the JWST RF-COMM subsystem was not spec'd specifically for those antennas.

During the JWST's years long integration process, DSN resource contention in the deep space environment necessitated adding additional capabilities to the near-Earth antennas- most important to the JWST, adding K/Ka-band

functionality. By the time the JWST launched, DSS-26 already had Ka-band functionality operational, and installation was underway at DSS-36 and DSS-56 (see Table 2). Once K/Ka functionality was added to the backup antennas, there was significant pressure for the JWST to move onto these antennas. With a much lower transmitter power of 250W [3] (de-rated in Autumn 2024 to 150W), this caused numerous S-band uplink difficulties as discussed more in following sections.

Table 2. Deep Space Network Antennas Allocated for JWST Mission Use and their Capabilities

ANT ID	Site	JWST Use	Capability for JWST	K/Ka Added	EIRP
DSS-14	Goldstone	Emergency	S-band down	N/A	U/L not used
DSS-24	Goldstone	Prime	S-band up/down K-Down	Prelaunch	92.9 dBm (at 5kW)
DSS-26	Goldstone	"Backup"	S-band up/down K-Down	Prelaunch	79.7 dBm (at launch) 77.6 dBm (Feb-2025)
DSS-34	Canberra	Prime	S-band up/down K-Down	Prelaunch	92.9 dBm (at 5kW)
DSS-36	Canberra	"Backup"	S-band up/down K-Down	February 2022	79.7 dBm 77.6 dBm (Feb-2025)
DSS-43	Canberra	Emergency	S-band down	N/A	U/L not used
DSS-54	Madrid	Prime	S-band up/down K-Down	Prelaunch	92.9 dBm (at 5kW)
DSS-56	Madrid	"Backup"	S-band up/down K-Down	June 2022	79.7 dBm 77.6 dBm (Feb-2025)
DSS-63	Madrid	Emergency	S-band down	N/A	U/L not used
DSS-65	Madrid	Emergency	S-band up/down	N/A	78.5 dBm

3.3 Network

As is typical for missions utilizing NASA's DSN, the network paths extend from the individual DSN sites around the world (Canberra in Australia, Madrid in Spain, Goldstone in California USA) to the Deep Space Operations Center (DSOC) at the NASA Jet Propulsion Laboratory (JPL) in Pasadena, California. Data Control at JPL processes the data for deep space missions and distributes it to the mission's home center. For JWST, this is NASA's Goddard Spaceflight Center in Greenbelt, Maryland, USA. From there data flows to the JWST Science & Operations Center (which contains the MOC).

For mission day 1, ESTRACK's Malindi station in Malindi, Kenya was configured under the DSN network to connect to DSOC, and the TDRSS Space Network ground station at White Sands in Las Cruces, New Mexico, USA was connected directly to Goddard Space Flight Center. Goddard's Flight Dynamics Facility (FDF) is responsible for maintaining the JWST's orbit and receives ranging data from JPL as well as exchanges information with the JWST Science & Operations Center in Baltimore. A generalized diagram of these connections can be seen in Figure 2.

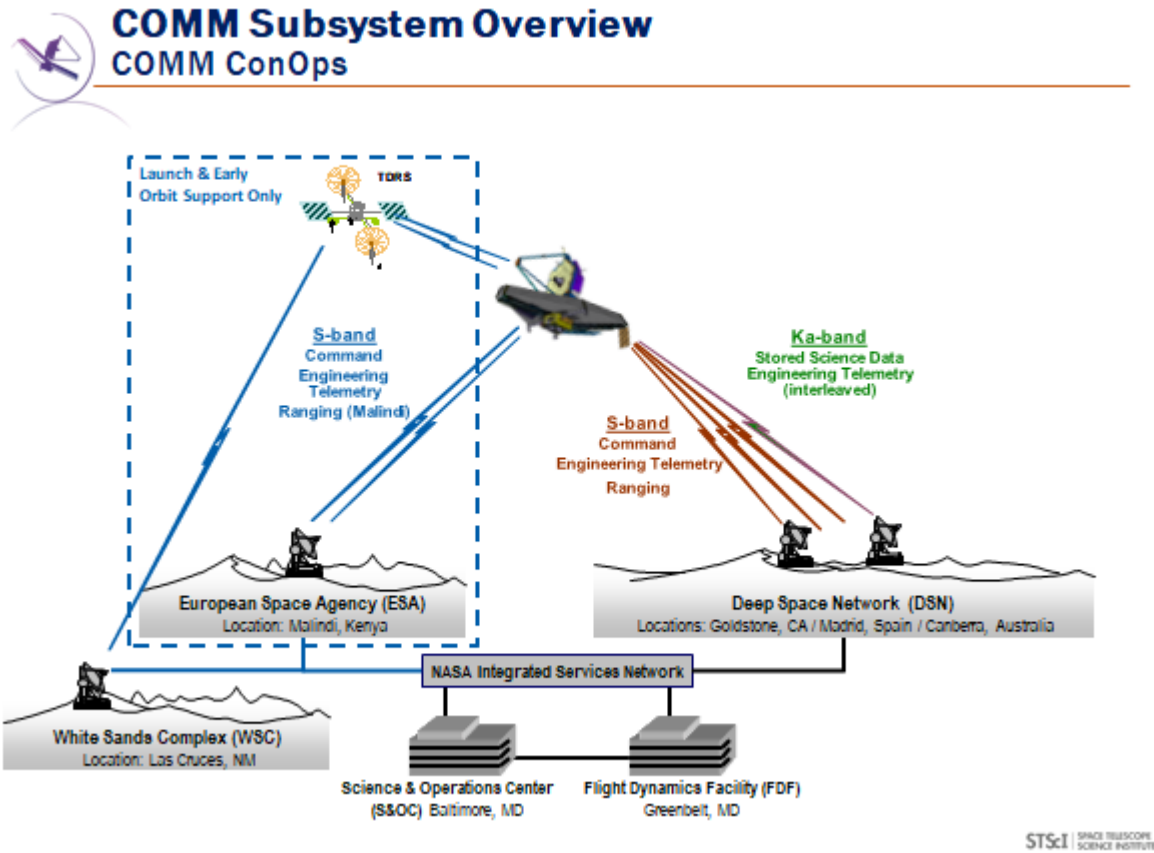


Fig. 2- JWST COMM Network Diagram [2]

4. Lessons Learned in Flight

This section is a summary of some of the major lessons learned in flight. Not all details regarding every event are captured, but the lessons deemed most important and relevant to future missions are represented.

4.1 Launch and the First Day

Launch was on December 25, 2021. At this time there was a third surge (Omicron variant) of the SARS COVID-19 pandemic. This limited in-person interactions and enforced room maximum counts in the JWST MOC. For launch, the RF-COMM team was split into 4-person strong 12-hour shifts. 2 engineers were located together in the MOC proper, and 2 were located separately in the adjoining offices taken to expand the footprint of the MOC to lower the risk of spreading of disease. These expanded offices were coined the xMOC. JWST launch was given a DSN support level of 1- the highest support level available with ~75 surge support staff.

The morning of launch day all network paths were tested utilizing test data flows and NO-OP commands originating from the JWST MOC. All network tests succeeded and the JWST launched on time at 12:20:00. The first packets were received and decoded approximately 4 minutes 20 seconds after liftoff, while on the launch vehicle in powered flight. A timeline of launch day contacts can be seen in Figure 3. The telescope omni antenna provided near continuous realtime telemetry until the spacecraft omni antenna established line of sight. First uplink was established nominally at Malindi. The ranging tone was enabled minutes later and the FDF reported reception of good ranging data. The first contact with the DSN began around 58 minutes after launch without issue.

From the RF-COMM team perspective, the mission was executing flawlessly for the first day. At this point, given a successful Mid-Course Correction maneuver, the surge support at DSN was dismissed. This was to be expected, as Level 1 support is unsustainable beyond 16 hours given the number of staff involved. Unfortunately, this was the point that things began to change from the experience on the first day.

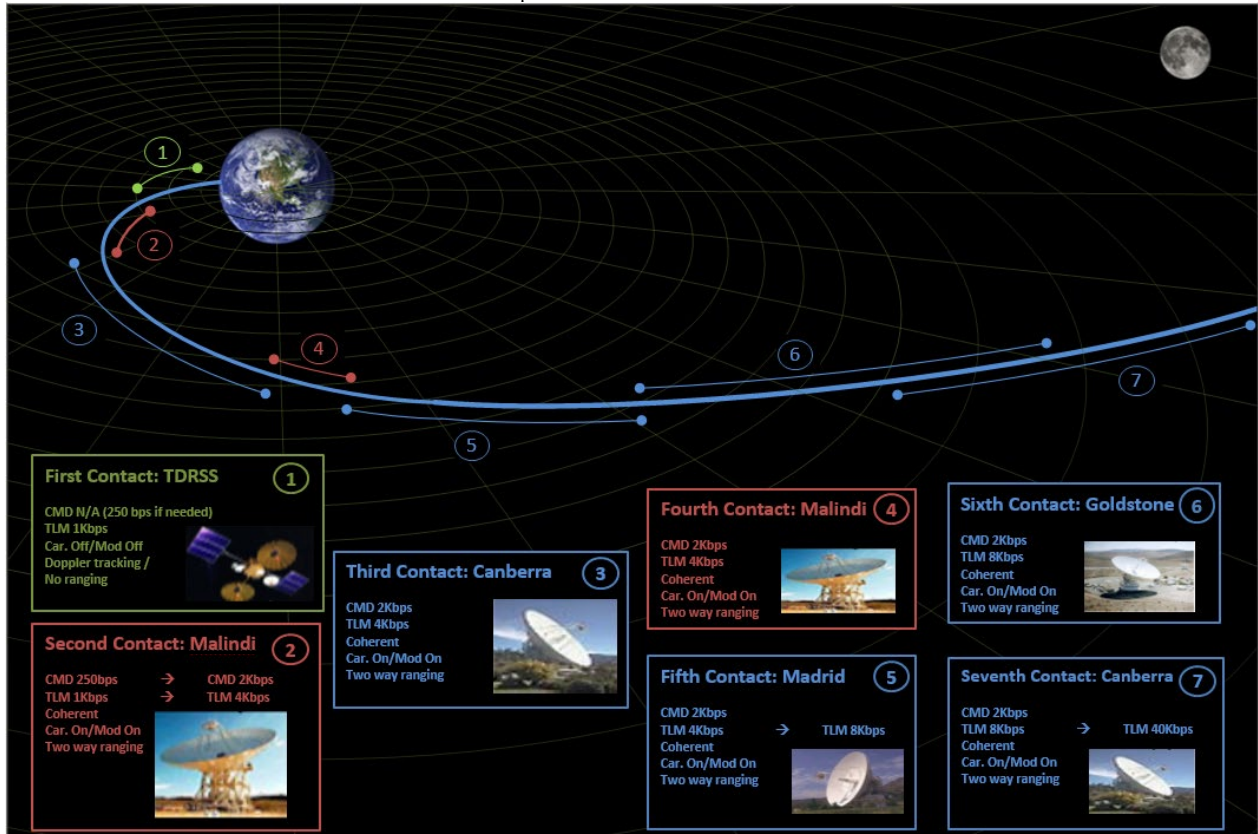


Fig. 3- JWST Launch Day Contacts [2]

4.2 Onset of Concerns

JWST performed 6 launch readiness exercises and 7 launch communication exercises with the ground station in advance of launch. The success of these rehearsal campaigns established a strong sense of nominal expectations. On day 2, numerous unexpected challenges were encountered that weren't expected per the rehearsal campaign, leading the RF-COMM team to create a file log to track all unexpected events.

Some of the unexpected events that were encountered were: resweeps when requested to turn command modulation on, incorrect or unsupported uplink rates configured, implementation of automated track teardown without RF-COMM team knowledge, a ground station low noise amplifier failing and requiring a failover to the backup station, and a network IP issue delaying AOS on the backup station. As described in the summary of issues of that day, JWST personnel had an incomplete understanding of DSN system configuration.

A review of issues months later revealed a major difference in operational philosophies: the JWST mission was accustomed to using real-time requests to change configuration (a characteristic shared with the NASA SN which itself is also organized under Goddard Spaceflight Center), whereas the DSN process is to rely more on automation. This difference in operational philosophies was exacerbated by COVID-19 pandemic, which prevented any face-to-face technical interface meetings, DSN training, or site tours from occurring. It is this unknown difference in philosophies that led to the misconfigurations.

Lessons Learned:

- (1) Face-to-face meetings should not be overlooked. Where absolutely necessary (in the interest of safety), a virtual site tour or web meeting series should be scheduled with the intentions of sharing operational philosophies, phraseology with scenarios, and operational plans to sequence or execute events.
- (2) As part of rehearsal campaigns leading up to launch, special attention needs to be given to communications between the flight operations teams, antenna operations, and network support in all phases of the mission. Focus needs to be on the transitions that are actually expected to take place, not just exercising every possible configuration in various instances. Rehearsals should be executed using the same voice communications as flight.
- (3) Space missions must have their subject matter experts review plans for automation script generation and ensure they cover the scope of the mission (in JWST's terms at launch, Sequence of Events (SOE) meant post

commissioning, whereas in DSN terms, SOE meant post initial acquisition). DSN SOE's are to enable automation and thus should be designed to minimize minute-to-minute verbal changes regarding timing of configurations.

4.3 Test Data vs. Real Data

Special care needs to be taken to keep test data separate from live telemetry. This can be accomplished a number of ways, such as designating the simulator with a different spacecraft ID than the actual spacecraft. In one particular instance, a test telemetry source generator was placed in line during a dataflow test, which was not taken out of the path by the time it was next utilized for operations. The result was test data being interleaved with live telemetry, resulting in hundreds of alarms and dozens of reconfigurations appearing to take place.

By this point, the K-band signal was available, which did not show these same issues. JWST was able to make use of the redundant K-band telemetry feed for a clear view and requested a second antenna until the source and cause was determined.

Lessons Learned:

- (1) Test data needs to be flagged in such a way that it is not able to be interpreted as real during site-specific tests, or otherwise kept in a dedicated testing location.
- (2) Operational equipment should clearly indicate when test data is flowing through them to aid in troubleshooting the system in the event an operational misconfiguration occurs.

4.4 K-Band Activation

K-band equipment was commanded to power on during day 25 of the mission. It was known ahead of time that the K-band signal would take a few minutes to stabilize after modulator and TWTA power-on. After the HGA was confirmed to be Earth-pointed, DSN was given the GO to acquire K-band. The team was surprised to find that the signal took about twenty minutes to lock, and when it did it was initially unstable.

The DSN had reported the symbol rate was off the expected by 93 Hz, and the receiver had a maximum tracking bandwidth of 25 Hz. This delta off the expected was a surprise to DSN given the difference from RF-compatibility testing results. The cause was symbol rate drift, a thermal relationship that would take weeks to discover and characterize. For the next few days, commissioning operations would keep the observatory relatively thermally stable, and the symbol rate drift abated. At the time it was believed to be caused by the modulator and TWTA power-on and that it would not return unless the unit were power cycled.

Lessons Learned:

- (1) RF-compatibility testing should occur over a wide range of operational environments to the degree possible. This should include thermal variations. Since RF-compatibility testing is usually performed at ambient temperatures, consider checking out the symbol rate drift and stability during thermal-vacuum testing for fully suppressed carrier modulation configurations.

4.5 K-Band Instability

Following 3 weeks of relatively stable K-band lock, commissioning operations would be increasingly slewing the observatory around, resulting in steeper thermal gradients and more of them. On day 45 of the mission, several ground stations experienced severe difficulty in locking the K-band signal.

This loss of lock was so severe (on 2 contacts, out of lock for more than half the track) that it triggered an anomaly response process and an anomaly resolution team was formed to determine the cause. Initially it was suspected that cold temperature was responsible for the issues, however during the next station keeping activity (which would expose the modulator to even colder temperatures), the loss of lock problem was not present. The K-band data rate was changed from its default of 28 Mbps to 14 Mbps, and finally 7 Mbps to help alleviate the issues but there was no noticeable improvement with these changes.

A troubleshooting fishbone diagram was formed with the help of the DSN engineers and it was determined that most likely some sort of symbol rate slipping was present. The fishbone identified components within modulator 1 as being plausibly responsible, but the team was unable to determine a final root cause for several more weeks.

The loss of lock would continue on and off in a mild sense, most often manifesting as a delay in acquiring the K-band signal lasting about 20 minutes. The loss of lock returned again a month later in early March 2022, with 3 contacts present over a 3-day period with loss of lock over a large fraction of the total track time.

Returning to the DSN report of symbol rate slippage, the FOT's RF-COMM engineer performed an analysis of the observed symbol rate over times the signal was locked (previous analyses had only looked at symbol rate during times the loss of lock was present). It was noticed that the observed symbol rate while locked had a characteristic thermal

profile appearance to it. When this profile was analysed, a strong, consistent linear relationship was found between the temperature of the modulator and the actual symbol rate of the modulator.

During the next period of instability, the RF-COMM team used the modulator's temperature and the linear relationship of symbol rate to suggest a 'calculated' actual symbol rate to relay to the DSN. When the DSN used this calculated symbol rate the signal immediately locked up.

It was seen that the actual symbol rate could vary by a large amount in just a few hours, up to 200 symbols per second. As mentioned in the previous section, the DSN's receiver had a symbol loop bandwidth of 25Hz, thus the loss of lock was attributed to the symbol rate being outside DSN's symbol loop bandwidth. To this point, the DSN was using the symbol rate observed at the previous end of track for the following track. However, if the observatory slewed from a hot attitude to a cold attitude (or vice versa) from the last track, the symbol rate could be several times outside of the symbol loop bandwidth, and loss of lock would be experienced.

With the observed symbol rate behavior, the attention quickly focused onto the crystal oscillator that was responsible for generating the symbol rate. Documentation and vendor confirmation revealed that although the crystal oscillator responsible for generating the carrier was temperature compensated, the crystal for generating the symbol rate was not. Further drilling down, it was determined that the symbol rate's crystal oscillator was behaving according to specs per the vendor.

The project documentation was reviewed and it was determined that no requirement for symbol loop stability existed on either the DSN side or the JWST side. In the case of JWST, the RF designers and operators were typically involved with low Earth orbit networks such as the Space Network and Near-Earth Network. DSN, being optimized for deep space, uses a much narrower symbol loop bandwidth to maximize signal to noise ratio. However, JWST's relative proximity to Earth (as compared with the planets) does not require such a narrow bandwidth.

The resolution to these issues were for DSN to bring in another receiver (not fully compatible with JWST K-band unfortunately but had a larger symbol loop bandwidth) to identify the current observed symbol rate, and then return the JWST compatible receiver in using the determined symbol rate. If this failed (typically due to high thermal gradient), FOT would provide the calculated symbol rate to DSN.

In cases where the TWTA was powered off, upon power-on the TWTA's high power dissipation would cause very rapid symbol rate migration, often necessitating DSN targeting a future symbol rate with FOT help, and attempting to lock as the symbol rate "passed through" the ground selected symbol rate.

The ultimate solution to these issues was a receiver upgrade in 2024 which widened the maximum symbol loop bandwidth from 25 to 100Hz, as well as an automated script at DSN which would perform symbol rate acquisition checks at set intervals until a lock was achieved. With the implementation of these changes, the loss of lock due to thermal induced symbol rate drift has stopped.

Lessons Learned:

- (1) When performing RF-compatibility testing, though it may be expensive, long duration (hours long) RF stability testing is worth it in the long run.
- (2) When performing RF-compatibility testing, the goal should be to determine the safe operational limits of uplink and downlink, for both spacecraft and ground, to include carrier frequency, symbol rate, and telemetry rate. All 3 aforementioned rates should be varied to investigate how the receiving system responds. Symbol rate variation is particularly important for suppressed carrier modulations.
- (3) Tolerance requirements need to exist for carrier frequency, symbol rate, and data rate no matter how large the tolerance may be. Leaving room for interpretation when paired with an unconventional or new solution can lead to complete incompatibility- especially when space-based relays are involved.

4.6 CFDP Latency

As if the symbol loop drift wasn't enough, starting from the first K-band recorder playback, there were network issues that delayed the file captures. The JWST uses CCSDS File Delivery Protocol (CFDP) Class 2, meaning files are acknowledged on the ground after being received and validated. Due to the network throughput limitations encountered, the ground was not acknowledging CFDP Protocol Data Units (PDU)s prior to onboard retry timers expiring. This would lead to duplicate PDUs being downlinked from the spacecraft and sitting in a buffer at the station. Eventually the ground processed all the buffered PDUs and duplicate acknowledgments were uplinked, causing onboard faults.

While without the ground file acknowledgement, the storage space is not released from the recorder. When the issue was present over long timespans, it could reduce the amount of free space and by extension the data that can be taken without filling the recorder. For DSN, the JWST mission was a new high-water mark in terms of data volume. The JWST mission is close to Earth and it is a data high volume science mission, resulting in a very high rate for deep space- 28 Mbps. DSN was able to implement a fix to boost the priority of mission data on the network, which allowed

some playbacks to happen but latency would still often occur, necessitating the recorder playback be halted and the fault log be dumped and cleared. An investigation revealed congestion was also present in the network intermediate path, which took several months to alleviate. The solution came in the form of a network congestion algorithm to more efficiently handle the data.

One reason this was not caught during testing is that file playback tests were limited in size and duration, only exchanging a few small files, rather than a flight-like situation of dozens of science files being played back. Also, the DSN didn't have a way to simulate the CFDP class 2 handshake with the spacecraft or simulators for the international sites.

After the mission data priority change was made, the majority of the latency was experienced at the international sites (Canberra and Madrid). Due to the testing limitations, these international antennas didn't handle JWST files until the mission took place (DSN test sites are in California, USA), meaning these network paths were not exercised at the JWST demand levels until the actual playbacks took place. For CFDP class 2 testing with the spacecraft, end to end testing was performed with a DSN emulator located at JPL to simulate a ground station, however this was not representative of actual network performance with international sites.

The impact of this issue on the JWST was so great that it increased the project's time allocation needs from 8 hours of contact time per day to 12 hours per day. This extra time was needed as the CFDP latency would build to the point of causing faults that require subsequent recovery before another playback could be attempted (with sometimes the same result). With the DSN oversubscription discussed more in the following sections, the contacts were not able to be spaced evenly.

Lessons Learned:

- (1) When performing ground segment end-to-end testing, a stress test at the maximum anticipated flight-like data generation rates should be conducted and last long enough to complete the activity as is expected in flight (for JWST, that would be 4 hours of continuous science data recorder file playback).
This experience has led DSN to develop a test setup to simulate network instability over the international sites to JPL, and now conducts network performance tests at missions' data rate requirements to identify any network issues early on.
- (2) If the mission requirements demand performance outside the normally exercised ground network capabilities, a stress test should be part of the ground segment end-to-end test campaign, using actual data paths in flight to the extent possible.

4.7 Task Saturation

In April 2022, 4 months after launch, JWST experienced a safing caused by an onboard software configuration mismatch. As part of the recovery, the uplink needed to be properly established to prevent a transponder reset. Unfortunately, despite best efforts, a misconfiguration of the uplink was present that caused a transponder reset.

As part of the debrief, it was made clear that the DSN support staff are stretched thin. This means one controller may end up staffing up to 3 missions at once, and if the workload increases, it can quickly reach saturation.

Another part of the issue was the aforementioned difference in operational paradigm, automated SOE changes vs. real-time procedural changes. Unfortunately, due to numerous launch delays, site face-to-face interface meetings were deferred until launch was more certain- however by that point the world had entered the COVID-19 pandemic and travel was not possible. No meeting series or virtual tour was set up, instead delaying these meetings until after launch. From experience, there is a very good chance these issues would have been avoided if some technical interface meetings occurred shortly before launch, even if virtual. In this case, the site was within a U.S. Army base and off limits to all tours during the COVID-19 pandemic. It needs to be understood that such policies have real consequences in spaceflight.

In response the JWST MOT changed their recovery process to be more concise, with additional configuration checks to prevent any misconfigurations. DSN is exploring options to decrease operator workload.

Lessons Learned:

- (1) There is no substitute for technical interface meetings. These meetings need to cover actual operational procedures that will involve the ground segment personnel and operational details must be exchanged with the flight teams. If these events cannot occur in person, they must occur virtually. Not conducting these meetings before launch can result in a general lack of understanding and many avoidable issues.

4.8 Mission Oversubscription

About 120 days after launch, the JWST mission was asked to scale back from continuous coverage to 16 hours per day given the enormous lost time those operations were causing to other missions. **Of the missions that use DSN, 35% of aggregate requested DSN time was not met** during JWST commissioning because of the demands placed by having an antenna in use for JWST 24 hours day. To put this in perspective, the DSN antenna count was 14 at the time, and at the absolute demand peak, 22 antennas would have been needed to ensure all requested time was allocated.

Unfortunately, there appears to be no end in sight to this problem, as the DSN antenna allocation is increasing by 1 to 15, however the DSN mission set is poised to double in the next few decades. This is forecast to cause the DSN to have an antenna oversubscription of 3-to-1 at times. In other words- 1 out of every 3 hours requested by a mission will actually be scheduled. This is discussed more in the sections below.

Lessons Learned:

- (1) The DSN is heavily oversubscribed and schedule flexibility is required to make adequate use of the network.
- (2) Mission designs should consider the use of multiple networks outside just DSN. Unless anything changes with mission set and antenna allocations, in the years ahead the schedule demands placed on the network will reach extreme oversubscription.
- (3) Oversubscription instances such as what happened with JWST need to be identified in advance and properly communicated across the DSN mission set. For Artemis 2 and 3, this has already happened as described in section 4.11 of this work.

4.9 The "Backup" Stations

The DSN scheduling pressure created by the JWST mission meant that it would have been impossible to restrict its use to the mission's "prime" antennas, which are also the only 34m antennas that can be used for uplink beyond the near-Earth environment. This would have effectively meant whichever prime antenna was facing the JWST, 4 of the approximately 10 hours of its view would be dedicated to this single mission.

Fortunately, it was determined that towards the end of commissioning, utilizing JWST's highest uplink rate was feasible on the "backup" antennas- but with very little margin to spare. The fewer missions utilizing the backup antennas meant that it was much easier for JWST to schedule time on them. By the end of 2022, the "backup" antennas were utilized over 2 out of every 3 JWST contacts.

This configuration worked without issue for a year. Then in summer 2023 (the first summer in the perpetual halo orbit) the Madrid backup station, DSS-56, was unable to close the uplink. A link analysis using the AGC readings determined that the command margin at the time was essentially 0. Throughout the summer, this loss of uplink kept occurring, and it was determined that a very low elevation combined with maximal slant range was responsible for the loss of uplink. This would explain why only Madrid had this issue- in the summer the JWST's latitude is far south, and the Goldstone and Canberra sites were further south and provided the JWST with higher elevations.

To increase the reliability of commanding (which is needed at all times for CFDP class 2 playbacks), a rapid response procedure was created to quickly step down the uplink rate from 16 kbps to 2kbps to boost the margins. This solved the issue for summer 2023 and summer 2024.

In the autumn of 2024, it was determined that the 250-watt transmitters operating on the backup stations were not intended for routine use beyond 150 watts, and an immediate de-rating took place which would lower all backup station EIRPs by 2.1 dB. For the JWST, this meant that the uplink would be negative on the backup stations for the majority of the year. To avoid changing the rates in advance of every backup station contact, the JWST mission made the decision to remain at the lower rate of 2kbps and instead raise the uplink rate to 16 kbps in rare occasions it is needed. Although the mission intended that JWST would use the highest rate available of 16 kbps, now through the intense commissioning phase, it was determined that 2 kbps would allow the mission to accomplish nearly all its objectives. In the case of JWST, this situation had a good outcome- but there were lessons learned in the process.

Lessons Learned:

- (1) When allocating ground assets in space mission design, future resource availability **MUST** be a major design driver. The DSN remains the most popular deep space network solution. While the DSN is one of the most capable networks on the planet with a proven history, it is already overburdened, and the mission set is poised to double with little added capability in the next 3 decades.
- (2) Better alignment needs to take place between mission design and antenna planning. In the case of DSN, recent upgrades have focused on moving deep space RF-COMM to X band and K/Ka band because of its higher data-rate capabilities. As such those capabilities are being expanded, and the S-band equipment was intended to be phased out. However, new missions such as Artemis and Davinci Plus [4] are continuing to design their missions with S-band hardware as these designs are robust and low risk. This mismatch can cause unnecessary resource contention that can otherwise be avoided with stronger strategic long-term planning and oversight.

- (3) To remain as flexible as possible, designs should incorporate compatibility with as many assets as possible, and consider intermediate operational command and telemetry rates to create that flexibility.

4.10 The HGA and Science Exposures

The JWST is now a world class space observatory, exceeding its science capability requirements [5]. A consequence of a more powerful telescope is a more sensitive telescope. It was noticed during commissioning that movement of the gimbaled antenna assembly, containing the MGA and HGA, would not impact science performance requirements, but would slightly degrade results [5]. The HGA, for K-band, is required to point accurately at Earth within a fraction of a degree, whereas the S-band MGA has a much wider boresight several degrees wide.

To accomplish the pointing requirements, a 10,000 second station lookahead was established at the beginning of an observation and the antennas would not be moved until either the observation completed, 10,000 seconds had passed and the antennas moved to the next lookahead position, or the DSN contact would be switched to another station.

This last item meant that every time a new contact was scheduled, the antenna would move to a new lookahead. With the original ConOps of twice a day 4-hour contacts, this meant 2 moves per day for that reason. However, due to scheduling limitations, 4 contacts could sometimes be scheduled on a given day- and with the higher telescope performance, this had a bigger impact on science than was expected.

The JWST RF-COMM team performed a study to determine the consequences of pointing the HGA lookahead at the center of Earth, rather than the individual DSN stations. This would mean the antenna would not need to be moved other than to maintain the center of Earth line of sight, eliminating the need to move when switching to another site.

The team determined that center of Earth pointing would cause minimal impacts, and in the autumn of 2023 the pointing ConOps change was made. In the year and a half since, no K-band signal loss can be attributed to center of Earth pointing.

Lessons Learned:

- (1) When designing complex interrelated systems, the ConOps should be periodically re-evaluated to determine if the system design is maximizing performance on all subsystems. In the case of the JWST, excess margin was present in the design, and excess performance was possible once the HGA pointing ConOps was revisited. In this particular case, the operation of the antenna could be changed post-launch.

4.11 Outlook for the Future

JWST had a nominal launch which resulted in minimal fuel expenditure to perform its mid-course correction maneuvers. As a result, the remaining onboard propellants are expected to last 20 years- and no limited life items are known to challenge this anticipated lifespan. For its RF-COMM subsystem, the greatest remaining challenge to solve for the future will be ensuring adequate contact time can be allocated.

In 1985, 10 DSN antennas were operational and 6 missions were tracked with them. The number of missions first exceeded the number of antennas in 1996 (15). Since that time, 1 antenna was decommissioned and 26 additional missions would be tracked. In the next 3 decades, an additional 42 missions are expected to be utilizing DSN, with only 1 new antenna planned [6].

Lessons Learned:

- (1) The continued success of the DSN and its mission set will require significant investment in expanding and refreshing the hardware, and reducing task saturation.

5. Conclusions

The JWST is a successful cutting-edge space Observatory. However, its continued success depends on the availability of its ground segment in the future. The experience has demonstrated that although the design of the system was robust, numerous challenges were faced and overcome. However, these challenges represent an opportunity for future missions to apply these lessons learned to better enable mission success.

To ensure mission success into the future, the JWST MOT will be seeking additional assets that it can utilize during periods of extreme oversubscription on DSN. The project has already begun reaching out to other communication networks to establish capabilities and options for the future.

Acknowledgements

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