Orbit Determination for the James Webb Space Telescope During Launch and Early Orbit

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ORBIT DETERMINATION FOR THE JAMES WEBB SPACE TELESCOPE DURING LAUNCH AND EARLY ORBIT

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The NASA James Webb Space Telescope (JWST) mission successfully launched on December 25, 2021, at 12:20 UTC. This paper details several novel challenges encountered in the orbit determination (OD) of JWST during the launch and early orbit. The first OD solution used only 6.5 hours of tracking data, much less than the 24 hours of data usually required for libration orbiters on an outbound trajectory. In addition, the observatory area exposed to solar radiation pressure changed through a series of sunshield deployments while concurrent momentum unloads and attitude telemetry outages occurred. This paper covers how the Flight Dynamics Team (FDT) prepared for these challenges, how these challenges were handled on-orbit, and the performance of the resulting OD solutions.

INTRODUCTION

The James Webb Space Telescope (JWST) is a NASA flagship observatory that will explore astronomical phenomena in the near to mid infrared spectrum in the exploration of dark matter, first light from galaxies, exoplanets, and other astronomy research topics. JWST is developed by the NASA Goddard Spaceflight Center in partnership with the Johns Hopkins Space Science Telescope Institute (STSci), the European Space Agency (ESA), and the Canadian Space Agency (CSA). The NASA JWST mission successfully launched on Dec 25, 2021, at 12:20 UTC and inserted into its operational orbit about the second Lagrange point (L2) in the Sun-Earth-Moon (SEM) system on Jan 24, 2022, at 19:00 UTC.

The JWST Flight Dynamics Team (FDT) consists of engineers who have a long heritage of mission support for SEM libration orbits for both L1 (ACE, SOHO, and DSCOVR) and L2 (WMAP) missions.[1,2,3,4] JWST brings several novel orbit determination (OD) challenges to this heritage to enable the next generation of astrophysics research. The JWST mirror and sunshield, driven by science research requirements, resulted in a multi-stage deployment sequence that continually changed the JWST dynamical model. This transition can be seen in Figures 1 and 2.[5] Additionally, the initial OD solution used to plan the critical first maneuver could only use a maximum of 6.5 hours of tracking data. This made estimating the outward-bound trajectory of JWST using only ground-based tracking a unique challenge.

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Figure 1. The JWST Initial Launch Configuration.

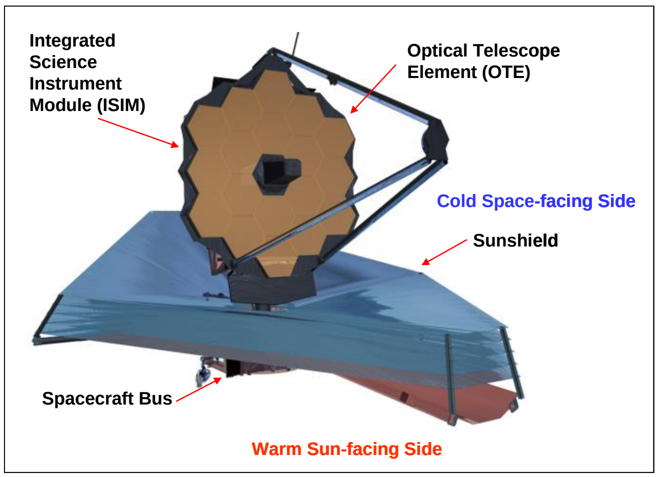


Figure 2. JWST Final Deployed Configuration (Launch+28 days).

This paper will detail the challenges and design solutions from the JWST early mission OD operations. Each of the OD estimation arcs are described and the on-orbit results are listed.

This is a part of a series of papers on JWST flight dynamics operations, with this paper focused on OD for the early mission. The overall JWST flight dynamics support is detailed in Reference 6. The mid-course correction (MCC) maneuver design and execution are described in Reference 7, while the MCC real-time support is detailed in Reference 8. Earlier papers have explored the impact of the launch date on the JWST MCC maneuver design and the resultant long term dynamical systems libration orbit characterization, Monte Carlo simulation of nominal MCC burn designs, and MCC contingencies and designs.[9,10,11] Finally, Reference 12 presents an OD analysis to assess if mission requirements could be met.

BACKGROUND

JWST is a deployable infrared telescope with distinct physical properties in the launch and early orbit. Over the course of 30 days JWST traveled to L2, performing three MCC maneuvers along the way. To plan each MCC, an accurate spacecraft orbital state was required which was obtained through OD. Figures 3 and 4 show the mission overview for JWST.[13]

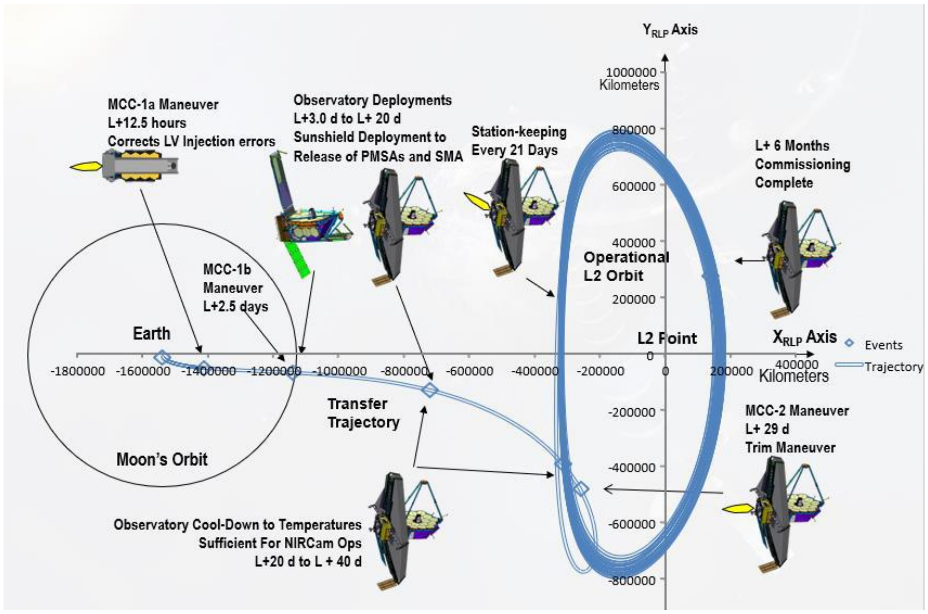


Figure 3. JWST Concept of Operations from Launch to SEM L2 Science Orbit Operations.

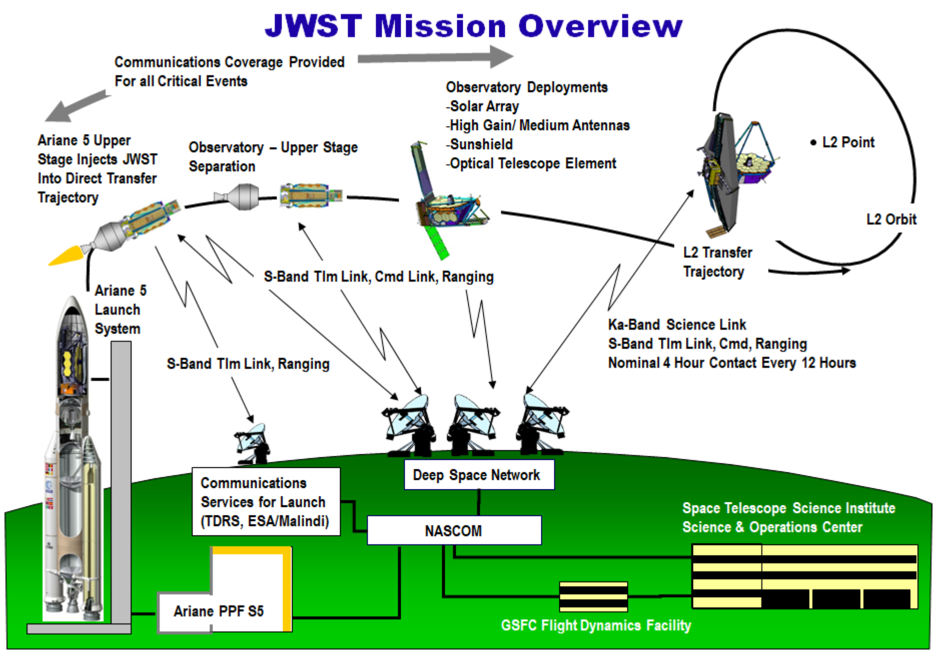


Figure 4. Operational Assets for the JWST Mission.

The primary navigation assets supporting JWST for its mission lifetime are the Deep Space Network (DSN) 34-meter Beam Waveguide antennas located in Canberra/Australia, Goldstone/USA, and Madrid/Spain. In the early mission, support was also provided by the NASA Tracking Data and Relay Satellites (TDRS) as well as the European Space Agency's Malindi ground station in Kenya. The DSN and Malindi ground stations provided two-way S-band range and range rate measurements while TDRS provided powered flight telemetry and communications in launch and early operations. JWST is equipped with a medium gain antenna (MGA) that is used for S-band tracking and telemetry, and a high gain antenna (HGA) that transmits Ka-band science data.

The two estimation algorithms used for OD were the Extended Kalman Filter (EKF), implemented in Orbit Determination Toolkit (ODTK), and Batch Least Squares (BLS), implemented in the Goddard Trajectory Determination System (GTDS). The ODTK smoother was also run after the EKF to refine the solution. There are tradeoffs to using either estimation technique. EKF's generally require initialization with at least several days of data, so they are only viable for longer arcs. Standard BLS estimators can be used effectively with shorter data arcs but do not use process noise, so the estimated trajectory exactly obeys the modeled dynamics. This can make BLS estimators inaccurate for long arcs as even small dynamics modeling errors can cause significant trajectory dispersions.

The early orbit was divided into four distinct OD arcs for each of the mission phases shown in Table 1, which also lists the primary estimator used during each phase. Due to the limitations of the EKF over short arcs, it was determined the BLS would be used to generate the OD solution states used to plan MCC-1a and MCC-1b. However, because BLS estimators can have trouble solving through maneuvers, two distinct OD arcs were used. The first arc nominally spanned from launch vehicle (LV) separation to 5.5 hours prior to MCC-1a and the second arc spanned from right after MCC-1a to 4 hours before MCC-1b. Because MCC-2 occurred at 28 days after launch (L+28 days) the EKF had sufficient time to converge and thus was used as the prime estimator for planning MCC-2. In that arc, the BLS estimator would have had trouble solving through frequent momentum unloads. GTDS also did not have an accurate model of the sunshield and deployments that was needed to accurately compute the solar radiation pressure (SRP) force during that phase. Table 2 shows the OD knowledge requirements specified as the root sum of the squared (RSS) errors at the execution time of each of the MCC and station-keeping (SK) maneuvers.

Table 1. Timeline of Mission Phases and Primary OD Estimator Used in Each.

Mission Phase	Nominal Start Time	Nominal Stop Time	Primary Estimator
LV sep. to MCC-1a	Dec. 25, 2021, 12:47 UTC	Dec. 26, 2021, 00:50 UTC	BLS
MCC-1a to MCC-1b	Dec. 26, 2021, 00:50 UTC	Dec. 28, 2021, 00:20 UTC	BLS
MCC-1b to MCC-2	Dec. 28, 2021, 00:20 UTC	Jan. 24, 2022, 19:00 UTC	EKF
MCC-2 to first SK	Jan. 24, 2022, 19:00 UTC	Feb. 16, 2022, 21:55 UTC	EKF

Table 2. 3-σ OD Knowledge Requirements at Each Maneuver Execution Time.

Maneuver	3-σ RSS Position Requirement	3-σ RSS Velocity Requirement
MCC-1a	50 km	30 cm/s
MCC-1b	50 km	10 cm/s
MCC-2 and SK	50 km	2 cm/s

The observatory was tracked by the DSN during the four arcs discussed in this paper with near continuous coverage. DSN sequential range and total count phase (TCP) measurements, which are analogous to Doppler measurements, were used in the estimators. There were two tracking data gaps in the first arc and a few more unplanned outages in later arcs, but tracking was frequent enough that these unplanned outages had minimal impact on OD accuracy. During the early mission, all OD requirements were met.

OD FOR MCC-1A

Arc Description and Challenges

JWST's nominal mission plan was to launch into an orbit with an eccentricity of approximately 0.99. Due to the highly eccentric orbit, JWST's velocity decreased significantly as it flew away from periapsis, and thus maneuvers became less fuel-efficient. Since propellant translates directly into mission lifetime, it was imperative to maneuver as early as possible to maximize the mission lifetime and scientific return of JWST.

Because of the need to maneuver quickly, JWST's first OD arc was nominally 6.5 hours long starting from LV separation. This is an unprecedentedly short tracking arc; most Lagrange point orbiters use at least 24 hours of data in the arc. This section documents the difficulties, preparation, and results associated with this OD arc.

MCC-1a was nominally scheduled to occur at L+12.5 hours. As the project timeline leading up to MCC-1a became more refined, the FDT learned it was required to deliver the final MCC-1a maneuver plan four hours prior to maneuver execution. This required the OD team to deliver a solution by L+7.5 hours to give the maneuver planning (MP) team one hour to generate the maneuver plan. The OD team estimated it would take 30 minutes to run and perform quality assurance (QA) on the OD solution, so the nominal data cutoff (DCO) to support this delivery was L+7 hours. Tracking data was acquired starting a few minutes past separation, so the nominal OD arc length was 6.5 hours.

The tracking assets used prior to MCC-1a can be seen in Figure 5. If only DSN data was used, there would be two large tracking gaps before the DCO. Malindi tracking data was used to fill these gaps after analysis showed it was necessary to meet requirements.

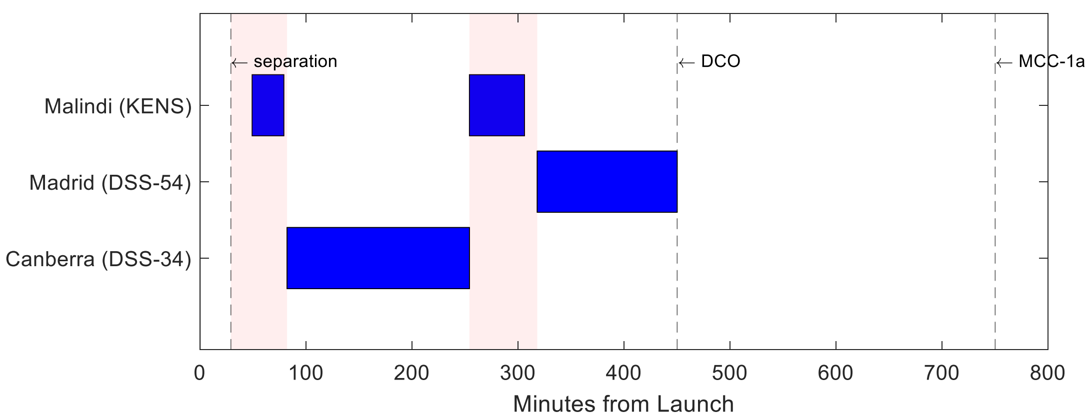


Figure 5. Tracking Schedule Prior to MCC-1a.

This short arc posed several significant challenges. Generally, these challenges can be grouped into three main categories:

1. Low observability. There was only 6.5 hours of tracking data. For a low Earth orbit mission this would span multiple orbits, but for JWST it was only a small fraction of the nearly hyperbolic orbit. Because the spacecraft was rapidly flying away from Earth,

ground station-based tracking provided little geometric diversity which made BLS convergence more challenging to achieve.

2. Lack of similar OD scenarios from other missions. There are several OD QA metrics, including thresholds for the BLS correlation matrix, used by FDT members on other missions. These tend to be heuristic tests derived from experience. These tests may not have been applicable to such an unprecedented arc.
3. Time-constrained operations. There was not time for flight dynamics engineers (FDEs) to make mistakes, iterate on a final solution, or solve unanticipated problems. There also was not much robustness to losing tracking data because there were no redundant passes in such a short arc.

To address these challenges, several analyses were performed to gauge how much tracking data was needed, what sort of anomalies could arise, how we would respond to anomalies, and how QA metrics could be applied to this arc. These analyses motivated operations procedures including the real-time QA of incoming data, and an automatic delay in the operations schedule if certain conditions were not met. Additionally, the FDT ran simulations and trainings focused on this phase of the mission for several years leading up to launch.

This preparation was necessary to ensure that OD requirements could be met given that the MCC-1a maneuver was nominally scheduled at L+12.5 hours. If an anomaly occurred that degraded the OD solution quality enough to risk violating requirements, the burn would be delayed to L+19.5 hours. This delay would be sufficient to receive Goldstone tracking, which would refine the OD solution. Based on analysis, this would likely be sufficient to rectify many tracking anomalies but not all. If MCC-1a was delayed to L+19.5 hours the total cost of the MCCs would increase by around 5 m/s, potentially limiting the mission lifetime. On the other hand, if requirements were violated and the OD team failed to recognize it, the L+12.5-hour burn would be planned using a poor OD state and then executed. This would lead to large amounts of wasted propellant and potentially result in acquisition issues with DSN. Although unlikely, in extreme cases, a severe overburn caused by large OD knowledge errors could cause a potential overshoot of L2. Since JWST cannot thrust toward the sun, this could lead to mission failure. Based on these potential consequences, addressing these OD challenges was considered essential for mission success.

Arc Preparations and Analysis

Before launch, extensive OD analysis was performed for the first OD arc. The analysis items discussed in this section will be summarized but not fully detailed. The goals of these analyses were to ensure that sufficient tracking assets were allocated to JWST to meet requirements, and that FDEs had sufficient information to act quickly and correctly during time-constrained operations. To this end, the following questions were studied:

1. Can requirements be met without Malindi tracking data?
2. Can requirements be met with Malindi tracking data?
3. In a variety of tracking scenarios, what OD performance can be expected?
4. What is the minimum amount of tracking required from each station to ensure requirements could be met?
5. What situations would mandate delaying MCC-1a to obtain more data? How long of a delay would be necessary?

To gain insight into the listed questions, Monte Carlo (MC) simulations using both the BLS and EKF were run with different tracking configurations. Though the BLS was the prime estimator for this OD arc, both the BLS and EKF were used. A sample of the tracking scenarios evaluated in the MC analyses using the BLS, along with a summary of the results are listed in Table 3. The BLS could not converge in any cases where a DSN pass or the first Malindi pass was lost, thus no contingent MC cases met requirements. The same MC analysis using the EKF initialized with a BLS solution produced similar results with few contingent cases meeting requirements as shown in Figure 6. Additionally, the OD solution using only DSN data was less stable, with many MC errors that were larger than the formal 3-σ covariance.

Table 3. Tracking Scenarios for BLS MC Analysis.

Case	Percentage of MC Cases Within Requirement
Nominal, tracking from all stations	100%
No 2nd contact from Malindi	100%
No 1st contact from Malindi	0%
No Malindi tracking	0%
No Canberra tracking	0%
No Madrid tracking	0%

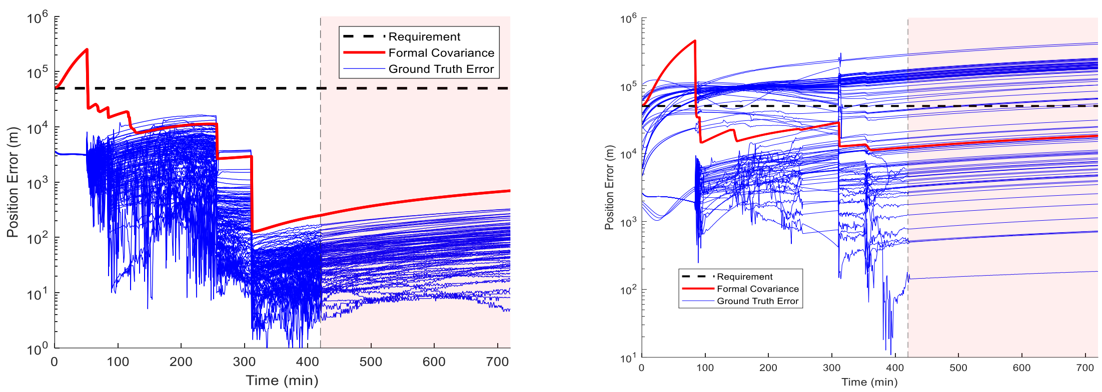


Figure 6. EKF MC Errors Up to MCC-1a Using DSN and Malindi Stations (left) vs. Only DSN (right). Definitive Portion of the Arc is Shaded in White and Predictive in Red.

From the results shown in Table 3 and Figure 6, it was concluded that Malindi tracking was necessary to meet requirements. The first Malindi contact was particularly important because of the increased geometric diversity associated with being closer to the earth in a more dynamic phase of the orbit. Because of this analysis, Malindi tracking was added as an OD requirement to maneuver at L+12.5 hours. If Malindi tracking could not be acquired, it was decided that MCC-1a would be delayed to L+19.5 hours in order to receive data from the DSN Goldstone station.

In addition to the BLS and EKF MC analyses, about 20,000 additional scenarios that varied the amount and timing of tracking from each station were analyzed through a covariance analysis using the Orbit Determination Error Analysis System (ODEAS), which runs much faster than a MC simulation. Consider parameters were used to quantify the effects of errors that would not be present in a formal covariance. In these scenarios, the total covariance (formal and consider) was judged to determine whether the RSS position and velocity uncertainties were below requirements.

From the covariance analysis runs, the minimum tracking time of each station necessary to meet requirements was determined. A buffer was added to each time to ensure that the FDT could receive and QA data from the station to ensure that it was valid before switching to the next station. These minimum times were used in operations to ensure that enough time was allotted for each tracking station. The 20,000 cases were useful for situational awareness as the effects of tracking anomalies were quantified before launch. In cases that did not meet requirements, extended arcs were analyzed to determine how long MCC-1a would have to be delayed to receive sufficient tracking data for an OD solution. In general, delaying the maneuver to L+19.5 hours improved solutions, as that was enough time to acquire data from Goldstone.

A thruster test firing (TTF) with a magnitude of around 7 mm/s was scheduled at the end of the tracking window at around L+7.5 hours, which was after the nominal DCO. Pre-launch analysis showed in the event that MCC-1a was delayed, the OD team could successfully run the BLS through the TTF without modeling it to utilize tracking data past the nominal DCO.

Arc Operations and Results

The observatory's separation from the launch vehicle occurred at 12:47 UTC on December 25, 2021. The nominal MCC-1a time was at L+12.5 hours, which was 00:50 UTC on December 26, 2021. This section documents the OD process used to generate the spacecraft state needed to plan MCC-1a.

To deliver an OD solution by 19:50 UTC, the nominal DCO was set to 19:20 UTC to allow the FDEs time to run and QA the solution. This number was chosen based on experience in past missions and simulations. The DCO was not a hard cut-off; in fact, FDEs chose to wait for slightly more data to increase confidence in the final solution. The final OD delivery was made at 19:52 UTC, with a DCO at 19:29 UTC. Actual tracking times from every station are shown in Table 4.

Table 4. Tracking Data Received vs. Requirement.

Station Name	Minimum Tracking Requirement	Doppler Data Received (UTC)	Range Data Received (UTC)
Malindi	30 min	13:08-14:28 (80 min)	13:28 - 14:28 (60 min)
Canberra (DS36)	90 min	14:32-16:47 (134 min)	14:35-16:40 (125 min)
Malindi	0 min	16:49-18:09 (80 min)	16:50-18:08 (78 min)
Madrid (DS54)	60 min	18:15-19:29 (84 min)	18:20-19:29 (79 min)

Note that Malindi was within JWST's line of sight during the entire Canberra contact. Canberra was preferred when both were accessible because it is generally more accurate and reliable. Malindi was used to fill in gaps between the DSN stations and to provide geometric diversity.

The FDT received 1-way, 2-way, and 3-way tracking data. The 1-way data and 3-way data was not included in the solution for two reasons. First, they are less accurate than 2-way data. Second, the software limits the number of measurements that GTDS can process. In addition, Doppler data was down sampled from a frequency of 10 seconds to 60 seconds to match the frequency of the sequential range measurements. This ensured one measurement type would not be weighted more than the other in the estimator. The BLS was initially able to fit both the Canberra and Madrid data very well, but the Malindi passes showed a large range bias. A 1545-meter range bias was applied in the BLS to the Malindi data to make the data fit in line with the DSN tracking.

The post-fit measurement residuals are shown in Figure 7. Residuals are the main tool used by the FDT to evaluate the quality of an OD solution. Typically, a quality OD solution should have residuals whose mean is close to zero. This assumes that the measurement errors are Gaussian. This is usually a good assumption because systematic errors are dominated by random errors, but that was not the case with JWST. The data was incredibly clean so there were not many random errors in the measurements. However, there were still systematic errors. It was known that modeling errors existed for this phase of the mission. For example, no antenna to center of gravity offset was modeled which caused a range bias as a function of attitude. In addition, the attitude rates induced Doppler errors, oftentimes much larger than the order of magnitude of the expected random measurement noise. Finally, a large Malindi bias was observed and while the OD team attempted to quantify it, there was likely some error in the quantification. Deleting all biased information would have improved residuals but limit the observability of the solution.

The observed residuals were small, even though they were structured. The FDT chose to not include Doppler data from the first Malindi pass since it was much noisier than the other passes. Past analysis indicated that the amount of tracking received was sufficient to meet OD requirements. Additionally, the BLS solution was converged and passed QA checks. For these reasons, the OD solution was deemed acceptable.

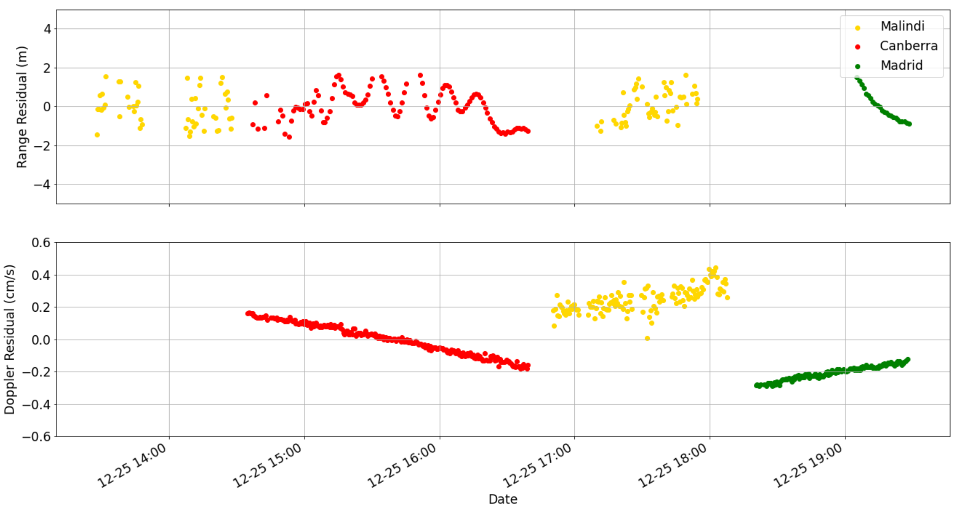


Figure 7. Post-fit Range (top) and Doppler (bottom) Measurement Residuals of the GTDS pre-MCC-1a Solution.

Though the BLS was the prime estimator at this phase of the mission, the EKF was run to build up a history of its performance and accumulate data for initialization.

The EKF and smoother were run for the same time period as the BLS solution used for MCC-1a planning. The initial residuals are shown in Figure 8. The EKF was not set up to ingest and process Malindi data since the filter was not used operationally until after MCC-1b. The first Canberra pass fit well since the initial uncertainties on the state were very large, but the next Madrid pass was edited out since the residuals exceeded the 3-σ bounds. The filter could have been tuned in several ways to accept this data, including increasing the sigma-edit threshold, but there was not much time to tune the filter with such a short delivery window. The BLS had much fewer models and settings to tune than the EKF which made it the clear choice to use on such a short arc given the time constraints on generating the solution.

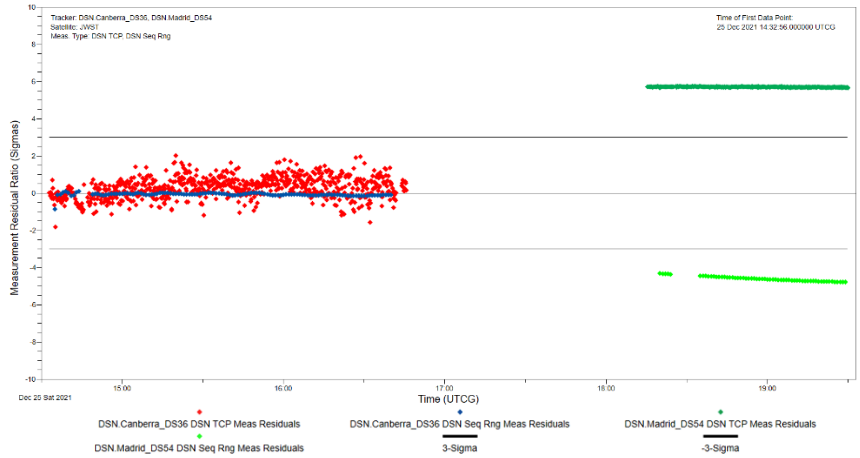


Figure 8. Post-Fit Measurement Residuals of the ODTK Pre-MCC-1a Solution.

The filter was tuned to accept all of the tracking data by reducing the state uncertainties in each Cartesian direction from 50 km and 5 m/s to 10 km and 1 m/s for the position and velocity components respectively. The residuals from that OD run are shown in Figure 9. This is further proof that the filter was not appropriate for the first OD arc. Tightening the a-priori covariance should not have caused more data to be accepted. Using the larger initial state uncertainties, the EKF settled on an incorrect state estimate throughout the first pass, and the state covariance at the end of the pass was too tight to allow that estimate to change as more data was processed. This indicates that the filter was dependent on an accurate initial state. While JWST was fortunate to receive such an accurate separation state, this was not guaranteed and the uncertainty on the initial state was set to cover the range of possible separation errors. The white noise sigmas on the sequential range measurements were set very conservatively for this arc but were later tuned to match the noise on the data. The tuned EKF and BLS solutions were within 4 km of each other during the definitive span.

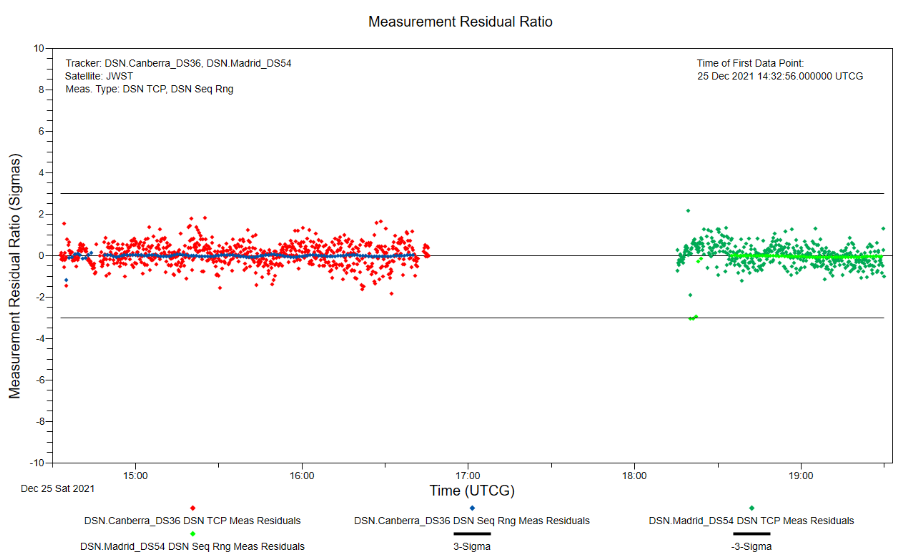


Figure 9. Post-Fit Measurement Residuals of the ODTK Pre-MCC-1a Solution with a Tighter Initial Covariance.

OD FOR MCC-1B

Arc Description and Challenges

MCC-1b occurred 2.5 days after launch and served as a clean-up maneuver given the MCC-1a execution errors. The OD arc was 31 hours long with an epoch several hours after MCC-1a. Constant DSN tracking alternating between Madrid, Goldstone and Canberra was acquired throughout this time. Though the OD arc was not as time-constrained as the MCC-1a OD arc, it still suffered from low observability. To ensure requirements could be met, MC and covariance analyses were run. In addition to the solution state required for planning MCC-1b, the MP team needed an OD solution up through 24 past MCC-1a to calibrate the MCC-1a maneuver.

Arc Preparations and Analysis

A variety of cases were studied through a covariance analysis including the nominal scenario, large MCC-1a dispersions, and the loss of tracking from Madrid, Canberra or Goldstone. All scenarios met the 50 km and 10 cm/s requirements and showed knowledge errors an order of magnitude below requirements.

Arc Operations and Results

The OD team ran the BLS several times after MCC-1a to assess the quality of the tracking data and ensure readiness for generating the OD state used for planning MCC-1b. The final OD arc included about 31 hours of tracking data from December 26, 2021, at 06:00 UTC to December 27, 2021, at 13:00 UTC. The residuals from the final OD run are shown in Figure 10. Though the OD team could have waited for more tracking data, 31 hours of data was enough to ensure the solution was converged and passed QA checks. This also gave the MP team additional time margin to generate the MCC-1b products. There was much less structure in the sequential range residuals on the top plot in Figure 10 compared to the previous OD arc. This is most likely due to lower Earth-relative velocities and using only DSN tracking in the solution. The Doppler residuals still showed significant structure, likely due to attitude and antenna offset modeling errors. Regardless, the OD run was well converged and the noise on the residuals was quite low, so it was deemed an acceptable solution.

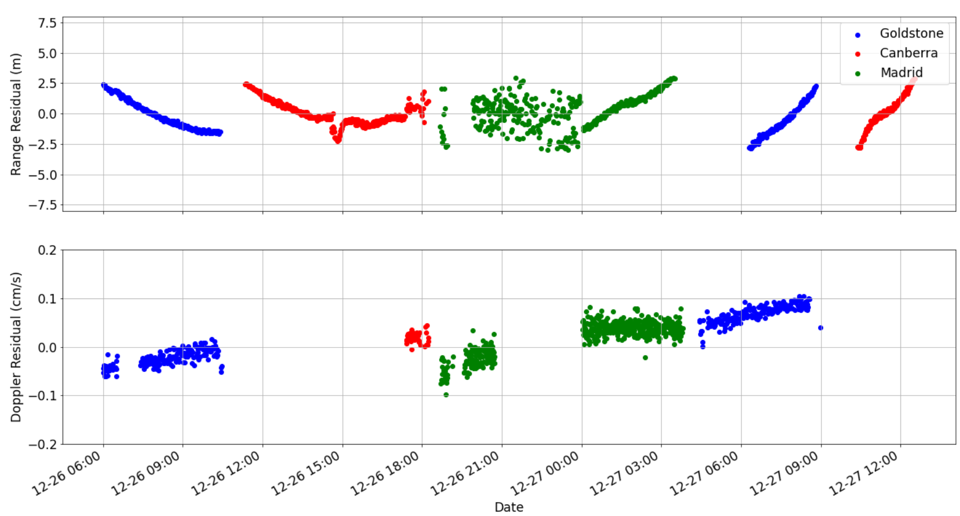


Figure 10. Post-Fit Range (Top) and Doppler (Bottom) Measurement Residuals of the GTDS Pre-MCC-1b Solution.

In parallel to the BLS runs, the OD team ran EKF solutions to prepare for the transition to using the estimator after MCC-1b. The EKF utilized a finite maneuver model for MCC-1a using the nominal burn design for the a priori delta-V. The maneuver execution errors appeared to be small based on Doppler tracking through the burn, so the EKF was able to fit through the maneuver with only small changes to the maneuver estimate. The residuals up through December 27, 2021, at 08:00 UTC are shown in Figure 11. Throughout this mission phase the OD team was iterating on various filter settings. These include the measurement white noise sigmas along with estimated parameters including per-pass range biases, transponder delay biases and SRP coefficients in each axis.

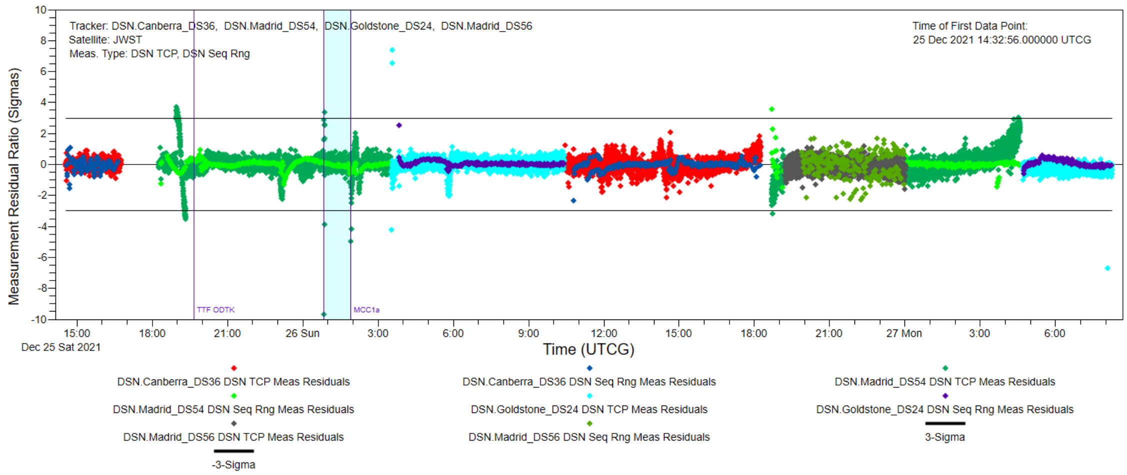


Figure 11. ODTK Residual Ratios From 12/27 Solution.

As tracking data started accumulating, the EKF solutions showed signs of convergence, including sharp reductions in the formal position and velocity uncertainties. Additionally, the trajectories generated from the EKF and BLS solutions became closely aligned as shown in Figure 12, which added confidence to the BLS solution and in the transition to the EKF as the prime estimator.

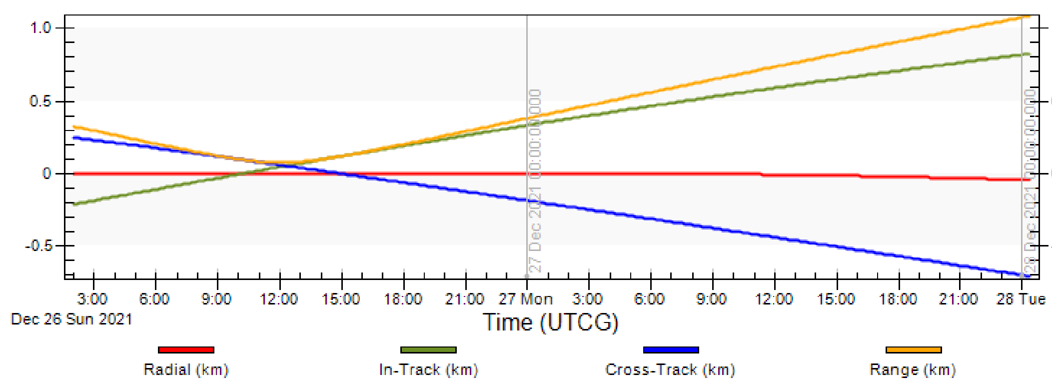


Figure 12. Trajectory Difference Between EKF and BLS Derived Trajectories from 12/27 Solution.

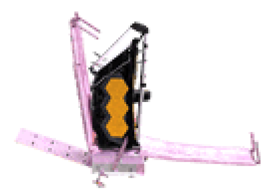
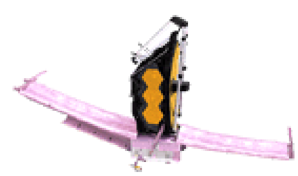
OD FOR MCC-2 AND SUNSHIELD DEPLOYMENT

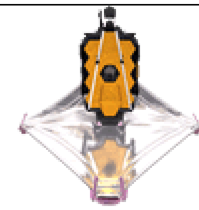
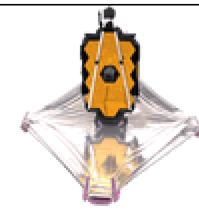
Arc Description and Challenges

MCC-2 occurred 30 days after launch. The OD arc before the maneuver spanned four weeks, much longer than the two prior arcs. During this arc, the sunshield deployment took place over approximately seven days. The deployments were significant because they caused large changes to the solar radiation pressure model and necessitated momentum unloads. In addition, the JWST attitude telemetry was incomplete for the majority of the OD arc because the observatory was in an attitude mode where the yaw angle about the +z axis, which is perpendicular to the sunshield, was not known. Along with degrading the range and Doppler measurements as discussed previously, the attitude mismodeling caused SRP errors which are significant given the sunshield has a deployed area of 161 m^2.

Table 5 shows the deployment schedule.[14] To model the SRP force, the OD team uses a polynomial curve fit based on a ray-traced SRP model that provides the observatory area exposed to the Sun as a function of attitude.[15] This more precisely models the spacecraft area facing the Sun compared to a N-plate model. This table highlights the SRP model configuration changes and the time each model was used. The planned and executed start and stop times for each deployment are also presented.

Table 5. JWST Deployment Schedule with Flight Dynamics Model Impacts

#	Description	Planned Schedule	Actual Start	Visual
1	Stowed Configuration	L to L+3 days (72 hours)	12/25/2021 12:47 UTC	
2	Forward Unitary Pallet Structure (UPS) at 50%	L+3 to 3.09 days (2.1 hours)	12/28/2021 15:14 UTC	
3	Forward UPS at 100%, Aft UPS at 50%	L+3.16 to 3.21 days (1.05 hours)	12/28/2021 23:01 UTC	
4	Forward and Aft UPS at 100%	L+3.21 to 3.27 days (1.05 hours)	12/28/2021 23:11 UTC	
5	+J2 Midboom 100% Assembly deployed	L+6 to 6.21 days (5 hours)	12/31/2021 21:45 UTC	

6	+/-J2 Midboom 100% deployed	L+6.23 to 6.4 days (4.2 hours)	01/01/2022 03:08 UTC	
7	Deployed MBA and tensioned sunshield membrane (used once the first layer was tensioned)	L+7.05 to 8.3 days (11 days)	01/03/2022 19:29 UTC	
8	Secondary Mirror Support Deployed, model and SRP estimation effective for mission operations	L+9.9 to 10.2 days (7.2 hours)	01/05/2022 16:22 UTC	

Arc Preparations and Analysis

Prior to launch, the sensitivity of the nominal trajectory to errors in the timing of each deployment was computed. This gave the FDT knowledge of which deployments were most impactful, and how much a timing error in any given deployment would impact the dynamics model. This allowed the FDT to confirm that timing errors in the deployments would not result in requirements violations. This analysis showed that deployments 5 and 6 caused trajectory dispersions an order of magnitude larger than the other deployments. Those are the sunshield mid-boom assembly deployments, which caused the largest changes of observatory area.

Each deployment took a finite amount of time but was modeled within the EKF as instantaneous due to software limitations. For this reason, the middle of each deployment duration was modeled as an instantaneous deployment within the EKF. This contributed to errors in the dynamics modeling but was small enough to not pose a risk to violating requirements based on pre-launch analysis.

Arc Operations and Results

After MCC-1b, there was a period of 39 hours before the sunshield began to deploy. During this period, the EKF had time to settle from the disturbance created by MCC-1b and the BLS could converge before large changes in the spacecraft area occurred. To get the EKF to converge, the measurement white noise sigma values were increased, and dynamic sigma editing was enabled. Without these two changes the EKF edited out measurements after the first station handover, but with these changes all passes were incorporated into the solution.

Given the limitations of GTDS to model momentum unloads and the sunshield deployment, the post-MCC-1b EKF solutions were compared an ephemeris generated by propagating the solution state from the pre-MCC-1b BLS solution with the nominal maneuver design. The MCC-1b execution errors appeared to be very small based on Doppler tracking during the burn, so the BLS derived ephemeris with the nominal maneuver plan was deemed to be the best estimate of the current trajectory. Figure 13 shows the residuals from an EKF run with data up through December 30, 2021, at 20:00 UTC. There was significant structure in the residuals due to the lack of full attitude knowledge, several momentum unloads, and the momentum flap deployment which occurred around Dec. 30th at 13:00 UTC.

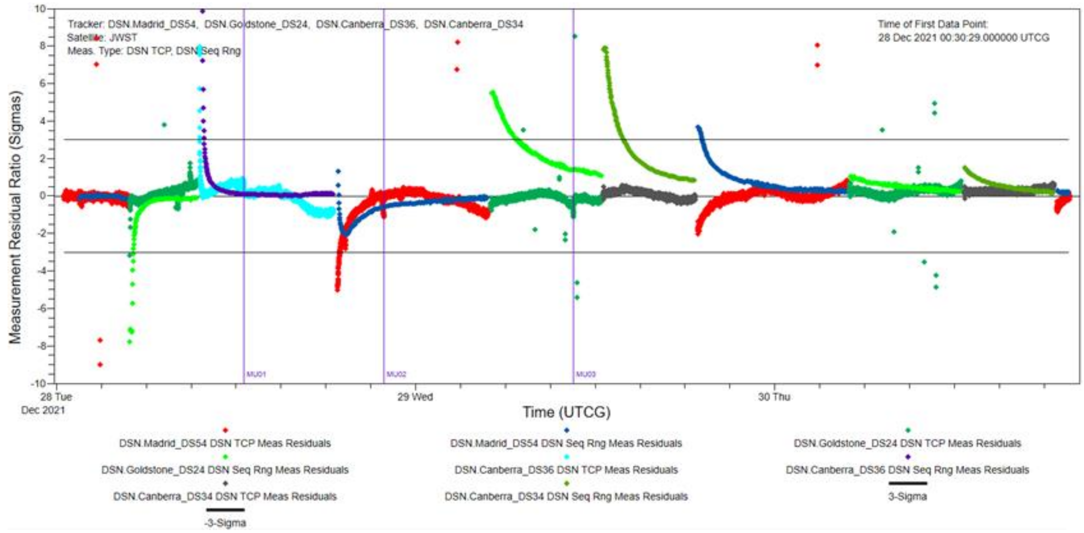


Figure 13. Range and TCP Residual Ratios from Post-MCC-1b ODTK Solution.

Figure 14 shows the trajectory differences between an EKF derived trajectory and the BLS derived ephemeris that used the nominal MCC-1b design. The difference between the trajectories in the definitive span was around 5 km, much less than the 25 km difference seen by a BLS solution using the same tracking data as the EKF, which implied a much larger maneuver error than what was observed. The lack of modeling of the momentum unloads in GTDS introduced large knowledge errors into the solution. Given these results along with previous comparisons, the OD team switched to using the EKF as the prime estimator.

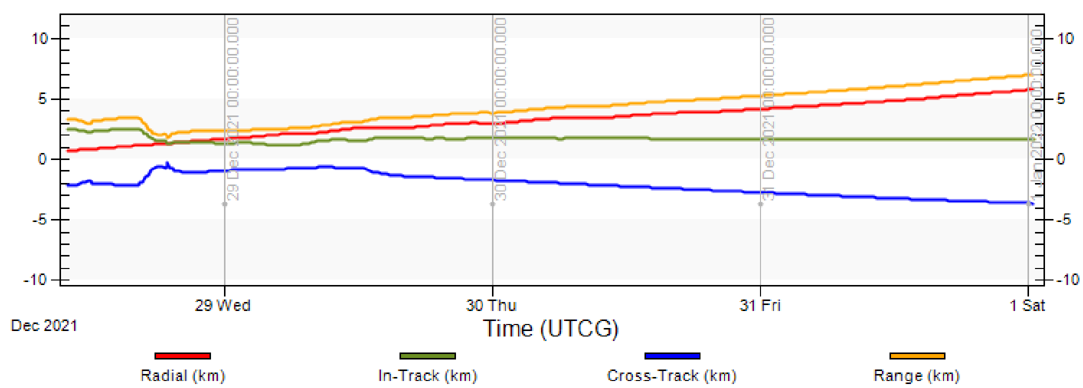


Figure 14. Trajectory Difference between the Dec. 29 EKF Solution and the BLS Derived Best-Estimate of the Trajectory.

Although the attitude telemetry was invalid for most of this phase, it was known that the sunshield was approximately pointed at the sun. This granted approximate knowledge of the SRP area, which limited the amount of SRP force error caused by invalid attitude telemetry. The spacecraft rotated about its body yaw axis such that the area stayed roughly constant.

Figure 15 shows the measurement residuals throughout deployments 5 and 6 from Table 5. Per pass range biases were estimated to get the range data to fit but the TCP residuals showed significant structure between the momentum unloads MU05 and MU06 where the deployments occurred.

This is likely due to the lack of attitude information combined with errors in modeling the deployments and momentum unloads.

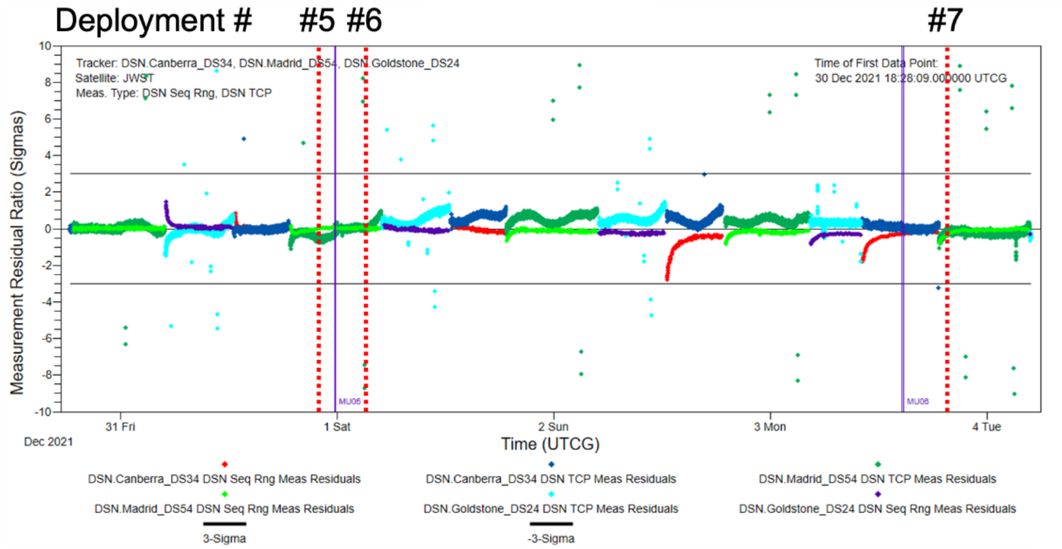


Figure 15. OD Measurement Residuals during Deployments.

Once the sunshield finished deploying, the coefficient of reflectivity in the +z direction, which is perpendicular to the sunshield, was added as a solve-for parameter to mitigate any SRP mismodeling. This SRP coefficient was not solved for during deployments because errors in deployment timing would have thrown off the estimate significantly.

Figure 16 shows the residuals from an OD run the day before MCC-2. The data fits much better compared to the solution shown in Figure 15. The solution is improved due to more accurate attitude information and the completion of major deployments. This improved attitude information also allowed the OD team to estimate the SRP coefficient more effectively. The white noise sigmas on both the sequential range and TCP measurements were set conservatively to 20 meters and 0.4 mm/s respectively to handle any potential attitude errors due to changes in the attitude mode.

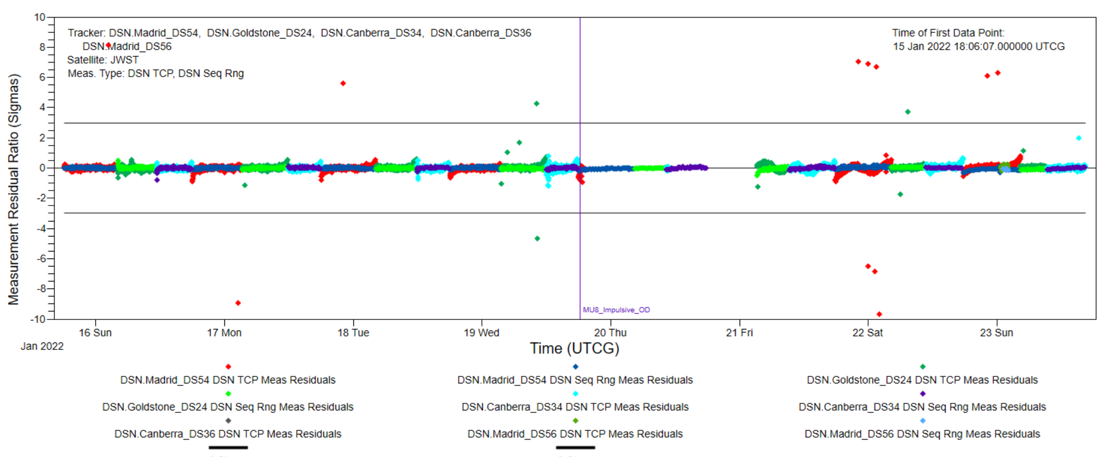


Figure 16. Range and TCP Residual Ratios from Pre-MCC-2 EKF Solution.

Figure 17 shows the SRP +z coefficient filter estimates for the pre-MCC-2 solution. The estimate took about a day to converge to a value around 1.04, or 4% higher than nominal, and was relatively constant throughout the arc. The fact that the SRP estimate was stable as new data was processed by the EKF suggests the attitude and SRP area modeling was accurate, and the relatively small change to the nominal value suggests the reflectivity modeling of the sunshield was also accurate. The ODTK smoother was run to get the final value for the SRP coefficient that was delivered by the FDT.

Compared to the reconstructed OD solution, the predictive portion of the OD solution used to plan MCC-2, which had a DCO on January 22, 2022, 14:00 UTC or about two days prior to the maneuver, showed prediction errors of 600 meters and 2.2 mm/s at the time of the maneuver. This is well below the 50 km and 2 cm/sec requirements. Though there were some challenges using the EKF throughout deployments and attitude telemetry outages, the OD team successfully transitioned to using the EKF as the primary estimator and successfully executed the MCC-2 burn to insert into the Lissajous orbit.

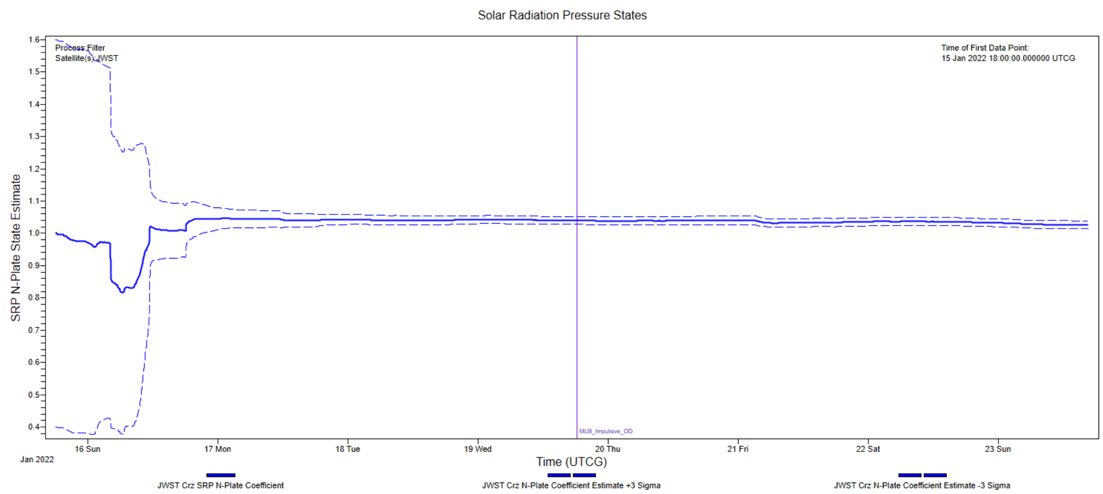


Figure 17. SRP +z Coefficient Filter Estimates from the Pre-MCC-2 EKF Solution.

OD FOR STATION-KEEPING

Arc Preparations and Analysis

To maintain the Lissajous orbit, SK maneuvers are nominally performed every 21 days. The OD team is responsible for generating solution states used for planning the SK maneuvers with a DCO at least 12-hours prior to the maneuver.

To assess the expected OD performance in the science orbit, a covariance analysis was run for a variety of cases. The amount of tracking data and estimated parameters were varied, and the analysis was run throughout the year to study any seasonal variations. Each OD arc consisted of 20.5 days of data and the errors were taken at the time of next SK maneuver, 12 hours after the DCO. All cases, aside from scenarios where the SRP coefficient was not estimated, met the 2 cm/sec requirement for the OD knowledge error at the execution time of the SK maneuvers. There also appeared to be a seasonal component to the OD errors with expected peaks in April and October.

Arc Operations and Results

The first SK maneuver was executed successfully on February 16, 2022, at 21:55 UTC. The OD team generated a solution state with data through February 14, 2022, at 15:00 UTC to plan the SK. This is an earlier DCO than what was assumed in the pre-launch covariance analysis, but the OD prediction performance up until that point was accurate enough to stay well below the 50 km and 2 cm/s requirements. The residuals from that OD solution were similar to those shown in Figure 16. At this point in the mission, the FDT was receiving the full attitude information, so there was much less structure in the residuals compared to previous phases. The SRP +z coefficient was estimated and stayed around 1.04 for this phase of the mission which is similar to the pre-MCC-2 OD solution. Figure 18 shows the 3-σ position uncertainty in the radial-intrack-crosstrack (RIC) frame. The EKF took about 2 days to converge and the RSS position uncertainty at the end of the arc was about 650 meters.

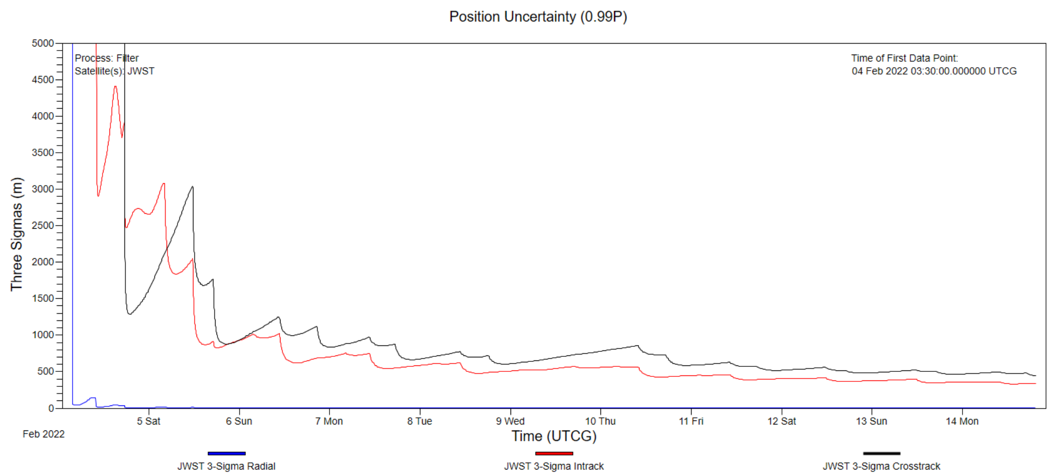


Figure 18. OD 3-σ Position Uncertainty from 2/14 OD Solution.

Figure 19 shows the differences between the predictive portion of the ephemeris generated on Feb. 14, 2022, compared to the definitive solution generated on Feb. 17, 2022. This comparison showed about a 400-meter difference between the two trajectories at the time of the SK maneuver, which can mostly be attributed to the prediction errors from the Feb. 14th solution.

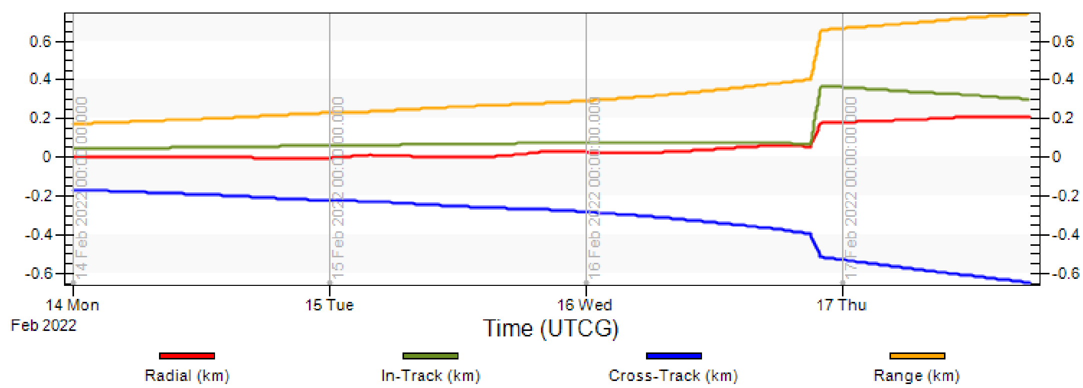


Figure 19. Position Difference between Feb. 14th OD Prediction vs. Feb. 17th OD Reconstruction.

CONCLUSION

Despite some unprecedented challenges, the JWST OD team supported several successful MCC maneuvers to get the observatory to L2, and a SK maneuver to maintain the Lissajous orbit. The first OD arc prior to MCC-1a was extremely short, but through careful pre-launch analysis the team was prepared for any contingencies and achieved a converged OD solution. The team also successfully supported the MCC-1b maneuver and transitioned from using the BLS to the EKF soon after. Additionally, though the OD solution was degraded, the team was able to perform OD throughout the large number of sunshield deployments that constantly changed the SRP area, along with frequent momentum unloads and attitude telemetry outages, to prepare for the MCC-2 OD delivery. Finally, the team developed a well-tuned setup for the EKF to successfully support the first SK maneuver and future operations in the science orbit. The experience gained from the JWST OD team will be invaluable and can help guide requirements and concepts of operation for future Lagrange point missions.

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