James Webb Space Telescope Navigation Optimization Challenges

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Abstract **– This paper details the orbit determination, solar radiation pressure (SRP) modeling, and station-keeping maneuver planning for the NASA James Webb Space Telescope during the routine science phase of the mission. The complexities of SRP modeling driven by the vehicle's large area, attitude profile, and attitude constraints for maneuver execution entail unique challenges for spaceflight navigation. The techniques utilized to combine predictive attitude and maneuver targeting modeling were refined using the experiences and data accumulated during and following the commissioning phase. The Navigation Team at NASA Goddard Space Flight Center's Flight Dynamics Facility responded to these challenges and implemented methods for trajectory optimization and improving maneuver efficiency.**

I. INTRODUCTION

The James Webb Space Telescope (JWST) was successfully launched by NASA in partnership with international collaboration on December 25, 2021, representing a significant milestone in the pursuit of scientific exploration beyond Earth's atmosphere. As a state-of-the-art astronomical observatory, the JWST operates within the near to mid-infrared spectrum, employing advanced technologies to investigate the mysteries of the universe with unprecedented precision. Its primary objectives encompass a wide range of scientific inquiries, including the examination of galactic and stellar origins, as well as the comprehensive study of exoplanetary atmospheres, with the potential to identify environments conducive to sustaining life.

Following its launch, the JWST seamlessly maneuvered into its designated operational orbit around the second Lagrange point (L2) within the Sun-Earth-Moon (SEM) system on January 24, 2022. The attainment of this critical orbital position was paramount to the mission's success, as it facilitated the telescope's ability to capture clear, accurate, and distortion-free observations of celestial phenomena.

The Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center played a crucial role in the success of the JWST launch and deployment phases and continues to perform dedicated navigation services during the science phase. As the primary navigation operations facility for the JWST, the FDF oversees the navigation and operational support necessary for the telescope's mission. The FDF's responsibilities span a wide range of flight regimes, encompassing tasks such as orbit determination (OD), maneuver planning, trajectory optimization, and covariance and contact analysis.

In addition to JWST, the FDF oversees managing the navigation needs of more than 30 active missions. These missions have diverse scopes and consist of satellites orbiting near Earth and probes exploring deep space, each with its own set of navigation requirements. By providing comprehensive capabilities and operational support, the FDF is crucial to the success of not only the JWST but also numerous other NASA missions.

A. Background

During the initial orbital phase of the JWST, a series of three midcourse correction burns were executed to precisely position the spacecraft in its designated libration orbit at the SEM L2 [1]. During the coast to L2, the vehicle's primary observatory and sunshield were deployed. Once the tennis-court-sized sunshield was unfurled and tensioned into place, the large area exposed to solar radiation dictated that the SRP force model would need to account for the vehicle's geometry, reflective properties, and orientation relative to the Sun. Following the insertion of JWST into its L2 libration orbit, the commissioning phase for the vehicle's observatory commenced along with the first cycle of routine station-keeping (SK) maneuvers.

Due to the complexity of the dynamical modeling, definitive OD for JWST is performed using an Extended Kalman Filter (EKF) to estimate the vehicle's trajectory and reflective properties using Deep Space Network (DSN) TRK-2-34 tracking data and spacecraft attitude telemetry [2]. For the purposes of orbit prediction and SK maneuver targeting, the sensitivity of the SRP force to the vehicle's orientation requires that predictive attitude information must be incorporated to generate accurate orbit predictions and maneuver plans.

Predictive attitude plans are provided to the FDF by the JWST Spacecraft Operations Center (SOC), located at the Space Telescope Science Institute (STScí). Short-term (28 day) orbit predictions are propagated using a Short-Range Attitude Plan (SRAP) to model the vehicle's future attitude states for up to a week. SRAP attitude data is highly reliable, as it reflects finalized planned attitude states that the vehicle will be commanded to attain during the ensuing week. For long-term (5 years) orbit prediction, a conservative approach of applying a Sun-Pointing Neutral (SPN) attitude configuration is utilized where reliable planned attitude data is not available. The SPN attitude mode aligns the net SRP force along the JWST-to-Sun vector where it becomes independent of the vehicle's angle of rotation about this vector, defined as the Sun yaw angle (Fig.1).

Given the dynamic instability of the libration orbit, SK thrust must be applied in either the sunward or anti-sunward direction to balance the resulting orbit. The attitude constraints of the vehicle also impose limits on the available pointing directions for station-keeping thrusters. The thrusters cannot be aligned with the optimal pointing direction for sunward maneuvers, rendering sunward maneuvers to be significantly less fuel efficient than anti-sunward maneuvers [3]. Consequently, SK maneuvers must be targeted to balance the orbit while ensuring that the next maneuver will also be performed in the anti-sunward direction to optimize propellant usage.

When targeting a SK maneuver, the attitude and SRP modeling configuration which is applied to the predicted post-maneuver trajectory will dictate the direction of the subsequent SK maneuver, assuming nominal propulsion system performance. If the predicted post-maneuver attitude states result in an SRP model that under-predicts the cumulative SRP impact on the post-maneuver orbit, a targeted anti-sunward maneuver will be larger than necessary and the next maneuver will need to be executed sunward to compensate. In contrast, an anti-sunward maneuver which is targeted using an SRP model that over-predicts the cumulative SRP impact will achieve station-keeping while ensuring that the next maneuver will likewise be performed anti-sunward. For this reason, SK maneuvers are targeted while applying the SPN attitude mode, as this mode entails the largest possible SRP area cross-section and therefore a larger modeled cumulative SRP impact.

II. ORBIT DETERMINATION

The flight dynamics support for the JWST mission involves the utilization of the EKF technique provided by the commercially available Orbit Determination Tool Kit (ODTK) to accurately determine the spacecraft's definitive orbit. The EKF was selected as the navigation filter of choice over the least square batch estimation algorithm because the sequential nature of the EKF allows for improved maneuver estimation while computing the time-history of the SRP coefficient.

By utilizing DSN tracking data, the ODTK's filter algorithm solves for the spacecraft's trajectory and various other parameters. Although operational workflows typically involve running the OD process at discrete intervals each week, with one week of definitive overlap, each run of the EKF begins with the final state estimate obtained from the previous run.

A. Dynamical Modeling

The primary forces influencing the OD of the JWST are the gravitational force exerted by the Earth and non-gravitational SRP. Because of the vehicle's proximity to Earth, smaller forces like Earth tidal effects are not considered. The precise dynamical modeling of the JWST incorporates an EGM96, 30x30 geopotential model, as well as the gravitational forces exerted by the Sun, all planets, and the Moon.

The SRP is the most significant non-gravitational perturbation that affects the orbit of the JWST. Inadequate modeling of SRP could lead to large prediction errors for the JWST. To address this, a high fidelity Light Reflection model for SRP is used. The model is a 49 degree polynomial that characterizes the SRP force and moment vector components with respect to the spacecraft's Sun pitch and Sun roll angles.

The orientation of the JWST in space is highly restricted to ensure that the telescope and its science instruments are shielded from direct solar illumination. Specific constraints are applied to the telescope's boresight pitch angles, which are limited to values between 85° and 135°, with 0° representing pointing towards the Sun. The roll angle about the telescope boresight is constrained to ±5°, while the yaw angle is unconstrained, allowing for a full 360° rotation around the sunline (Fig.1).

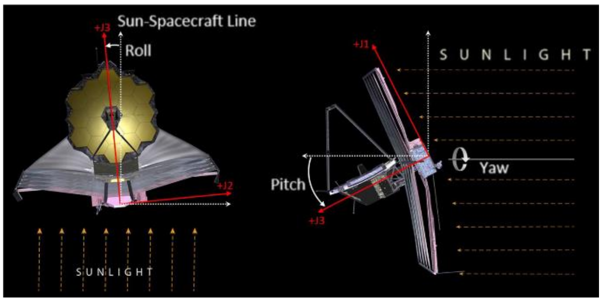

Fig. 1. *Sun angle definition for JWST.*

The FDF receives both definitive and predicted attitude history files from the SOC. These attitude files contain information about the rotation between the inertial frame and the body frame of the spacecraft. They are utilized to calculate the inertial location of antenna phase center, which is defined in body coordinates relative to the spacecraft's center of mass. The ODTK filter uses these attitude files to determine the direction of the Sun in the spacecraft's body frame and accurately compute SRP accelerations in the same frame.

Fig.2 displays the time history of pitch, roll, and yaw angles for the JWST, providing a graphical representation of how these angles change over time. Fig.3, on the other hand, depicts the corresponding four-dimensional quaternions associated with the JWST's attitude. Quaternions are mathematical entities used to represent rotations in three-dimensional space. The quaternions in Fig.3 capture the precise rotational information of the spacecraft's attitude at different time points.

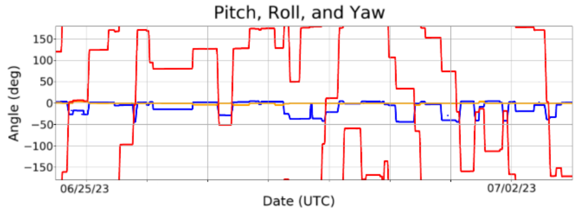

Fig. 2. *The time history of Pitch, Roll, and Yaw angles for JWST.*

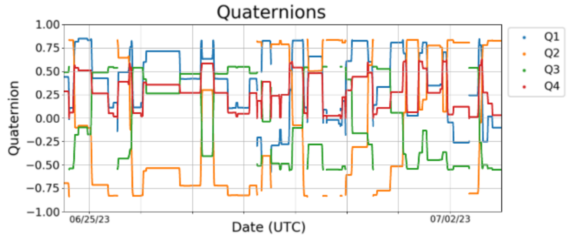

Fig. 3. *The time history of Quaternion states for JWST.*

B. *Measurement Modeling*

The DSN regularly tracks the JWST and obtains navigation data in the TRK-2-34 format. The DSN utilizes specific antennas, namely DSS-24 (or 26) in Goldstone, DSS-34 in Canberra, and DSS-54 in Madrid, to track the spacecraft. These antennas transmit signals to the JWST's onboard antenna, and then JWST's onboard antenna transmits them back to the respective DSN stations. This transmission is achieved by applying a predefined transponder ratio. The JWST's communication subsystem facilitates two-way communications, employing a 0.6 m Ka-band high-gain antenna (HGA) and a 0.2 m S-band medium-gain antenna (MGA). The MGA is primarily used for tracking and telemetry purposes, providing communication in the S-band frequency. On the other hand, the HGA is responsible for transmitting scientific data in the Ka-band frequency. This arrangement allows for effective and efficient communication between the JWST and the DSN during tracking and data transmission operations.

The FDF utilizes S-band TRK-2-34 tracking data to accurately compute JWST OD. The filter processes both sequential range and total count phase (TCP) data simultaneously. These measurements undergo corrections for the perturbing effects caused by various components of the intervening media, namely the Earth's troposphere and ionosphere. In addition to the media corrections, a two-way transponder delay of 11062 nanoseconds is applied to account for the time delay between the reception of the signal on the spacecraft and its re-emission back towards Earth. Moreover, a white noise sigma value of 1.5 meters is used for range measurements, while a value of 0.02 is used for TCP measurements. These values reflect the operational settings for the uncertainty of the respective measurements.

C. *Filter Tuning*

The objective of filter tuning is to establish a filter configuration that operates independently or with minimal supervision, enabling highly accurate and predictive OD and realistic covariance estimation. To achieve this objective, all potential sources of error and forces must be carefully considered during the dynamic modeling process.

During the filter tuning phase, it is crucial to address both the accelerations that are nominally modeled, and the anticipated errors associated with these forces. Additionally, the filter must incorporate realistic models for all types of orbit measurements, accounting for the presence of white noise and potential biases in measurement. The ODTK offers a range of stochastic models that can be employed to estimate bias and force model parameters. However, in most cases, practical experience or empirical testing is required to determine the most suitable model and to identify which parameters should be estimated.

D. *Data Processing*

The goal of data processing is to estimate the precise definitive OD of JWST and improve its prediction accuracy. To achieve this goal, a key implementation strategy involves utilizing the restart capability of the ODTK software. In ODTK, the filter processing can be temporarily halted, typically after processing the most recent daily measurement data. It can then be resumed later, with the filter initialized to the state it was in when the restart record was created during the previous run.

This capability allows for seamless continuation of the filter processing, building upon the progress made in prior runs. The JWST's ODTK filter has undergone continuous refinement over more than 2 years, incorporating a series of individual runs. For each run, a restart record is generated, capturing the filter's state at that specific point in time. During subsequent operational runs, the filter retains crucial information such as covariance data and estimated values for parameters like state vectors and SRP coefficient from the previous run. This information serves as a starting point for further refinement and optimization in subsequent runs.

To obtain a definitive solution, the FDF utilizes a 14-day data arc, which includes a 7-day overlapping period from the previous run. The data arc is processed using the EKF techniques. The EKF uses the linearized model of the nonlinear system, utilizing the partial derivatives of the nonlinear state equations and measurement equations. These partial derivatives are computed for each state estimate. However, computing these derivatives, along with the Kalman gain matrix, for each estimate can be computationally intensive. To mitigate computational complexity, the measurements within the OD arc are down sampled to one point per 60 seconds.

The ODTK filter operates forward-in-time, producing a discontinuous definitive ephemeris that spans the 14-day period. As the filter progresses through the fit span, each filtered estimate at a given point incorporates information from all previous measurements. However, no future measurements are considered during the filtering process. Once the filter execution is completed, the fixed-interval smoother is employed to refine the estimation backward in time, covering the entire OD span. The smoother maps information related to later measurements to earlier points in time, effectively propagating the effects of future measurements to earlier epochs. This backward smoothing process results in a cohesive and smooth ephemeris over the entire OD span.

E. *Orbit Predictions and Challenges*

The prediction of the JWST trajectory is accomplished using the dedicated Flight Dynamics Ground System (FDGS) software, which has been specifically developed for the JWST mission. The FDGS receives the estimated parameters from the ODTK filter solution as inputs. These parameters serve as the basis for executing maneuver planning (MP) and generating trajectory predictions. The aforementioned orientation constraints pose challenges for precise modeling of SRP and MP for the JWST. If the spacecraft's orientation is not considered, accurate SRP modeling and maneuver planning become more difficult and unrealistic. Detailed information on these challenges is provided in later sections.

F. *Results and Accuracy Assessment*

In this section, we present the OD results utilized by the FDF for quality assurance. Fig.4 showcases the normalized range and TCP residuals obtained from a sample 14-day data arc. These residuals have been normalized by the white noise, assigned independently for each DSN station. Vertical lines within the figure highlight Momentum Unload (MU) maneuvers that occurred within the OD arc. These events are essential considerations when analyzing the residuals.

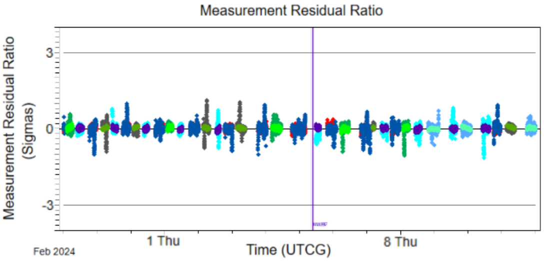

Fig. 4. *Range and total count phase (TCP) normalized residuals. The vertical line represents a pair of momentum dump maneuvers.*

Fig.4 exemplifies the typical behavior of JWST OD residuals. In most cases, the residuals fall within a range of ±3 sigma, indicating that they are close to the level of measurement white noise. This suggests that the residuals align well with the expected noise characteristics, providing an initial assessment of the OD's quality and the efficiency of the filter. Furthermore, the performance of the filter is evaluated by analyzing the time history of estimated parameters, filter covariance, and the consistency between the filter and smoother outputs.

Fig.5 depicts the time history of the estimated SRP coefficient. The filter provides estimates at each step of the integration process. The figure demonstrates the typical behavior of the estimated SRP coefficient value. By utilizing a high-fidelity attitude model, the estimation of the SRP coefficient remains stable and consistent across different solutions. This indicates that the filter can provide reliable and consistent estimates of the SRP coefficient throughout the integration process.

The larger covariance observed at the beginning of the filter run suggests that the estimation of the SRP coefficient is not initially constrained. However, as the filter progresses and incorporates more measurements in the analysis, the SRP coefficient quickly settles down to its final value. This behavior highlights the robustness of the filter tuning process, as it successfully achieves convergence and stability in estimating the SRP coefficient.

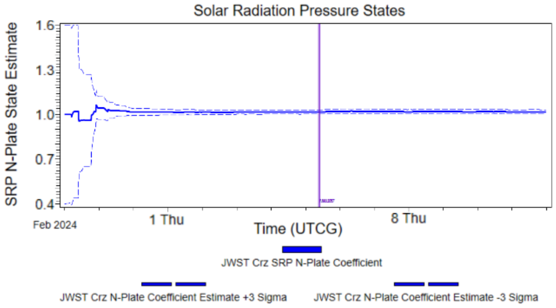

Fig. 5. *Time history of estimated solar radiation pressure coefficient.*

The FDF employs McReynold's filter-smoother consistency test as an additional criterion to assess the quality of the OD. This test evaluates the consistency between the estimated positions and velocities derived from the filter and smoother outputs.

The test calculates a unitless metric at each overlapping point between the filter and smoother, which represents the ratio of the difference in state estimates (positions and velocities) between the filter and smoother to the difference in their formal covariances. Consistency between the filter and smoother is generally considered acceptable when this metric stays within ±3 over the fit interval. This consistency test serves as a powerful diagnostic tool for optimizing the force model used in the OD process. It helps identify discrepancies and refine the force model parameters to improve the overall accuracy of the estimation.

Fig.6 and Fig.7 display the results of the position and velocity consistency test for the fitted span of the OD. These figures demonstrate that the estimates from both the filter and smoother remain highly consistent throughout, with the metric staying within acceptable bounds. However, there may be brief periods of inconsistency, primarily during maneuver activities, which is expected.

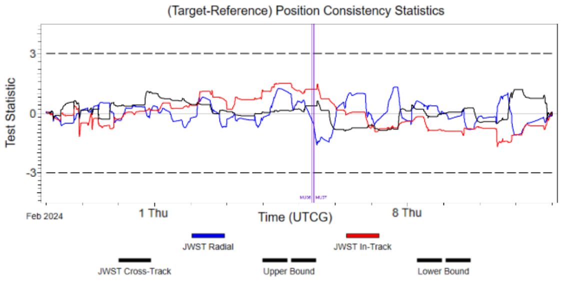

Fig. 6. *The position filter-smother consistency test for the fitted span.*

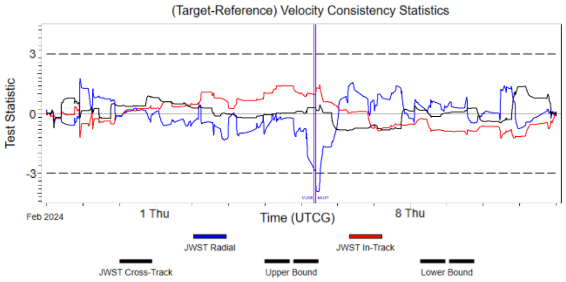

Fig. 7. *The velocity filter-smother consistency test for the fitted span.*

III. MANEUVER PLANNING

The JWST conducts regular SK maneuvers for orbit maintenance. These maneuvers are necessary due to the inherent instability of the L2 libration point. Planning a maneuver requires applying a set of targeting constraints to a definitive OD state to ascertain the delta-v needed to balance the orbit. Once the maneuver magnitude and direction are determined, the finite burn duration and spacecraft attitude are calculated based on the latest Attitude Control System (ACS) telemetry.

Planned finite maneuvers are modeled in short-term trajectory predictions, and long-term trajectory predictions also model a series of impulsive balancing maneuvers. These balancing maneuvers are targeted to occur twice per orbit to simulate the overall effect of SKs for multi-year predictions.

A. Targeting Parameters

The maneuver planning sequence is initialized by propagating a recent OD state vector to the planned burn epoch. Short-term attitude states are modeled using the latest attitude plan during pre-maneuver propagation, and the maneuver attitude is determined by optimizing the Secondary Combustion Augmented Thrusters (SCAT) thrust direction for the given orbital position [3]. To maintain anti-sunward SK maneuvers, the definitive SRP coefficient derived from ODTK is applied to the SPN attitude mode during post-maneuver propagation.

Typical SK cycles for JWST are 6 weeks in length, and the predicted attitude plan data is only available 7-10 days out. As a result, early-cycle maneuver plans require several weeks of pre-maneuver trajectory propagation without the benefit of finalized attitude predicts. To improve trajectory prediction accuracy and maneuver planning consistency, the SRP coefficient applied to SPN pre-maneuver propagation is biased down by approximately 6%. The Sun neutral attitude mode entails the largest attainable SRP cross-section, so trajectory predictions generated using the definitive SRP coefficient will overpredict the cumulative SRP perturbation.

B. Neutral SRP Calibration

To improve trajectory prediction accuracy while utilizing the Sun-pointing neutral attitude mode, the applied SRP coefficient is scaled down from the definitive value to produce a mean-SRP model. Calibration of the neutral SRP coefficient is achieved by performing iterative SPN propagation tests to determine the value which minimizes the prediction error versus the definitive trajectory.

Fig.7 shows common SPN-prediction versus definitive trajectory comparison results for a variety of SRP coefficients. For the span of attitude and trajectory sampled, the largest prediction error is achieved when the definitive SRP coefficient is used (~1.02), while the minimum prediction error is achieved with an applied SRP coefficient between 0.94 and 0.95.

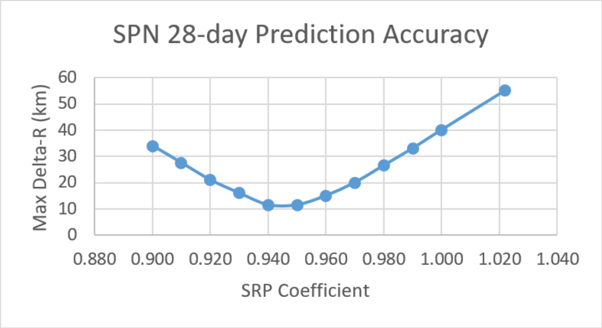

Fig. 7. *Applied SRP coefficient vs orbit prediction error*

The optimal neutral SRP coefficient for a given analysis span will directly correlate with the average sun pitch angle of the spacecraft over that span. This is because the spacecraft's instantaneous SRP cross-sectional area is maximized when the sun pitch is roughly -7° and minimized at -53°. To account for attitude trending, neutral SRP calibration results from a variety of attitude and orbit samplings are aggregated to produce the final coefficient to be used for maneuver targeting and trajectory prediction.

C. Maneuver Performance Evaluation

The FDF utilizes two methods for maneuver performance evaluation: Delta-V Along Line of Sight (DVALOS) and OD calibration. The former is a semi-empirical method which involves observing the Doppler shift in the TCP residuals between the pre- and post-maneuver orbit to measure the line-of-sight component of the delta-V. ACS telemetry is then used to compute the vertex angle between the line-of-sight vector and the thrust vector. The latter method requires using definitive post-maneuver OD state data to iteratively solve for the achieved maneuver magnitude and direction. Both methods offer an assessment of the achieved delta-V which is independent of the results obtained via telemetry reconstruction. The calibrated thrust scale factor for a given maneuver is determined by computing the ratio of the observed delta-V to the reconstructed delta-V.

Achieving an accurate OD solution following a completed SK is paramount for maneuver performance evaluation and subsequent SK planning. Maintaining a confident, realistic SRP coefficient estimate through the timespan of an executed SK is critical, as an over-estimated SRP coefficient will yield an under-estimated thrust calibration factor, and vice versa.

IV. CONCLUSION

The NASA Goddard Space Flight Center's FDF support for JWST on-orbit operations, and the experiences and data accumulated have presented several novel challenges for libration orbit navigation. The results of FDF analysis efforts have been used to implement improvements to orbit prediction accuracy and maneuver efficiency which have the potential to prolong the lifespan of JWST to continue to conduct ground-breaking infrared astronomy for decades to come.

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