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THE IMPACT OF IMPULSIVE VS. FINITE MANEUVER MODELING ON LAUNCH TRANSFER TRAJECTORIES FOR THE ROMAN SPACE TELESCOPE

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The Nancy Grace Roman Space Telescope (RST) is a flagship astrophysics observatory developed by the NASA Goddard Space Flight Center for launch in the mid-2020's. The nominal mission orbit for RST is a Sun-Earth L2 quasi-halo orbit subject to stringent geometric and dynamical constraints necessary for achieving mission science objectives. After award of the launch vehicle contract to SpaceX, comparing the launch solutions produced by the RST Flight Dynamics team and the SpaceX team revealed that despite targeting the same interface states, modeling the second-stage insertion burn with an impulsive delta-V vs. a higher fidelity finite burn model can result in substantial differences in achieved libration point orbit properties. In this paper, these differences are explored and leveraged to update the models and targeting strategies used by the RST Flight Dynamics tools. These updates allow the mission to achieve more flight-like ascent and insertion dynamics for the libration point transfer, as well as reveal interesting relationships between the dynamics of impulsive models and finite burn models for libration point transfer trajectories in general.

INTRODUCTION

NASA Goddard Space Flight Center is developing the Nancy Grace Roman Space Telescope (RST), a flagship infrared space observatory planned for launch in the mid-2020s. The observatory seeks to answer pioneering questions identified by the United States National Research Council Decadal Survey[1] in infrared astrophysics, dark energy, and the search for exoplanets. RST will launch to a quasi-periodic halo orbit at the dark-side co-linear Sun-Earth Lagrange point (L2) to take advantage of the well-known thermal and radiative stability of this environment for deep-space observations and communications.

The RST launch contract was awarded to SpaceX in July 2022, kicking off work to prepare for the beginning of the iterative design cycle of launch target deliveries between SpaceX, the Launch Services Program (LSP) at Kennedy Space Center, and the RST Flight Dynamics team. The first iteration of this cycle began in June 2023 with the delivery of a set of launch targets spanning approximately a year from the RST Flight Dynamics team to LSP and SpaceX. A few months later, new versions of the targets were returned to the Flight Dynamics team for analysis.

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An overview of the components of a typical transfer and mission orbit for RST is shown in Figure 1. Instantaneous daily launch targets are obtained by targeting an agreed upon interface point after Second-Engine-Start-2 (SES-2), referred to as the Transfer Insertion Point (TIP). The original targets from RST Flight Dynamics are crafted such that if the C3 energy of the transfer at the TIP state is obtained perfectly, no Mid-Course-Correction (MCC) maneuver is necessary to adjust the transfer, and very little libration orbit insertion (LOI) delta-V is necessary to insert into the final mission orbit upon arrival at L2. When analyzing the returned solutions from SpaceX, it was observed that although the energy of the target TIP states obtained by SpaceX was nearly perfect for achieving the desired orbits, well within the bounds described by the contract, the resulting geometry of the transfer was different enough to still require an MCC maneuver to obtain the original desired mission orbit at L2.

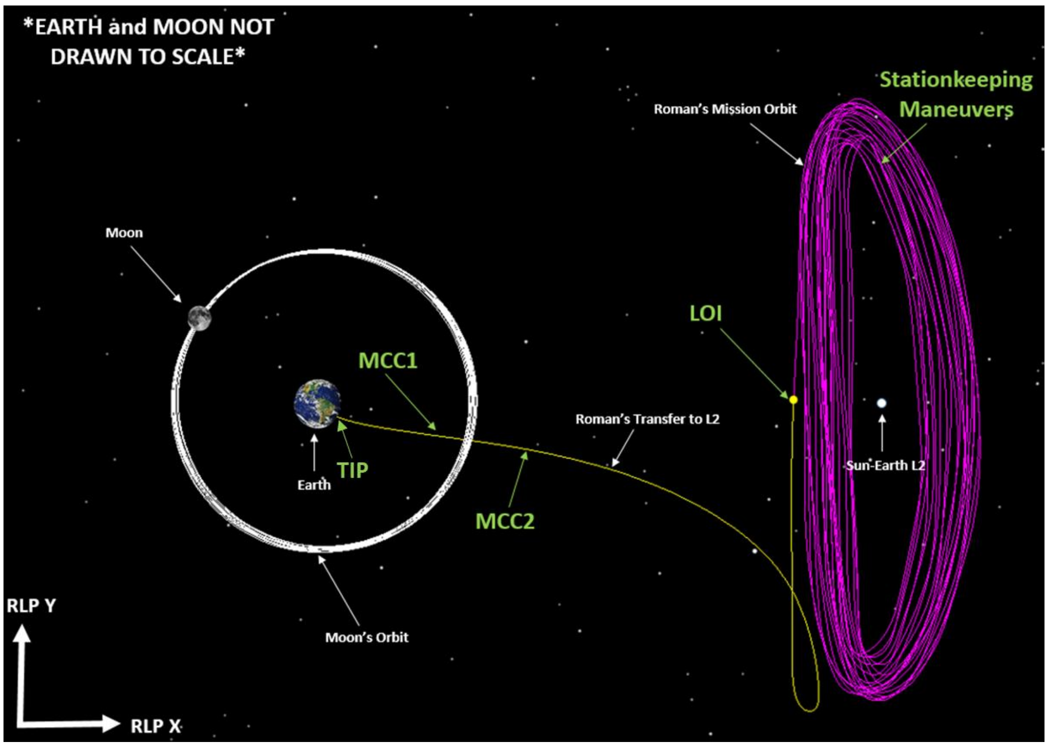

Figure 1: Rotating libration point frame overview of transit from LEO parking orbit to a Sun-Earth L2 quasi-halo orbit. TIP = transfer to insertion point; MCC = mid-course correction; LOI = libration orbit insertion

It was postulated that these differences must be a result of the flow down of inherent dynamical differences in achieving the TIP state. Due to the need to obtain and analyze candidate mission orbits far in advance of the launch vehicle contract being awarded, details of the ascent vehicle properties could not be accurately modeled or assumed. Therefore, the RST Flight Dynamics team has up to this point modeled the early portion of flight between the LEO parking orbit and TIP using a simple impulsive model for the second-stage burn. Conversely, the LSP/SpaceX tools use a realistic finite-burn model for first-stage ascent and the second-stage transfer burn that more closely matches the performance that will actually be seen in-flight.

It is important to understand and determine how to account for the impact of these modeling differences prior to the next iteration of the design cycle. Doing so will produce targets from both RST Flight Dynamics LSP/SpaceX that result in mission orbits that meet requirements and can be achieved cheaply and easily. Therefore, this paper will explore the impacts of modeling the launch to a Sun-Earth L2 orbit with a realistic finite burn vs. an impulsive delta-V when targeting the same interface state.

We will explore specifically how small differences in LEO orbital elements have a downflow impact on the resulting target RLP states, and how these differences appear to be inherently influenced by the dynamical modeling differences. We will discuss which variables appear to dominate the relationships, and how these observations can be leveraged to better control the ability to achieve target states using a finite burn model. Finally, a non-linear optimization strategy for re-targeting the original states with a finite burn model will be presented.

BACKGROUND

The series of events involved in defining a launch target are shown in Figure 2. A Falcon-Heavy first-stage ascent will place RST into a low Earth orbit (LEO) parking orbit for a brief coast phase, after which the vehicle will execute a large second-stage burn (SES-2) to put the payload on a course to L2. Determining this maneuver in the form of a ΔV from the launch vehicle such that a desirable mission orbit is obtained is the ultimate goal and outcome of the RST Flight Dynamics mission design process.

For the purpose of interfacing with LSP and SpaceX, the RST Flight Dynamics team uses a constant Earth Fixed Second-Engine-Cut-Off-1 (SECO1) state for defining the parking orbit, regardless of launch date. The exact time at which the SECO1 state occurs for each launch day is a free variable for design, as well as the length of the coast time between SECO1 and SES-2. These variables essentially defined the true anomaly and right ascension of the ascending node for the outbound trajectory.

The SES-2 burn is defined as the maneuver that transfers the spacecraft from the parking orbit to the LOI interface point in the vicinity of L2. For design purposes, the SES-2 burn is assumed to occur strictly in the velocity direction of the vehicle (in practice, approximately a degree off-velocity may be allowed but this is assumed negligible here). The SES-2 burn results in a Transfer to Insertion Point (TIP) state, defined to be 10 minutes after SECO-2. The TIP state is then the primary target state information that is passed back to the Launch Services Program (LSP) and ultimately SpaceX for launch design and analysis.

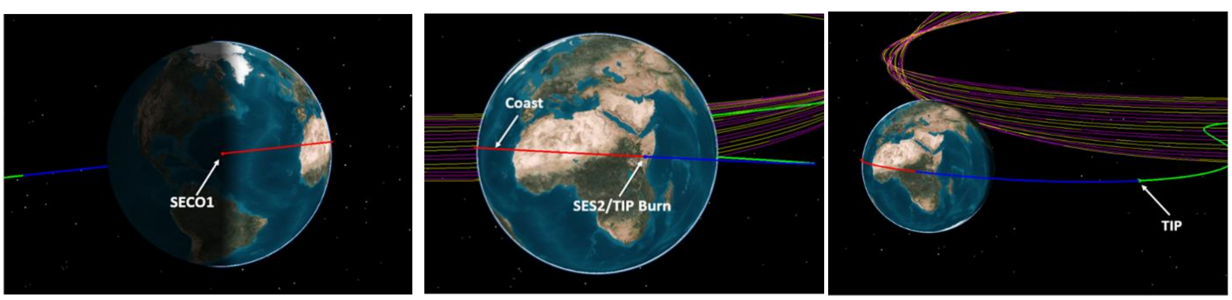

Figure 2: Depiction of key events during the initial transfer sequence

Placing RST in an orbit around L2 is sufficient for meeting many of the mission science goals and objectives. The specific design strategy for RST however is unique for Libration Point Orbit (LPO) design because the requirement that most constrains the design is a desire to be able to downlink a large amount of science data to the Earth for every day of the mission orbit, in particular through the White Sands Ground Station. This highly constraints the geometry of the mission orbit: due to the massive data volume expected from the survey campaigns (expected to be at least 1.3TB of data a day), the observatory must be in view of the appropriate ground stations for a sufficient amount of time every day of a nominal five year mission.

Given the seasonal tilt of the Earth coupled with the latitude of White Sands and resulting field of view, this requirement restricts RST to particularly small amplitude halo orbits, compared to past missions like the James Webb Space Telescope. Additionally, the seasonal tilt of the Earth's axis makes certain families and sizes of quasi-halo orbit manifolds more or less available when launching from the Earth. As explored in a previous paper, this is a complicated intersection of requirements to meet and physics to balance for every day of the year.[2] To break down the problem, the process for obtaining launch solutions is performed on a monthly basis due to strong driving seasonal relationships.[2] Feasible transfer solutions that result in quasi-halo orbits of appropriate size for the particular month are selected as initial guesses that are representative of the types of feasible answers for each season.

A series of GMAT scripts then solve for a constrained launch solution for each day in the month that results in the cheapest possible orbit (in terms of LOI delta-V) that meets all requirements. The variables available for manipulation are the specific SECO-1 epoch within the launch date, and the RA at which the LV burn occurs. These variables, shown in Figure 3, directly influence the size and shape of the resulting quasi-halo orbit as well as the maneuver cost to insert into the desired orbit.

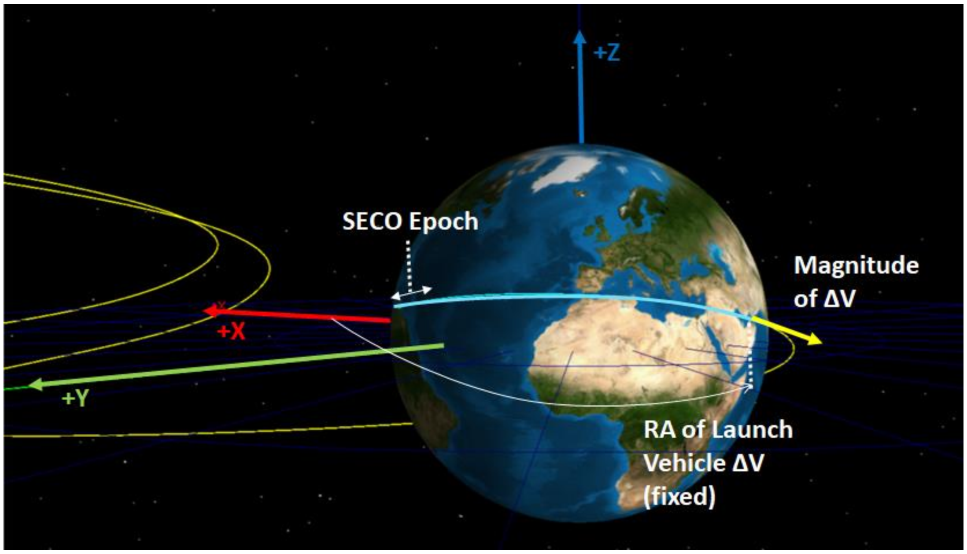

Figure 3: Launch-side variables which directly influence orbit size and LOI delta-V

Due to this direct relationship, a non-linear optimization problem can be constructed to target mission orbits that meet constraints. This process has been previously described in depth, and was used to obtain the original launch solutions for delivery to SpaceX using the impulsive delta-V model for the SES-2 burn.[2] The process has since been refined to use improved models and account for the observations that will be described in this paper. The development of the optimization process based on analysis of solutions will be described, as well as the implementation and results of the optimizer.

REFERENCES

[1]Blandford, R.D., Haynes, M. P., Huchra, J. P., Rieke, M. J. "New Worlds, New Horizons in Astronomy and Astrophysics." *National Research Council, The National Academies Press*. (2010).

[2]Schlenker, L., Farres, A., Webster, C., Donaldson, J., & Pritchett, R. E. "A Unique Approach to Achieving Size-Constrained Quasi-Halo Orbits for the Roman Space Telescope." *2020 AAS/AIAA Astrodynamics Specialist Conference*. 2020.