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The Space Weather Follow On – Lagrange 1 Mission

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Abstract

The Space Weather Follow On – Lagrange 1 (SWFO-L1) Observatory will be situated in a Sun-Earth L1 Lissajous orbit with the goal of providing continuous measurements of the space environment and observations of the Sun's outer atmosphere, and contributing to accurate forecasts of space weather disturbances. Unique to the SWFO-L1 mission are challenges of a rideshare launch, immoderate momentum management delta-V residuals, and spacecraft maneuver design considerations, resulting in specialized operational approach, management, and support.

INTRODUCTION

The Space Weather Follow On - Lagrange 1 (SWFO-L1) Observatory will be positioned into a Sun-Earth L1 Lissajous orbit with the goal of providing continuous measurements of the space environment and observations of the Sun's outer atmosphere, and contributing to accurate forecasts of space weather disturbances. "Space Weather" refers to those conditions in Earth's space environment that may be damaging to human health or to technological systems deployed in space or on the ground.

The National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite and Data Information Service (NESDIS) has established the Office of Space Weather Observations (SWO), a parent program to the SWFO-L1 Observatory Mission, with acquisition and implementation assistance from the National Aeronautics and Space Administration (NASA) [1]. The SWFO Program's main goal is to provide critical data to the National Weather Service's (NWS) Space Weather Prediction Center (SWPC). The Program and related NOAA activities are aligned with the National Space Weather Strategy and Action Plan (2019). SWFO-L1 Flight Project is managed by NASA/GSFC and consists of a spacecraft and instruments integrated into the SWFO-L1 Observatory, associated ground support and simulation equipment, launch services interfaces on the Interstellar Mapping and Acceleration Probe (IMAP) Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA), and Flight Dynamics support.

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In a 2019 agreement between the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), SWFO-L1 was formulated as a Class C, ESPA-class rideshare mission.[2] While in formulation, a Level 1 requirement was established for a 5-year mission lifetime. Though generally NASA Class C missions have lifetime requirements of 2-3 years, actual on orbit mission lifetimes for Class C missions have been considerably longer. In fact, a recent study shows that for missions with a 5-year design life, there is little differentiation in actual in-space lifetime between Class A and Class C missions [2]. Applying the standard Goddard Space Flight Center (GSFC) Class C engineering and design practices to SWFO-L1 is an acceptable approach in meeting SWFO-L1 mission life requirements within the specified mission risk classification. The SWFO-L1 Observatory will establish observational continuity of real-time solar imagery and solar-wind measurements while, ultimately, replacing two legacy operational missions; the SOlar and Heliospheric Observatory (SOHO), a joint NASA and European Space Agency (ESA) mission carrying the Large Angle and Spectrometric Coronagraph (LASCO) telescope; and NOAA's Deep Space Climate Observatory (DSCOVR) mission. The instrument compliment onboard SWFO-L1 include the Compact Coronagraph-2 (CCOR-2) – Naval Research Laboratory (NRL), the Solar Wind Plasma Sensor (SWiPS) – Southwest Research Institute (SwRI), San Antonio, TX, the Magnetometer (MAG) – SwRI/University of New Hampshire (UNH), and the Supra Thermal Ion Sensor (STIS) – University of California, Berkeley (UCB).

The Goddard Navigation and Mission Design branch, code 595, provides for pre-launch analysis support, ground system development and testing, and operational support via Goddard's Flight Dynamics Facility (FDF). This support spans launch and early orbit, transfer trajectory, orbit insertion, and initial stationkeeping until handover to the SWO NOAA Satellite Operations Facility (NSOF) who performs routine navigation and maneuver support. The FDF provides backup services as required.

Space Weather Follow On – L1 Observatory

The SWFO-L1 Observatory is a Sun-pointed, 3-axis stabilized satellite stationed in a Lissajous orbit around the Sun-Earth L1 point. SWFO-L1 is planned to launch as a rideshare with NASA's Interstellar Mapping and Acceleration Probe (IMAP) in 2025. SWFO-L1's size and configuration are compatible with the Secondary Payload Adapter (ESPA) Grande, which is used on the Air Force's Evolved Expendable Launch Vehicle (EELV). A 4-meter ring procured by NASA for the IMAP mission will be provided for integration. The three-axis-stabilized spacecraft accommodates a CCOR-2 instrument and three other instruments for in-situ solar wind measurements at L1.

SWFO-L1 will separate from the IMAP launch vehicle and maneuver independently to an L1 orbit. IMAP has selected a SpaceX Falcon-9 as the launch vehicle. Repeatability is a consideration for the design of the SWFO-L1 to facilitate future follow-on missions to be accommodated on rideshare or independent launch opportunities. A simplified 3D model of the SWFO-L1 spacecraft design is illustrated in the Figure 1. The spacecraft is shown facing towards Sun. The solar arrays, instrumentation, magnetometer boom are pointing to the right and the communications antenna (pointing towards Earth, which is down and to the left). The boom houses the magnetometer.

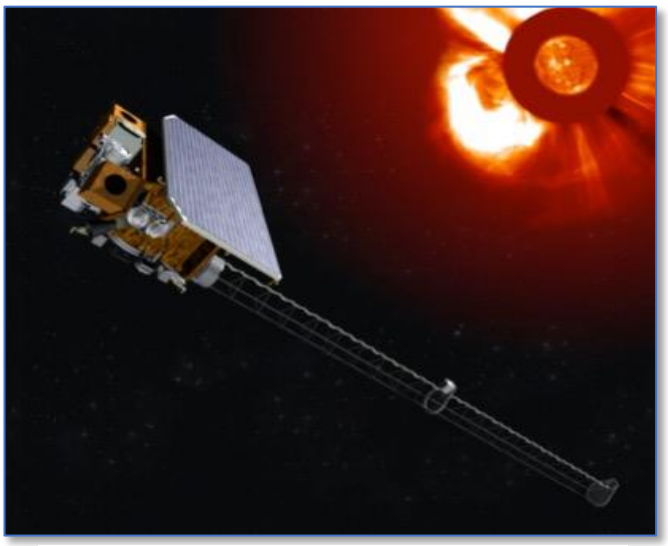


Figure 1. Space Weather Follow On-L1 (SWFO-L1) Spacecraft

SWFO-L1 Propulsion System Design

Influencing several challenges is the SWFO-L1 propulsion system design, a simple monopropellant propulsion system that has heritage from many other British Aerospace (BAE, formally Ball Aerospace) missions. [3] The uniqueness for SWFO-L1 as shown in Figure 2 is that there are a total of four thrusters, each canted by ~ 10 deg with respect to the spacecraft primary center line, the X axis. These 5N thrusters along with a single fuel tank provides the propellant for both translational and momentum management control during the entire mission duration. The propulsion system contains one diaphragm tank with hydrazine (N_2H_4) propellant and gaseous nitrogen (GN_2) pressurant. The system is operated in blowdown mode for the life of the mission. The total initial thrust using the four thrusters at beginning of life is ~ 18.35 N and will drop to 5.87 N at the minimum pressure level. The amount of fuel used for the insertion maneuver takes approximately half of the 72 kg of fuel loaded at the time of launch.

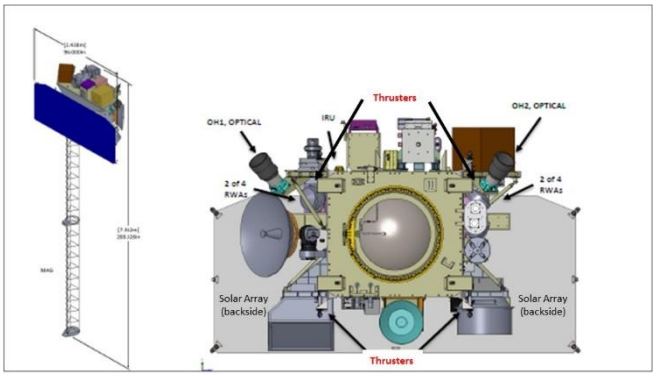


Figure 2 SWFO-L1 Bus and Propulsion Layout

Because of the four thruster configuration, each thruster is fired at a specific duration during translational maneuvers to maintain the required attitude pointing. As the pressure drops, onboard tables that control the off-to-control thruster durations are updated. These ratios are uploaded to the spacecraft via a table load prior to each of the maneuvers as these ratios are dependent upon the current tank pressure. A table of the off-to-control table load is shown in Table 1. The duty cycles are listed as thruster 1 through 4 from left to right in the table. Note that the selection of which duty cycle table to upload is determined by choosing the pressure in the table that is closest to the estimated tank pressure at the middle of the maneuver, e.g., if a maneuver pressure decreases from 340 to 320 psi, the mid-point pressure would be ~330 psi, so a pressure of 325 psi in the table is selected and table V4 would be uploaded.

Table 1. Table of pressure vs thruster duty cycles

Pressure	Table Version	Duty Cycle
385	v1	[0.70606, 0.70087, 0.99264, 1.0]
360	v2	[0.70755, 0.70237, 0.99267, 1.0]
350	v3	[0.70798, 0.70281, 0.99267, 1.0]
325	v4	[0.70917, 0.70401, 0.99270, 1.0]
300	v5	[0.71056, 0.70542, 0.99272, 1.0]
275	v6	[0.71220, 0.70707, 0.99274, 1.0]
250	v7	[0.71417, 0.70907, 0.99278, 1.0]
225	v8	[0.71659, 0.71152, 0.99282, 1.0]
200	v9	[0.71962, 0.71458, 0.99287, 1.0]
175	v10	[0.72353, 0.71854, 0.99293, 1.0]
150	v11	[0.72878, 0.72385, 0.99302, 1.0]
125	v12	[0.73618, 0.73134, 0.99314, 1.0]
100	v13	[0.74740, 0.74269, 0.99333, 1.0]

The impact of this propulsion system design, especially the limit of only four thrusters, means that for each maneuver, the spacecraft will need to slew to the appropriate maneuver attitude to place the thruster action vector aligned with the Delta-V (DV) vector. A set of maneuver quaternions in a J2000 frame is delivered as part of the maneuver planning products for every maneuver type, e.g. Midcourse Correction (MCC), Trajectory Correction Maneuver (TCM), Lissajous Orbit Insertion (LOI) and Stationkeeping (SK).

There are no constraints or limits on the overall pointing of the spacecraft other than a desire that restricts of field of view of one instrument to not dwell in the direction of the sun. This angle is checked as each maneuver is planned.

MISSION SUPPORT CHALLENGES

There are several noteworthy challenges in support of the SWFO-L1 mission that can impact operations, Lissajous orbit selection and insertion, and the DV and fuel budget. These include; weekly momentum management operations (momentum unloads (MUs)) which may result in residual DVs of 5.77 cm/s in the sunward direction and potential MUs occurring prior to and after each maneuver; the effect of the launch vehicle rideshare on mission design and the Lissajous orbit size and orientation requirements to maintain minimum and maximum Sun-Earth-Spacecraft angles; the design of the Lissajous Orbit Insertion (LOI) maneuver based on spacecraft design constraints and system dynamics; and meeting quantity and quality of tracking data measurements required for orbit determination using a newly developed SWFO-L1 Antenna Network (SAN). The effects of these challenges and how they are accommodated by operations or by trajectory design are described in this paper.

Lissajous Orbit Requirements

The Observatory will host a number of space weather monitoring instruments; the Compact Coronagraph (CCOR)-2 telescope, the Solar Wind Instrument Suite (SWIS), an instrument suite similar to DSCOVR's PlasMag suite with an additional ion flux sensor. SWIS consists of three solar wind instruments: the Solar Wind Plasma Sensor (SWiPS), the Magnetometer (MAG), and the SupraThermal Ion Sensor (STIS). The High Gain Antenna (HGA) located on the Earth facing side of the spacecraft has a limit of 20 degree angle of rotation. To meet the orbit geometry requirements for the instruments and high gain antenna, the Lissajous orbit must meet minimum and maximum Sun-Earth-Vehicle (SEV) angle constraints. Figure 3 shows the planned Lissajous orbit as viewed from the Earth looking towards the sun and appears to evolve clockwise. Figure 4 shows the classic Sun-Earth rotating frame view of the transfer and libration orbit from above and within the ecliptic plane. The SWFO-L1 Class-I Lissajous orbit is required to remain within a SEV angle of 4 x 13 deg as measured from the Earth center wrt the Earth-Sun line. The maximum transfer SEV is less than 32 deg. The Class-I Lissajous orbit appears to evolve clockwise about SEL1 as viewed from Earth. The SEV angle constraints result in the amplitude in the Solar Rotating Frame coordinates of ~ 300,000 km in the X-Y plane and ~ 215,000 km in the X-Z plane. These amplitudes are similar to those of the DSCOVR mission launched in 2015. The minimum angle is set to compensate for the minimal SEV angle that can result in a loss of tracking when the SEV angle is below ~3 deg. However, it was agreed to by the project that to minimize the LOI DV, the SEV angle is permitted to decrease to 2.5 deg. The duration below a nominal 4 deg during the LOI is ~

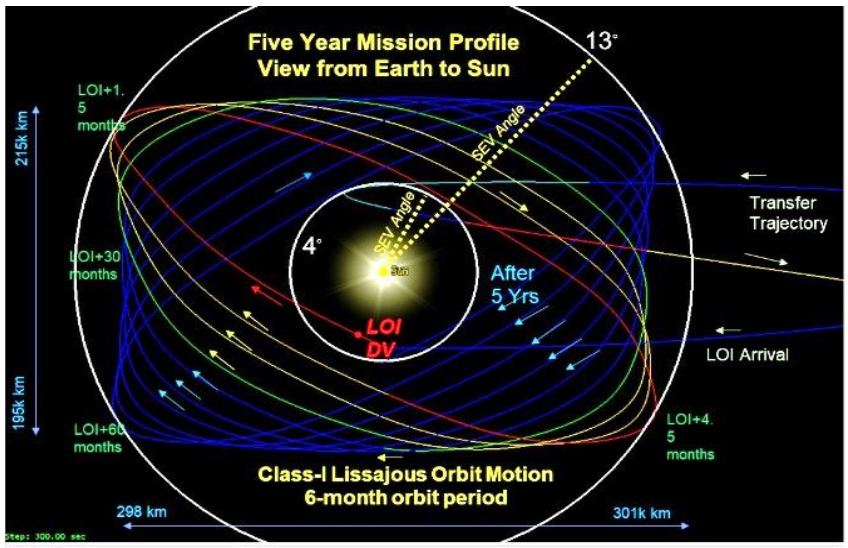


Figure 3. SWFO-L1 Lissajous Orbit as viewed from Earth in a Sun-Earth Rotating Frame

7 days. More information on this is provided in the section on Lissajous Orbit Insertion Considerations.

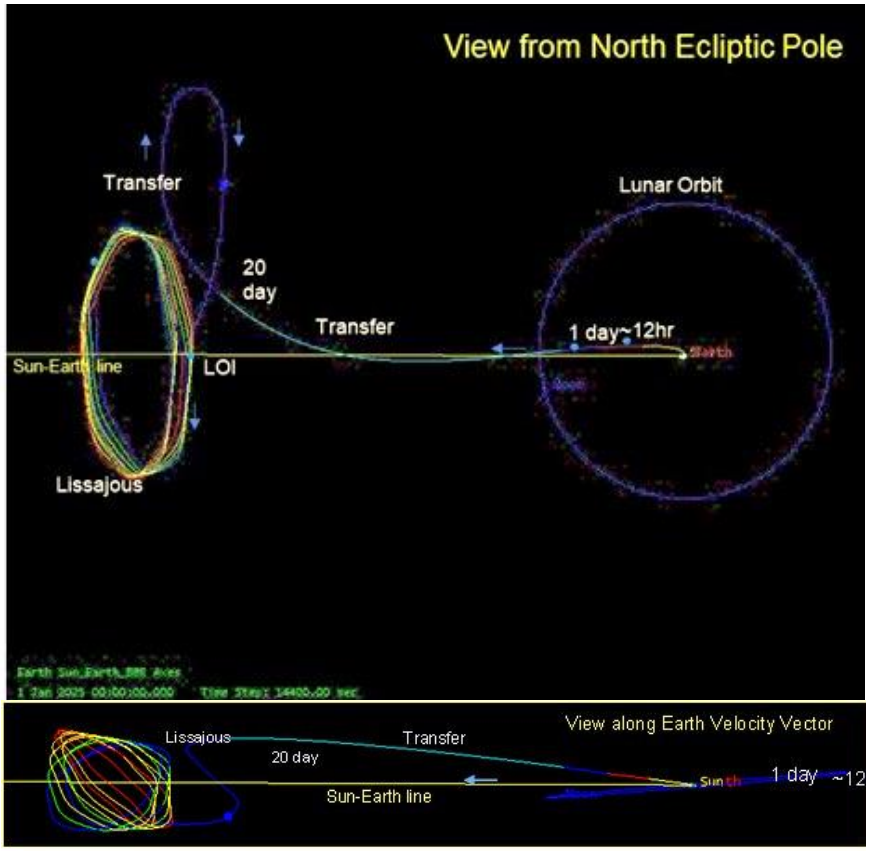


Figure 4. SWFO-L1 Lissajous Orbit and Transfer Trajectory as seen from North Ecliptic Pole (top) and within the Ecliptic Plane (bottom)

Rideshare with IMAP, Transfer Design and DV Budget

Because SWFO-L1 is a secondary rideshare spacecraft on the IMAP launch that uses a SpaceX Falcon-9 launch vehicle, the launch window and launch C3, and the selected IMAP Class-I Lissajous design drives the SWFO-L1 transfer design, correction maneuvers to target the SWFO-L1 LOI requirements, and the selection of the Lissajous orbit. Once deployed, SWFO-L1 is required to maneuver onto its own transfer trajectory to attain the Lissajous orbit insertion conditions chosen to minimize the Lissajous Orbit Insertion (LOI) DV and to achieve the opening Lissajous pattern shown above. As part of the Space-X Performance and Guidance Accuracy Analysis-2 (PGAA-2) delivery, a 6-DOF (Degree of Freedom) and 3-DOF states and 6x6 covariance defines performance and operations that are used to analyze the entire transfer and LOI. An example of the DV requirement for the mission is show in Table 2. The allocated DV budget is 303 m/s for a 5 year design with a 10 year goal, with approximately half of the DV required for LOI.

Due to the rideshare status and the need for SWFO-L1 to acquire its own transfer trajectory as soon as feasible, a Midcourse Correction (MCC) is required 24 hours after deployment. This maneuver will correct for launch vehicle performance and to also place SWFO-L1 on the proper transfer trajectory. An example

of two cases are presented in Figure 5 to illustrate the DV and tracking needs to support this critical maneuver, which if delayed or missed can result in a prohibited DV and an increase in the number of transfer maneuvers to attain the LOI location.

For the first case, a missed MCC1, a maneuver can be executed within a timespan less than six hours from the nominal MCC1 epoch so the orbit determination (OD) solution used for this maneuver plan will need to be valid for an additional six hours. Hourly MCC1 maneuver plans will be delivered (MCC1 at 25 hrs, MCC1 at 26 hrs, …, MCC1 at 30 hrs) in the event that an updated maneuver command can be uploaded within this timeframe. The MCC1 DV increases linearly near the nominal epoch. For the second case, a missed MCC1 that must be executed more than six hours after the nominal MCC1 epoch, the OD must be re-run to incorporate new tracking data and additional perturbations, and an updated maneuver plan will be re-delivered. The new OD solution will use all newly available tracking data and the maneuver plan will be re-generated for the next available maneuver epoch. In the case of a delayed MCC1, considerations are needed to deconflict the SWFO-L1 and IMAP tracking schedule. IMAP's first maneuver is set at approximately TIP+36hrs which requires continuous tracking pre and post-maneuver – as does SWFO-L1's MCC1. Figure 5 shows the DV increase for delayed MCC1 scenarios. A partial executed MCC1 can be assessed by updating MCC2 planned to occur at launch plus 20 days. Using the PGAA-2 and PGAA-3 (PGAA-3 to be delivered in early 2025), the entire transfer trajectory design along with determining the optional Lissajous insertion location will be replanned.

Table 2. Monte Carlo Delta-V Assessment

Maneuver	Results (P<99.7%) [m/s]	Allocation [m/s]
MCC1	27.8	< 30
MCC2	3.7	< 5
LOI	156.5	< 160
Transfer Total (Statistical sum-per-iteration)	185.4	< 195
Stationkeeping (0-5 year)	21.8	< 22.5
Rephase	58	< 62
Stationkeeping (5-10 year)	21.8	< 22.5
EOM	1.0	<= 1
Mission Total	288.0	303

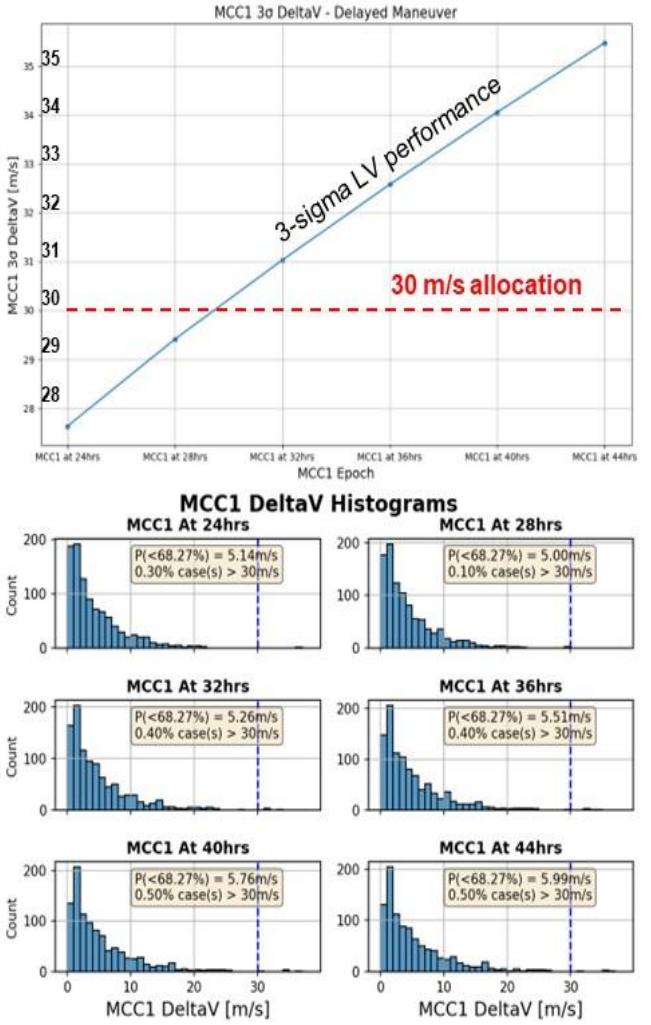


Figure 5. MCC1 Delta-V Increase and Histrograms

Momentum Management and Stationkeeping

The main torque on SWFO-L1 is due to the Solar Radiation Pressure (SRP) on the magnetometer boom which causes momentum to increase. The selection of the SWFO-L1 spacecraft reaction wheel size and placement requires a weekly momentum unload (MU) to reset the reaction wheels from the maximum positive wheel speed to the maximum negative wheel speed, crossing through zero. This unload

via thrusters results in a residual DV of 5.77 cm/s imparted into the sunward direction, within the Ecliptic plane. Due to the sensitivity of the Lissajous orbit, these perturbations have a larger impact on orbit stability. The magnitude of this weekly MU residual DV is approximately the size of an otherwise unperturbed orbit monthly routine stationkeeping (SK) maneuver, and thus will affect the magnitude of the monthly SWFO-L1 SK maneuver [4]. Once the operationally observed MU torques have been established, the magnitude or schedule of SK maneuvers will vary depending on the actual size of these MU residual DVs.

These weekly residual DVs are modeled in the nominal orbit integration and during the maneuver planning simulations to provide an accurate orbit design and predictions. With the weekly MUs perturbing the nominal Lissajous orbit, the monthly SK DV is approximately 35 cm/s, much larger than typically encountered for a Sun-Earth L1 mission. Each MU is currently scheduled to occur on a Monday with a stationkeeping maneuver on the fourth week recurring monthly. To accommodate this MU operation, analysis determined several options for placement of the SK maneuver. Originally a method was proposed that employed the residual MU DV magnitude pointed it in a direction that was dynamically more accommodating, e.g. the stable or unstable mode direction of a three-body dynamical system.[4] That meant that the MU could potentially be used as the SK maneuver at the same time as the MU. An investigation into this maneuver plan proved mathematically (dynamically) favorable, but alas, due to the need to slew SWFO-L1 using thrusters to achieve the proper attitude resulted in additional fuel being consumed. We also analyzed the use of an attitude that would minimize any orbit perturbation, but this also resulted in unwanted slews. With those options disqualified, it was determined to simply use a "stable mode" direction that would remove the added sunward MU perturbations, e.g. a SK DV in roughly the opposite direction of the MU residual DV, but dynamically situated. This design can also be optimized and leads to the ~ 35 m/s monthly SK maneuver magnitude. The benefit of this option was to permit a repeatable SK direction for all SK maneuvers over the life of the mission. A spacecraft operations procedure was developed and will be used onboard to slew SWFO-L1 153 deg about the spacecraft Y axis, which is nominally pointed towards the north ecliptic pole, to slew to the same attitude for each SK maneuver.

Figure 6 provides basic information on the planned SK direction and magnitude to accommodate the MU sunward residual DV direction. The right figure, in an L_1 centered rotating libration frame, shows the direction of the MU residual DVs and the SWFO-L1 designed SK maneuvers that use the Sun-Earth libration orbit dynamics to permit a SK direction that is constant with respect to the Sun-Earth line over the lifetime of the mission. This also indicates the direction of the Sun-Earth L1 centered dynamical stable and unstable mode directions. The left figure shows the varying SK DV magnitude over a year's simulation duration that incorporates the MU residual DVs during the integration. [4] The modeling of this analysis includes an Earth 8x8 potential, Sun and moon point mass, SRP, and other planetary 'third' bodies. The integrator is based on a Runge Kutta 8/9 that includes accelerations from maneuvers.

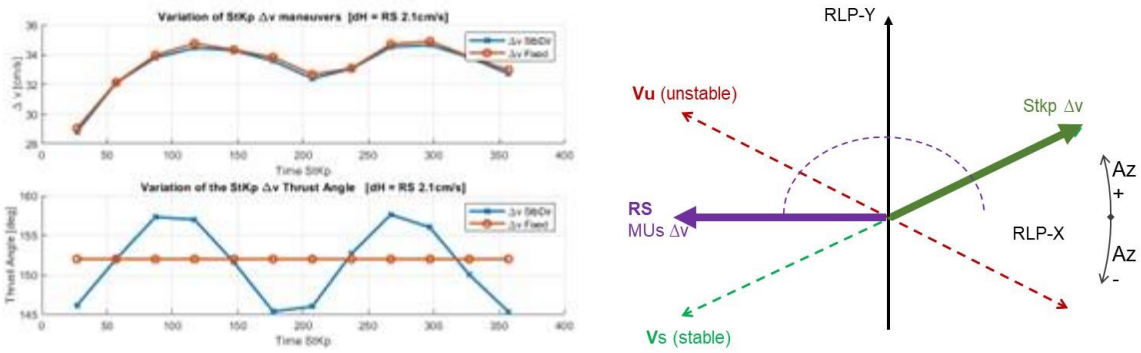


Figure 6. SWFO-L1 Stationkeeping DV and Geometry, Left Figure Showing Delta-Vs, Right Figure Showing DV, Stable and Unstable Directions in Rotating Frame

Stationkeeping maneuvers are planned at four week intervals to accommodate the perturbations due to the MU DV residuals and navigation uncertainties. As typical for any multi-body dynamical system, these maneuvers are set to correct for the drift off the planned nominal Lissajous orbit design which meets the orbit requirement stated above. To permit a stationkeeping maneuver procedure to execute, the total momentum must be less than 0.66 Nms. Thus momentum unloads occurs on a weekly, Monday cadence, with analysis indicating that on a Thursday, the momentum reaches the near zero tolerance to execute a stationkeeping maneuver. The stationkeeping analysis shows that there is a wide variation in execution times to meet the 0.66 Nms momentum level, and this span is on the order of +/- 4 hours of the originally planned SK epoch.

Lissajous Orbit Insertion Considerations

The general design of the Lissajous orbit insertion began similarly to many other SEL_1/L_1 missions, with a single maneuver planned to change the SEL_1 velocity to attain the Lissajous pattern at the appropriate location. A nominal single LOI design using the propulsion system and parameters stated above would require a 155 m/s maneuver performed over a 90 minute duration. The spacecraft design with respect to thermal and power constraints limits the duration of a single maneuver to less than 30 mins, and inclusive of the time for any slews to and from the maneuver attitude as well. For SWFO-L1, this required that the maneuver design limit any "large" maneuver to a maximum of 20 minutes, with a conservative 19 minutes maximum being used to permit a tolerance for unknowns. [6] Therefore, the 90-minute LOI is segmented into several smaller, 19 minute, maneuvers (current prelaunch plan), with a separation of three days to allow for an update to the orbit determination in order to plan the next set of maneuvers based on previous performance and to allow a MU to execute to ensure that the wheel speeds are near zero, +/- 0.66 Nms at the next LOI segment. For all maneuvers, the momentum must be managed to be within 0.66

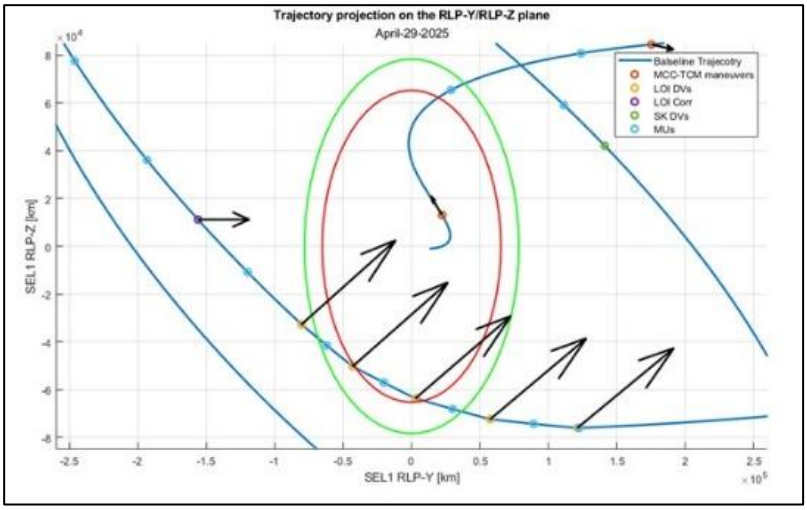


Figure 7. LOI Insertion Trajectory and Direction of LOI DVs in a SEL1 Rotating Frame Looking Towards the Sun

Nms. The MUs are planned to occur at the midpoint between LOI segments, thus the entire LOI sequence will take approximately 15 days to complete. Because of the change from a single impulsive maneuver to several finite maneuvers, the resultant trajectory will follow a more curved insertion orbit rather than a single velocity change as shown in Figure 7. The long sequence duration means that the SEV angle may violate the routine operational value of 4 deg, and may even reach 2.5 deg depending on the start date of the LOI sequence, the LOI segment performance, and the number of require segment as it crosses the Sun-Earth line. Figure 7 shows a representation of the location of the planned five segments for one of the analyzed cases using the PGAA-2 injection conditions. The arrows indicate the DV direction in the rotating X-Z plane.

LOI Segmentation and Momentum Management Requirements

With the understanding that the LOI maneuver must be segmented into several smaller maneuvers to accommodate the spacecraft thermal and power operational constraints, an LOI plan was constructed to permit an updated orbit determination solution to occur between each maneuver segment to allow for assessment of the previous maneuver segment and to update the plan for the remaining segments. This would permit the NASA-Flight Dynamics team to correct actively and continuously each of the LOI maneuvers to meet the orbit insertion parameters. With the need for an update to the orbit determination for maneuver planning, navigation analysis indicated that a three-day span of tracking data was optimal and required in order to update the state (position and velocity) to plan the next maneuver. This scenario of three-day tracking durations leads to a series of five (5) LOI maneuvers performed over a duration of 15 days, e.g. one maneuver every three days. This is the current LOI maneuver plan.

It is understood that momentum must be managed during the LOI sequence. The current scenario of an LOI segment every three days and the need to manage the momentum at a frequency of every 7 days (based on pre-launch estimates) led to the following LOI momentum management plan. To accommodate the need for the wheel speeds to be at or near zero with a tolerance of +/- 0.66 Nms at the time of each LOI maneuver and the need for minimal perturbation to aid the navigation process, a plan was constructed with MUs occurring every three days, centered between each maneuver segment. This LOI maneuver and momentum management plan schedule is show in figure 8 depicting the first three LOI maneuver segments with an approximation of the momentum increase and the location of the MUs.

A major issue facing the Goddard Flight Dynamics Operation support team in the support of LOI operations arise from the MUs during the LOI sequence. Due to the sensitive of the orbit determination Extended Kalman Filter (EKF) process during this high-dynamic time, the OD runs the risk of not converging, or exceeding allowable time to converge due this relatively large perturbation during the arc. The orbit determination accuracy runs the risk of exceeding 5 cm/s RSS accuracy velocity requirement needed for maneuver planning. The LOI reconstruction and calibration may be unable to assess prior LOI performance to assist in LOI maneuver planning.

Therefore, to accommodate the LOI maneuver planning and navigation, the MU sequence during the LOI is set to occur at a midpoint between LOI maneuver segments and to target a wheel speed that will meet the maneuver requirement of +/- 0.66 Nms at the time of the next LOI maneuver. As seen in figure 8, a MU is performed 1.5 days after a maneuver and will target the momentum at the next LOI segment.

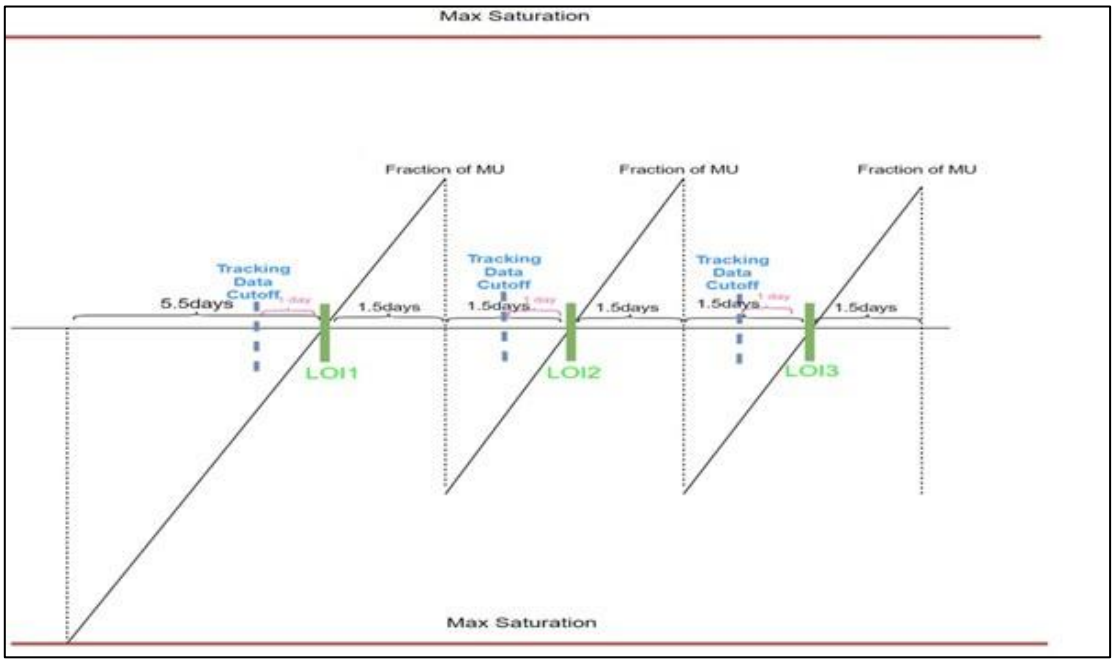


Figure 8. Proposed Momentum Unload Strategy during LOI Maneuvers

SWFO-L1 Antenna Network (SAN) and DSN support

The routine S-band Range and Doppler tracking measurements during the nominal mission in the Lissajous orbit are performed using a combination of the new SWFO-L1 Antenna Network (SAN) and the Deep Space Network (DSN). The DSN stations with antennae located in Madrid, Goldstone, and Canberra are planned per a typical DSN support coordination. The SAN antennae used for tracking, telemetry, and commanding proposes are located at the Wallops Command and Data Acquisition Station (WCDAS) site, with a Consolidated Backup at the West Virginia site (CBU). The MidCourse Corrections, and Lissajous Orbit Insertion, will be supported by increase DSN coverage and routine navigation support will be supported from both the WCDAS and DSN. The preferred tracking coverage during routine operations will consist of one hour passes each from WCDAS and Canberra, with additional coverage required for transfer and LOI maneuvers.

The challenge for SWFO-L1 comes from the use of DSN during launch and early operational (L&EO) support during the first week to support MCC1 and other critical spacecraft operations and checkouts, and from the use of the SAN WCDAS and the DSN Canberra stations during the later part of the transfer trajectory and during the nominal mission orbit. During L&EO, a full complement of DSN S-band compatible antennae will be used to support the initial orbit determination convergence to determine launch vehicle performance and to plan the MCC1 maneuver set for launch + 24 hours. Tracking is anticipated to begin approximately one hour after spacecraft deployment with several hours of tracking requested depending on visibility per the launch date. Figure 9 show the initial ground track of SWFO-L1 depending on launch date once the injection from the parking orbit is achieved.

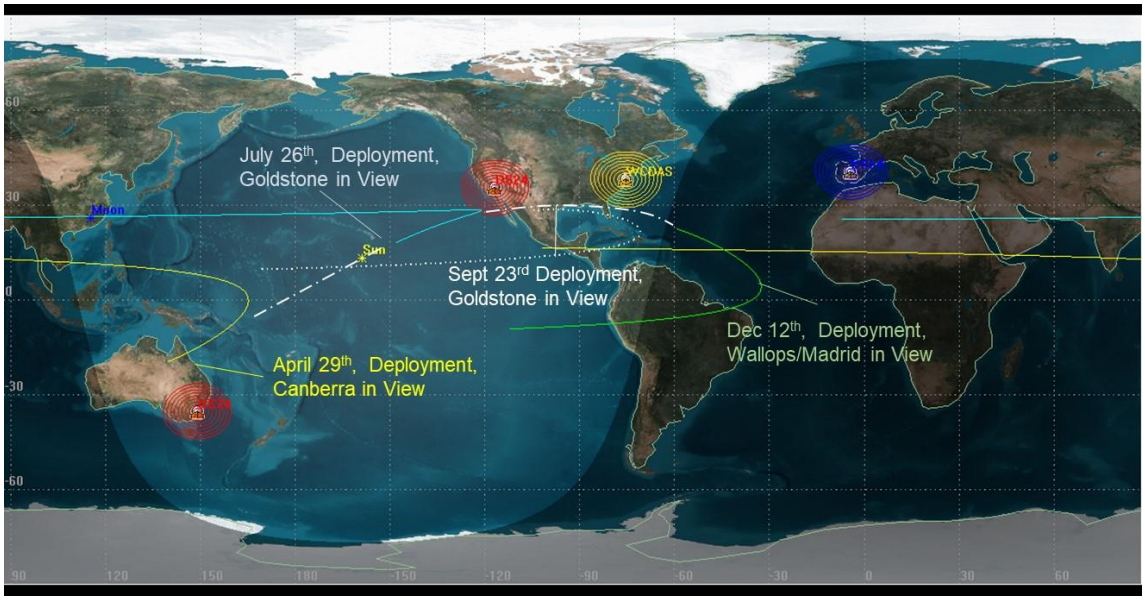


Figure 9. Post injection ground track for several launch dates to indicate station coverage

Launch and Early Operations Tracking Support

As shown in table 3, the amount of tracking data and the stations used is dependent on the mission phase. The L&EO support will be negotiated with DSN services at approximately launch minus six months. The need for near continuous DSN services is required for planning and reconstructing the MCC1 maneuver as well as to plan the MCC2 maneuver that corrects for MCC1 performance and navigation uncertainties. During the transfer, a lower amount of tracking data is requested which is similar to the tracking used in the nominal mission orbit. As SWFO-L1 approaches the LOI location, an increase in the total amount of tracking data is requested to support the multi-segment LOI maneuvers and the associated MUs that are required between each maneuver segment. A request for three different DSN stations with 4 hours of tracking per station between each LOI segment is needed to ensure convergence with the MU executed and to permit the accuracy required for planning the next series of LOI maneuver segments. Once in the nominal mission orbit, a cadence of 1 hour per day of tracking from WCDAS and DSN Canberra is required to meeting nominal mission requirements to generate the definitive and predictive ephemeris and the associated view period products and monthly maneuver plans.

SAN Certification

Additionally a certification of the SAN stations used for tracking and orbit determination is required. This certification is performed by the Goddard FDF support team (under the Flight Dynamics Support Services III contract) in cooperation with the SAN KBR (formerly Kellogg Brown & Root) using tracking measurement data from operational spacecraft in similar orbits and using similar conditions of the measurements. For SAN certification, the DSCOVR Sun Earth L1 orbiter mission has been used primarily to certify both range and Doppler measurements for the routine mission support. It is proposed to use other FDF supported missions such as Magnetospheric Multiscale (MMS) to obtain data in a higher dynamic environment (elliptical orbit) to meet post deployment and transfer trajectory dynamics.

Table 3. Planned Tracking Coverage Based on Mission Phase.

Phase	Ground Stations	Pass Duration/Frequency
Deployment to MCC1	DSN (Canberra, Madrid, Goldstone)	Near Continuous (Coverage being negotiated)
MCC1 to MCC1+10 days	DSN (Canberra, Madrid, Goldstone), Wallops	MCC1 to MCC1+3 days: Near Continuous (Coverage being negotiated)
		MCC1+3days to MCC1+10 days: 4-hrs per day from each of Canberra/Madrid 7-hrs per day from Wallops
MCC1+10 days to MCC2 (MCC1+20 days)	Wallops and Canberra	1-hr per day from each of Wallops/Canberra
MCC2 to LOI (~ 95 days)	Wallops and Canberra	1-hr per day from each of Wallops/Canberra
LOI to Stkp #1	DSN (Canberra, Madrid, Goldstone)	Two weeks surrounding LOI campaign: 4-hrs per day from each of Canberra/Madrid/Goldstone
	Wallops and Canberra	After LOI campaign: 1-hr per day from each of Wallops/Canberra
Routine Mission Orbit	Wallops and Canberra	1-hr per day from each of Wallops/Canberra

CONCLUSION

The SWFO-L1 mission support is challenging due several spacecraft design or operational choices. As discussed, these include; weekly momentum unload management operations which may result in larger than normally experienced residual DVs of 5.77 cm/s in the sunward direction, potential momentum unloads occurring prior to and after each maneuver; launch vehicle rideshare impacts on mission design and maneuver timing, Lissajous orbit size and orientation requirements needed to maintain minimum and maximum Sun-Earth-Spacecraft angles, the design of the Lissajous Orbit Insertion maneuver based on spacecraft design constraints and system dynamics, and certifying the quantity and quality of tracking data measurements required for orbit determination using a newly developed SWFO-L1 Antenna Network. As described above, each challenge has been thoroughly analyzed and an approved operational approach is being scripted and tested for each challenge. The NASA Goddard Space Flight Center's (GSFC) Navigation and Mission Design Branch, code 595, is working with the GSFC SWFO-L1 project office and the NESDIS Office of Satellite and Product Operations (OSPO) to ensure a successful mission that continues the observation of the Sun and space weather.

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