On the Maneuvers Operational Response for NASA's Soil Moisture Active-Passive (SMAP) Mission

Joseph Tirona
Joseph.F.Tirona@jpl.nasa.gov
818-393-8203
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109

Abstract— **The Soil-Moisture Active-Passive (SMAP) spacecraft requires various kinds of in-orbit maneuvers over the course of its three-year mission. The types of maneuvers include pre-planned commissioning maneuvers to reach its science orbit, regularly executed orbit maintenance maneuvers to overcome drag and other nominally occurring phenomena, as well as (the possibility of) collision avoidance maneuvers. The architecture of the spacecraft – in terms of availability of commanding via ground assets, the inherited avionics' ability to sequence and execute commands, and the capability of available subsystems able to carry out maneuvers – was well defined early in the development of the spacecraft and mission, well before the operational plan for responding to maneuver requests was cemented. [2] The systems engineering challenge became: how to accommodate all three types of maneuvers in the confines of this well-defined architecture.**

This paper will describe how the operations team on SMAP successfully met this challenge. Specifically, it will dive into the three pronged approach that SMAP developed to handle each type of maneuver described above – to meet the timeliness requirements leveraged on the operations team to execute said maneuvers, while continuing to fit within the allotted staffing profile during nominal operations. Defining this paradigm to fit the mission's architecture meant re-defining the original paradigm, (planned maneuvers being thought of separately than collision avoidance maneuvers), and re-classifying all responses to maneuver requests as variations and permutations of a singular operational response to a maneuver request. This paper will also describe the tools that were created to simplify the human interface and automate as much of the response as was possible. Finally, this paper will describe, at a very high level, some of the problems encountered and lessons learned by the operations team when this process was executed the first four times during the first ninety days of operations. Though the architecture of the operations team's response to maneuver requests will never be repeated exactly, the flexibility that was inserted via redefining the scope of the problem and by redefining the human interfaces should influence future projects' architectures earlier in their development – in the hopes that said influence will save time and money in the future.

TABLE OF CONTENTS

1. SMAP AND ITS MANEUVERS.....1
2. OPERATIONAL ARCHITECTURE 2
3. THREE PRONGED APPROACH.....3
4. BETTERING RESPONSE TIMES THROUGH PRACTICE 4
5. LESSONS LEARNED 4
6. CONCLUDING REMARKS.....6
ACKNOWLEDGEMENTS.....6
REFERENCES.....6
BIOGRAPHY .....ERROR! BOOKMARK NOT DEFINED.

978-1-4673-7676-1/16/$31.00 ©2016 IEEE

1. SMAP AND ITS MANEUVERS

The Soil-Moisture Active-Passive (SMAP) spacecraft [1, 2] requires various kinds of in-orbit maneuvers over the course of its three-year mission. The three types of maneuvers are: pre-planned commissioning maneuvers to reach its science orbit, regularly executed orbit maintenance maneuvers to overcome drag and other nominally occurring phenomena, as well as (the possibility of) collision avoidance maneuvers. The different flavors are described below to differentiate their purposes and timelines, to frame the response that the operations team takes to react to each maneuver occurrence. The details of the team's responses will be described later in this paper. The common theme between all three types of maneuvers is the following: from the time that the maneuver details are determined, the operations team's response is a race against the clock.

Figure 1 below shows a timeline of the SMAP mission (taken from SMAP's official website [4]). This figure is meant to provide the reader with context for each type of maneuver described in this paper. At the writing of this paper, SMAP is currently in the "Science Observation" portion of its mission.

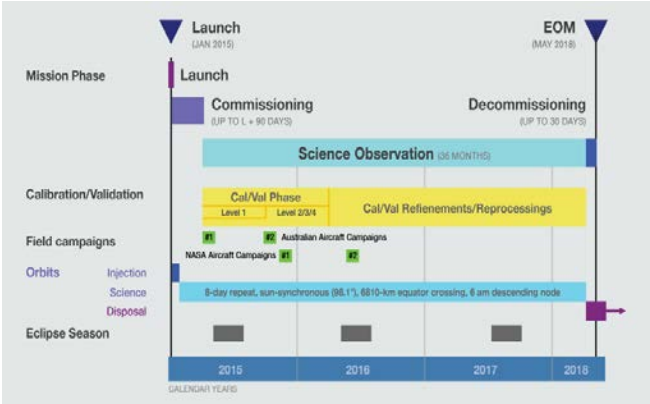

Figure 1 – SMAP Timeline [4]

The first maneuvers that SMAP executed were what the operations team called "preplanned commissioning maneuvers" – maneuvers intended to raise the orbit from where the launch vehicle inserted the spacecraft into orbit to the final (desired) science orbit. [4] These "commissioning

maneuvers" took place in the first 90 days of the mission – (see "Commissioning" in Figure 1). A certain amount of time and a certain number of maneuvers were allotted to achieve the necessary delta-V based on a worst-case launch vehicle insertion, but the orbit insertion ended up being better than expected – and only a subset of those "preplanned commissioning" maneuvers were necessary. The word "preplanned" is a semi-misnomer in this sense – because the maneuvers had to be planned based on whatever orbit the launch vehicle injected SMAP into, and the specific details of those maneuvers could not be planned until SMAP was already in orbit. [5]

The second 'flavor' of maneuver that SMAP executes is the orbit maintenance maneuver, in order to maintain the science orbit (due to atmospheric drag and other effects). These maneuvers typically occur every couple of months during nominal science operations (after the commissioning period). See the "Science Observation" line in Figure 1. Given their routine nature, the time and magnitude of these maneuvers can typically be predicted well in advance based on orbit requirements and the extrapolation of the current orbit and its decay.

The third 'flavor' of maneuver is the collision avoidance variety – to alter SMAP's trajectory in order to avoid orbital debris. This maneuver is unique because of the short turnaround required between the operations team being notified of the necessity and the execution time of the maneuver. The details will be discussed later in this paper, but this maneuver may often be paired with another maneuver, depending on how far outside (if at all) the science orbit the original collision avoidance maneuver leaves SMAP. Note that this maneuver could have occurred at any point in the mission – but is now only a consideration during the "Science Observation" phase seen in Figure 1, since none occurred during SMAP's commissioning phase.

2. OPERATIONAL ARCHITECTURE

The operational architecture of SMAP's mission was detailed long before the operations team developed processes and procedures for handling maneuver requests. The details of SMAP's architecture have been identified and detailed in other papers [1, 2] – but some details related to operations will be described here. The following operational details will be discussed: telecommunications and ground station tracks with SMAP, how sequencing on SMAP works at a high level, how much advanced notice the team is usually given before imminent collisions (and how that affects which maneuver response the team executes), and finally maneuver-centric details on the staffing and organization of the operations team.

SMAP communicates with the Near-Earth Network (NEN) as part of regular operations – and has the ability to talk to the Space Network (SN). [3] Though the SN was used to downlink data during SMAP's initial maneuvers, this was considered a bonus – and not a requirement or part of the standard operating procedure. SMAP primarily uses the NEN for tracking/Doppler data, uplink of commands and downlink of science data and telemetry. The geometry and mechanics of SMAP's orbit are not the focus of this paper – but the key takeaway is the amount of contact that the operations team has with the spacecraft. During commissioning, the team had roughly two separate five to ten minute passes per orbit (with one orbit lasting roughly ninety minutes). During nominal/science operations, the team has (on average) one pass per orbit. Negotiations can be made when special circumstances dictate more passes are necessary – but the average contact times are given to provide context.

SMAP's maneuvers are triggered via an absolutely timed, on-board sequence specific to the maneuver and a separate activation command – both of which are sent during the passes (mentioned above) prior to maneuver execution. The sequence itself: readies the spacecraft to execute the maneuver, turns the spacecraft to the appropriate attitude, executes the maneuver, returns SMAP to its nominal science attitude, and returns the spacecraft's hardware and software to nominal operations. The process that the operations team goes through to create these sequences will be described in a later section. There is one exception (which is described later) to this sequence architecture: a specific instance of the collision avoidance maneuver.

The amount of advanced notice the operations team is given before maneuver execution is a function of the type of maneuver being executed. The dates and general orbit locations of the commissioning maneuvers were known before launch [4] though their magnitudes were not specifically known. The orbit maintenance maneuvers that occur every couple months during nominal operations can be estimated fairly well ahead of time, but the details may change as the execution time approaches. The next orbit maintenance maneuver is calculated after the execution of the previous maneuver – taking into account the implementation accuracy of the previous maneuver, predicted orbit decay as a function of time, and practical considerations like team holidays and vacations. Since SMAP's nominal operations team (described next) is very streamlined, operational roles are clearly defined and maneuver procedures have been practiced and refined for optimum efficiency (described later in this paper).

SMAP's operations team went through a very piece-wise staffing profile – showing a major difference in staffing between commissioning and nominal operations. The organization and roles on the team remain unchanged between these two phases of the mission – but the difference in the amount of staffing (described above) during commissioning was planned specifically for training purposes and anomaly response. During nominal operations, only a primary person staffs each role on the operations team – with the trained backups available in case of emergencies or other necessary personnel adjustments.

The maneuver-centric roles on SMAP's operations team are defined below. This paper is being written by the flight director/activity lead of SMAP's commissioning maneuvers – and the person who trained replacements to take his place during nominal operations. A flowchart showing a high-level abstraction of different roles and responsibilities is shown below in Figure 2. It is permutated based on the type

of maneuver, but as a general outline it is applicable to most maneuvers that SMAP executes.

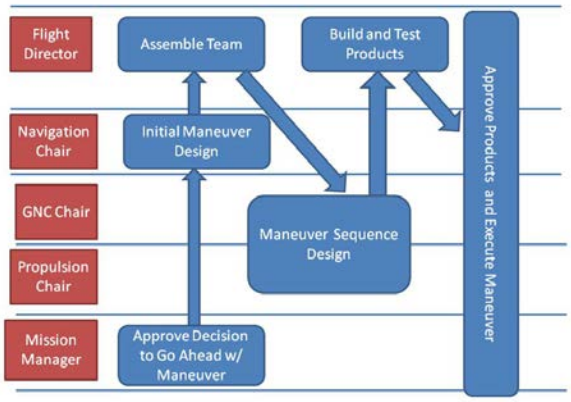

Figure 2 – SMAP Operations Team Roles and Responsibilities

The Flight Director (also known or referred to as the Activity Lead) was the person responsible for leading the team and ensuring that any hindrances to people doing their jobs are removed. During preparatory activities, the flight director was also responsible for taking the maneuver sequence designed by the Guidance Navigation and Control (GNC) and Propulsion Chairs and building and testing the flight products that will eventually be uplinked to the spacecraft. During the uplink process, the flight director is in charge of the uplink process and maneuver execution – and serves as a single point of contact (POC) for all parties (including those not listed here or seen in the diagram – like the NEN).

The Navigation Chair is actually the person that initiates the maneuver out of a need to either: get to or maintain SMAP's science orbit, or to avoid a collision with orbital debris. After the Mission Manager approves the decision to go ahead with the maneuver, the Navigation Chair designs a maneuver and hands it to the Flight Director. They continue to be a participant in the maneuver design process, are a part of the maneuver sequence approval process, and evaluate the maneuver (using NEN station Doppler as mentioned above) after execution.

The Guidance, Navigation and Control (GNC) Chair is responsible for taking the maneuver design from Navigation and designing a maneuver sequence (based also from inputs from the Propulsion Chair). The GNC Chair is also responsible for verifying that the maneuver is valid when compared against the mission's approved flight rules.

The Propulsion Chair is responsible for delivering current best estimates of the fuel on board the vehicle – which is an input to the sequence design that the GNC Chair delivers.

The Mission Manager is responsible for approving the decision to go ahead with the maneuver – allowing the operations team to go ahead with the entire maneuver process. They also have authority at any time to call a stop to the maneuver process based on any outside influences, based on an evaluation of the mission's overall needs.

3. Three Pronged Approach

As mentioned at the beginning of this paper, the operations team takes a different flavor to the maneuver design process described above - based on the type of maneuver. This section of the paper will describe, in detail, each one of those permutations (based on the type of maneuver).

The team has three different responses when it decides to execute a maneuver. It is not, however, a one-to-one relationship between the three types of maneuvers described above and the responses of the operations team. The main differentiator between the three responses is the amount of notice between the notification of a need for a maneuver and the execution date and time. Please see the Figure 3 below:

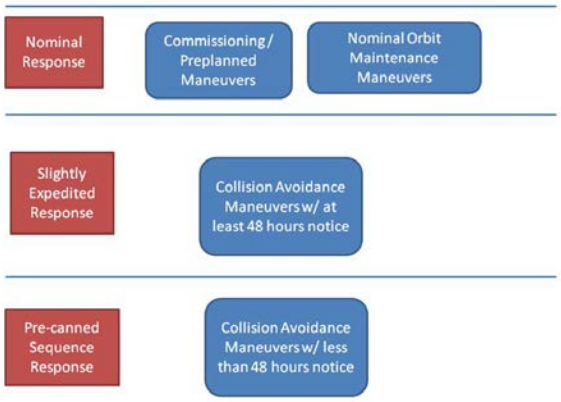

Figure 3 – Response to Maneuver Type Mapping

For maneuvers during commissioning and nominal operations, the team runs through what is called a 'nominal response'. (The only difference between the commissioning maneuvers and the regular orbital maintenance maneuvers were their magnitudes and the number of people on the operations team. These did not have an impact on the response. For commissioning/pre-planned maneuvers to put SMAP in its final science orbit, SMAP had a fairly large operations team [roughly three people per "chair" {or subsystem} that rotated being the "primary" person. This overlap was put into the staffing plan for purposes of training, 24/7 operations during the first week of operations, and bandwidth to address anomalies that were encountered during SMAP's first ninety days in orbit.])

In this response, (the first row in Figure 3 above), the response follows the outlined in Figure 2 fairly closely. The decision to execute a maneuver is approved, the Navigation Chair designs a maneuver, the GNC chair sequences the maneuver, the Flight Director builds and tests the products, the products are verified and approved, and the maneuver is executed then evaluated by the Navigation

Chair. This process usually extends roughly three days from initiation to maneuver execution.

The second and third types of operations responses are for the collision-avoidance type maneuvers – again, depending on how much notice the team has to respond to the collision threat.

If the team is given at least 2 days notice before collision with the debris is set to occur, then the team uses a very similar approach to the nominal approach above; with several steps downgraded from 'required' to 'optional' if the collision deadline is imminent. These two steps downgraded to 'optional' are: the test execution on the avionics testbed and the test review by the team. Combined, these two steps (because they can occur on different work days) can take up to 24 hours from start to finish – which is the difference in the response timeline between this two-day-option (the middle row in Figure 3) and the three-day 'nominal' timeline described above and in the top row of Figure 3. Instead of the test execution and test review, a team visual inspection of the sequence and activation products is substituted. This strategy was given approval by mission management because of the confidence the operations team has gained from successful execution of more than 10 on-orbit maneuvers. The automated tools used as part of this process are described later in this paper.

If the team is given less than 2 days between the notice of an imminent maneuver and the collision deadline, then the team exercises an 'emergency' maneuver sequence that is kept on board the spacecraft. In this scenario, only one product gets built: an absolutely timed activation of that emergency sequence already on board. This response is completely devoid of the process in Figure 2 – the only product, (the absolutely timed activation), may or may not be tested in the testbed. The bare minimum verification of this product is a team inspection and approval of the sequence activation's date and time (based on the Navigation Chair's recommendation). To be clear, this is an emergency response that has not been exercised in orbit. In fact, no collision avoidance maneuvers have been needed on orbit; but both variations have been tested on the ground to assess the team's ability to execute these responses.

This extremely expedited scenario (the bottom row in Figure 3) is different in more ways than just a major reduction in steps. Because the sequence is a 'pre-canned' sequence kept on board the spacecraft at all times, the direction and magnitude of the maneuver are non-negotiable. The only control that the operations team has in this scenario is the time and date of maneuver activation. A byproduct of this lack of control is that a coupled/second maneuver might be necessary – because a maneuver in the 'wrong' direction (to avoid collision with orbital debris) may cause SMAP to exit the boundaries of its science orbit. It is worth noting that the operations team considered having multiple versions of this "emergency sequence" on board to facilitate additional flexibility, but the additional risk involved in potentially activating the wrong sequence in a truly dire scenario dissuaded the team from exercising that option.

4. BETTERING RESPONSE TIMES THROUGH PRACTICE

The processes described above are the end product of multiple years of practice and refining. The SMAP team began preparing for Mission Scenario Tests (MSTs) in the summer of 2013. Originally designed to test the flight hardware's functionality, these MSTs were also the first tests of the maneuver sequence architecture – and consequently were the first steps in streamlining this process. These sequences were developed by hand – and had to be pseudo-arbitrarily designed because the vehicle was still on the ground. (The propulsion tanks, heaters and other hardware that would have threatened vehicle safety were bypassed and simulators were used in their place.)

As the focus shifted from testing hardware functionality towards testing the operations team's preparation, the SMAP team began executing Operational Readiness Tests (ORTs). These ORTs were executed on the testbed (instead of the flight hardware) – with the intent of understanding if the team could respond to requests for maneuver executions within the appropriate time frame and with correct flight-like products.

The first outcome/finding of these tests were that repeatability and timeliness were of the utmost criticality – and that more tools and practice were needed to improve the response time of the team in preparing for the execution of maneuvers. Tools were developed to expedite sequence generation, scripts were written to expedite setup of the testbed, and more ORTs were run for repetition and scoring the team versus real operational scenarios.

It was at this point that mission management decided that the team needed to have multiple responses – depending upon the timeliness requirement of the desired maneuver. Tests were specifically designed and run to exercise these different scenarios.

5. LESSONS LEARNED

The lessons that the SMAP operations team learned, (from the previously described practice and actual maneuver operations), can be grouped into several categories. First, the lack of high fidelity simulators during development is a major risk against operational readiness – and really caused a lot of headaches from an operational perspective. A sub-lesson learned is that practice without these high-fidelity simulators is a risk. Finally, scripted automation saved the operations team major amounts of time, and allowed for the flexible strategies described in this paper.

Lack of High Fidelity Simulators – A Major Risk

The lack of high-fidelity simulators on SMAP for the NEN ground station interaction and the telecommunications radios on SMAP were decisions made well ahead of the birth of SMAP's maneuvers strategy. The decisions not to spend the money and time on these simulators were project decisions, based on cost, schedule, and other factors. This paper attempts to convey the lessons learned from not having higher fidelity simulators of these

interactions, and that not having them being a risk that SMAP's project management decided to take. The benefit in cost, schedule, and other savings are not discussed here – and may have outweighed the benefit of preventing these "lessons learned".

Lack of a higher fidelity radio simulator in the SMAP testbed was a result of the combination of software simulators and hardware connections incorrectly modeling the behavior of some communications states – allowing the avionics in the SMAP testbed to talk to the ground in some instances when it was not supposed to be able to talk to the ground. The first incarnations of maneuver sequences were tested on the SMAP testbed before running them on the flight vehicle during MSTs (to guard against harming the flight hardware). Unfortunately, this caused some very tense moments during MSTs, where the operations team lost communications with the flight vehicle – since the flight radios were behaving differently than the simulators in the testbed had behaved. This was a result of a flaw in the architecture of the maneuver sequence that was not caught until tested on the actual flight vehicle.

The second lack of fidelity came in the modeling of the ground station (NEN) interaction with the operations team. This would have been very difficult to simulate on the ground – and ended up being a discovery of the operations team during its second maneuver execution. NEN stations are given a file (by SMAP's Navigation Chair) that helps them predict where SMAP is in its orbit – so that the ground assets can point correctly to communicate with SMAP. Normally, these files are delivered by the SMAP operations team every 18 hours. Thread tests were executed between NEN operators and the SMAP team, in order that this file format and the tools that generated/accepted these files were verified.

SMAP's second maneuver turned out to be its largest magnitude maneuver (in terms of the change in velocity achieved, hereinafter referred to as "delta-V") – and it also happened to be an out of plane maneuver. A mistake was made in the file delivery directly prior to the maneuver – and the change in SMAP's expected position due to the maneuver was not included. This meant that a large discrepancy was to occur between NEN tracking files (from where the NEN expected SMAP to be in the previous tracking file when compared to where the NEN expected SMAP to be in the next tracking file that contained the maneuver adjustment). In order to avoid this large discontinuity, an intermediate file was delivered to the NEN that smoothed this transition.

There was an error in transitioning from the old file to the new intermediate file – and the tool that received this file and implemented the tracking in the NEN ground stations did not fail in such a way that either the NEN operators or the SMAP operations team were aware that the ground assets were still using the old file.

It turns out that the relatively large magnitude of the delta-V, combined with the out-of-plane element of the maneuver, caused SMAP to exit the tracking threshold of the old tracking file – and the SMAP operations team experienced what appeared to be a Loss-Of-Signal (LOS) in the middle of a NEN pass.

This apparent LOS was a serious scare to the SMAP team – and many possibilities were considered before identifying that this was an issue with the tracking file that the NEN was using in order to point its ground assets at SMAP.

There are several takeaways from this scare. The first is that an intermediate file substitution 'thread test' could have been part of SMAP's development testing suite – and in hindsight, this would have caught the error. But without knowing the need for this during development, it would have been a 'hard sell' to project management that spending the time and resources towards this test were worth the time and cost.

Another lesson learned is that the training time that the team spent in reacting to LOS scenarios through the suite of ORTs facilitated a quick, thorough, and appropriate response to this apparent LOS. The 'off-nominal' ORTs that the SMAP team went through (in non-maneuver related tests of the SMAP operations team's readiness) showed that cross-training of personnel and documented contingency plans and procedures pay dividends when unforeseen circumstances arise.

Automation, Automation, Automation

The second lesson learned – that scripted automation saves time and money while providing maximum flexibility – has been touched on in previous sections of this paper. SMAP had a general operations philosophy of increased automation – a result of the staffing profile that was pitched to NASA – so it made sense that the team's maneuver strategy continued this effort and automated as many sections of the maneuvers process as possible. This helped to decrease reaction time, but also to eliminate human error (very typical reasons for general automation of processes).

At the onset of the first maneuver readiness tests during development, there was a 'one response fits all' process for maneuver execution. As the team learned more about the timeliness requirements of responding to collision avoidance alerts, adjustments had to be made. Specifically, the reaction time and products specific to each maneuver type had to be refined.

To recap, two very specific lessons learned are identified from automating these processes. First, the project's automation-centric mindset (relative to other JPL-operated missions) really allowed the team the flexibility to take the 'one response fits all' approach and mold it into the multi-pronged approach.

The second, more subtle, lesson learned from the increase in automation was the necessary increase in training. While the first iterations of this process took longer and were more rigid, there was less training required (and therefore it was easier to substitute personnel). The introduction of new tools meant that manual tasks were removed from the process. But without making sure that these tools were documented and that people were cross-trained in the content of these tools, a single unexpected bug could have broken the

team's schedule or forced a pause while the team de-bugged the code.

6. CONCLUDING REMARKS

The specific implementation of this maneuver strategy may not be applicable to other missions or applications – but it is the hope of the author that the general approach of maintaining flexibility and increasing automation (both of which allow teams to react to and counter unpleasant surprises along the way) are properly conveyed. This paper documents the strategy, the lessons learned along the way (both those that contributed to the creation of this strategy and those that were especially memorable in the implementation of this strategy), and the methodology behind the decisions described.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

© 2015 California Institute of Technology. Government sponsorship acknowledged.

REFERENCES

[1] D. Entekhabi, "The Soil Moisture Active Passive Mission" in Proceedings of the IEEE Volume 98, No. 5, 2010.

[2] K. Kellogg, "NASA's Soil Moisture Active Passive (SMAP) Observatory" in IEEE Aerospace Conference, 2013.

[3] Official JPL Site for the Soil Moisture Active and Passive Mission http://smap.jpl.nasa.gov/

[4] Official Timeline for the Soil Moisture Active and Passive Mission http://smap.jpl.nasa.gov/mission/timeline

[5] Official JPL Blog for the Soil Moisture Active and Passive Mission http://smap.jpl.nasa.gov/blog/1226/

BIOGRAPHY

Joseph Tirona *received a B.S. in Mechanical Engineering from California Polytechnic University, Pomona in 2012 and is currently attending graduate school at the University of Southern California. He has been with JPL for more than 5 years. After working on SMAP's project system engineering team during development, he went on to become the Flight Director for SMAP's commissioning maneuvers and spacecraft checkout activities. Since starting his career at JPL as a systems engineer in the System Verification and Validation Group at JPL, he has become a mechanical engineer in the Mechanical Systems Group.*