GPM Orbital Maintenance Planning and Operations in Low Solar Activity Environment

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The orbital maintenance operations of the GPM Core Observatory was predicted to have routine drag makeup maneuvers to maintain the mission orbit. The maneuver frequency and estimated fuel usage calculated prelaunch were very comparable to the actual values observed after launch for the first two years. However, when the solar minimum was being entered, instead of seeing the need for less frequent station keeping maneuvers the operations team had to adjust the maneuver plan operations in order to maintain orbit requirements during the low atmospheric drag period predicted to last as long as 2021. This paper will provide the original plan, requirements and restriction, and the plan changes that were made to adjust to this condition. The document will also discuss lessons learned.

I. Nomenclature

BLJ2	=	Brouwer-Lyddane mean elements
DMU	=	Drag Make-Up maneuver
DPR	=	Dual-Frequency Precipitation Radar
ECC	=	Mean Eccentricity
FDS	=	Flight Dynamics System
FOT	=	Flight Operations Team
GMI	=	GPM Microwave Imager
GPM	=	Global Precipitation Measurement
HGT	=	Geodetic Height (km)
INC	=	Mean Inclination
LOP	=	Local Operating Procedure
MOC	=	Mission Operations Center
RMM	=	Risk Mitigation Maneuver
SMA	=	Mean Semi-Major Axis

II. Introduction

THE Global Precipitation Measurement (GPM) is a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the Japan Aerospace Exploration Agency (JAXA). The mission was designed to serve as a successor to the Tropical Rainfall Measuring Mission (TRMM) by enhancing precipitation coverage from the Tropics to a more global scale. GPM was launched via a Japanese H-IIA Expendable Launch Vehicle (ELV) from the Yoshinobu Launch Complex (YLC), Tanegashima Space Center (TnSC), Japan in 2014. The GPM Core Observatory as seen in Figure 1, which will be referred to as GPM in this documentation, operates in a near circular orbit of approximately 407 km with a 65-degree inclination. The GPM Core Observatory, is part of an international network of satellites that provide the next-generation global observation of rain and snow. GPM's role in the network is to utilize an advanced radar/radiometer system to provide a calibration reference standard for unifying precipitation measurements from the constellation of satellites.

The mission has enough fuel to potentially last until 2035 depending on the solar activity experienced on orbit. The spacecraft original operational concept was to use posigrade maneuvers throughout the mission to maintain the orbit and at the time of decommissioning perform a series of retrograde maneuvers to execute a controlled re-entry. For the first two years of the mission the maneuver operations were following the trend predicted prior to launch, however, upon entering the first solar minimum of the mission, the orbital maintenance began to approach the threshold limits of the near circular orbit requirements. The maneuver plan that was expected to be used throughout the mission had to be reevaluated to maintain fuel life and optimal science capture.

GPM is a three-axis stabilized spacecraft (see Figure 1), nadir pointing for instrument observation of the Earth and its atmosphere, with the X-axis aligned with the velocity vector. Depending on Solar Beta angle, GPM flips 180 degrees in yaw such that it flies with either the +X or –X axis forward. However, since it has thrusters on both sides, it can execute maneuvers in both orientations without slewing.

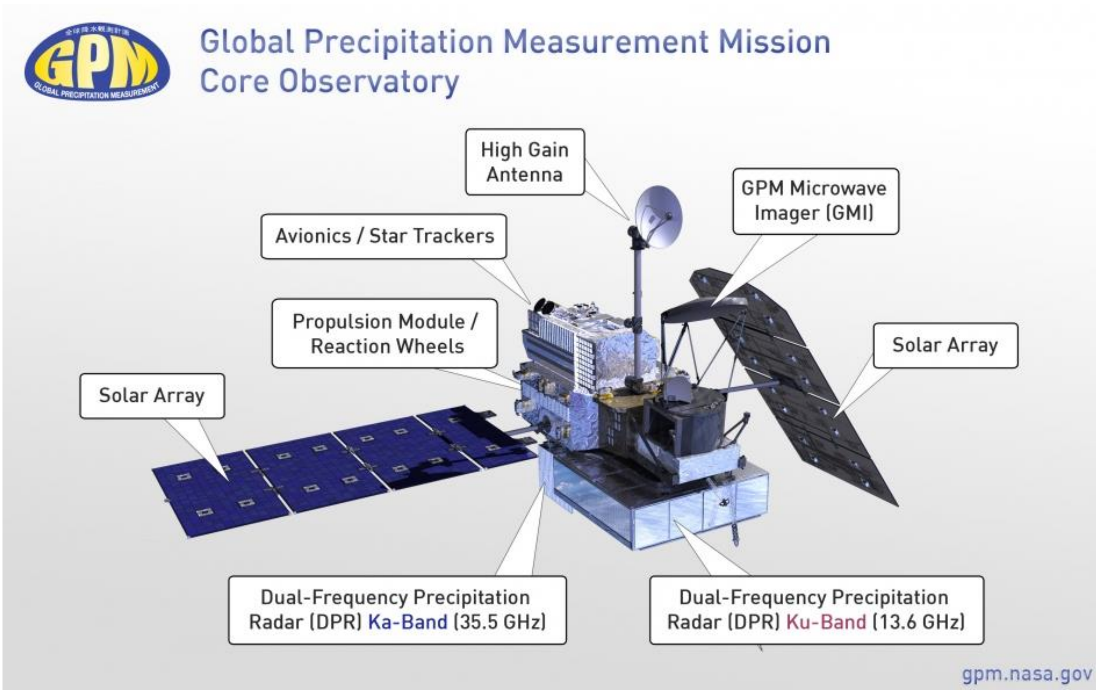

Fig. 1 GPM Core Observatory Spacecraft.

III. Original Orbital Maintenance Plan

A. Orbit Requirements

GPM's orbit was chosen to optimize science data capture for the platform's Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI) instruments and provide coordination with GPM Mission partner satellites. The science objectives lead to the control box requirements outlined in Table 1. Both the Semi-Major Axis and eccentricity requirement tolerance allows for the geodetic height (HGT) of the Core Observatory to be maintained within 397 km to 419 km for effective DPR operation and minimize the altitude variation per latitude crossing over the life of the mission. The inclined (65 degrees) non-sun-synchronous orbit allows the observatory to sample precipitation across all hours of the day from the Tropics to the Arctic and Antarctic Circles, and expand on the observations performed by TRMM, the Core Observatory's predecessor. The Flight Operations Team (FOT) manages the fuel usage based on an orbital maintenance plan derived from these parameters.

Table 1 Nominal BLJ2 Elements with Tolerance

BLJ2	Nominal	Tolerance
SMA	6776.14 km	±1.0 km
ECC	0.0001	Range of 0 to 0.0005
INC	65.0 degrees	±0.2 degrees

B. Maneuver Maintenance Targeting

Maintaining the orbit to these constraints requires the capability for the Flight Operations Team (FOT) to have software capable of performing short and long-term orbit predictions to minimize the impact of orbit maintenance on science activities and optimize fuel usage as the orbit experiences changes due to predictable Earth perturbations and the impact of flying in a variable drag environment.

GPM Maneuvers are planned on the ground by the FDS Engineers of the FOT. The engineers use a ground software program that autonomously maintains the semi-major axis control box window based off the latest GPS ephemeris data downlinked to the ground. Whenever the spacecraft semi-major axis reaches the lower limit of the control box, a maneuver is planned to restore the semi-major axis to the upper limit. The software determines the location in the orbit that will minimize eccentricity (usually near apogee) and determines the correct burn duration.

With the script automatically targeting the semi-major axis, the Flight Dynamic Engineer performs quality assurance checks of the geodetic height and eccentricity.

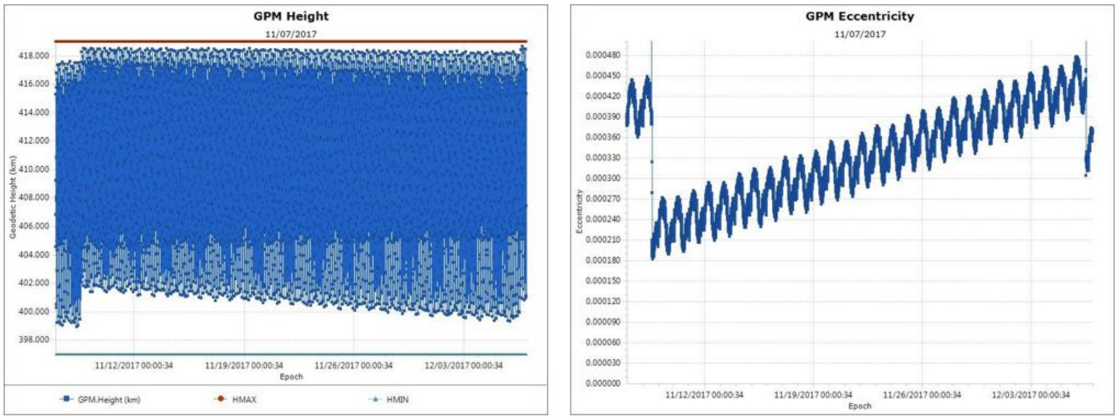

Fig. 2 Example of Geodetic Height and Eccentricity Plot Checks.

The script allows the FDS Engineers to tailor the burn to a specific day and orbit. This flexibility allows coordination with the FOT for best maneuver time in relation to view periods and other spacecraft activities. The script is executed on a daily basis and monitors a 30 day forecast period for planning and modification purposes.

C. Maneuver Maintenance Script Variable Input

Outside of the daily ephemeris updates, the maneuver script requires some inputs values that are supplied by the flight dynamics engineer in order to properly forecast a targeted maneuver. The flight engineer monitors the beta angle region the spacecraft is predicted to fly through in order to provide the software the correct thruster set to use in planning the burn. GPM has thrusters on both sides of the spacecraft. Mission thermal constraints drive the spacecraft to perform a 180-degree yaw flip when passing through a solar beta of zero; this occurs approximately every 40 days. Depending on the direction of flight the spacecraft will be in for the predicted maneuver, the engineer must supply the correct thruster set to use in order for the burn to be properly modeled. In addition to the thruster set, the engineer also must supply the latest fuel tank pressure and temperature retrieved from telemetry.

In the event that a potential Risk Mitigation Maneuver (RMM) may be needed to avoid another space object the script allows the operator to specify the burn time and semi-major axis upper limit. As a preventive measure, the FOT leaves a buffer at the top of the geodetic height window after each maneuver so that if a RMM is needed a maneuver can be executed without violating the orbital requirements. This cushion is provided by the operator lowering the targeted top of the Semi-major axis within the inputs.

The drag profile used to propagate the initial vector up to and after a maneuver is also a variable input that the flight engineer can provide to the software. GPM was designed to feather (configure the solar array to be edge on to velocity vector) the solar arrays during spacecraft night to minimize the effects of drag on the spacecraft and maximize mission life. The mission has multiple profiles on board that optimize power and drag during different beta angles. If the operation team decides to switch between profiles onboard the spacecraft then the flight dynamics engineer can select the corresponding ground configuration file to load to the maneuver planning script.

D. Maneuver Maintenance Constraints

When planning maneuvers, there are three constraints that must be observed outside of the orbital requirements. The first constraint is that after a maneuver, a second maneuver should not be executed for at least 10 hours. This constraint prevents air bubbles from building up in the fuel lines. The second constraint is that a maneuver duration must be at least 10 seconds in duration. This constraint is so that the thrusters reach a steady state so that burns are efficiently executed on board and properly tracked for bookkeeping purposes for fuel accounting. The last constraint was an operational constraint to keep routine drag make up maneuvers less than 90 seconds in duration to minimize impact on the momentum wheels.

E. Maneuver Maintenance Frequency Predict

Prelaunch analysis predicted that orbit maintenance maneuvers would occur as frequently as once a week during high solar activity and as infrequently as every eight weeks during low solar activity. The predictions were based off the -2 sigma, Mean-Nominal, and +2 sigma Schatten predicts. With the maneuver cadence dependent on the drag environment, the FDS engineers execute the maneuver planning process each day. Whenever the spacecraft SMA reached its lower limit, a posigrade maneuver was performed to restore the SMA to the upper limit.

F. Maneuver Propulsion Budget and Lifetime Analysis

After each maneuver is planned and executed on board, the estimated fuel remaining is tracked in the FDS database. The daily maneuver planning provides a short-term outlook on the orbital requirements, but for long term orbit constraint checks and fuel accounting a lifetime analysis is run. The run is similar to the daily plan but the duration is extended out to when the fuel limit is reached. This analysis is executed whenever a new Schatten predict is provided which is nominally twice a year. An example of one of the runs is shown in Figure 3.

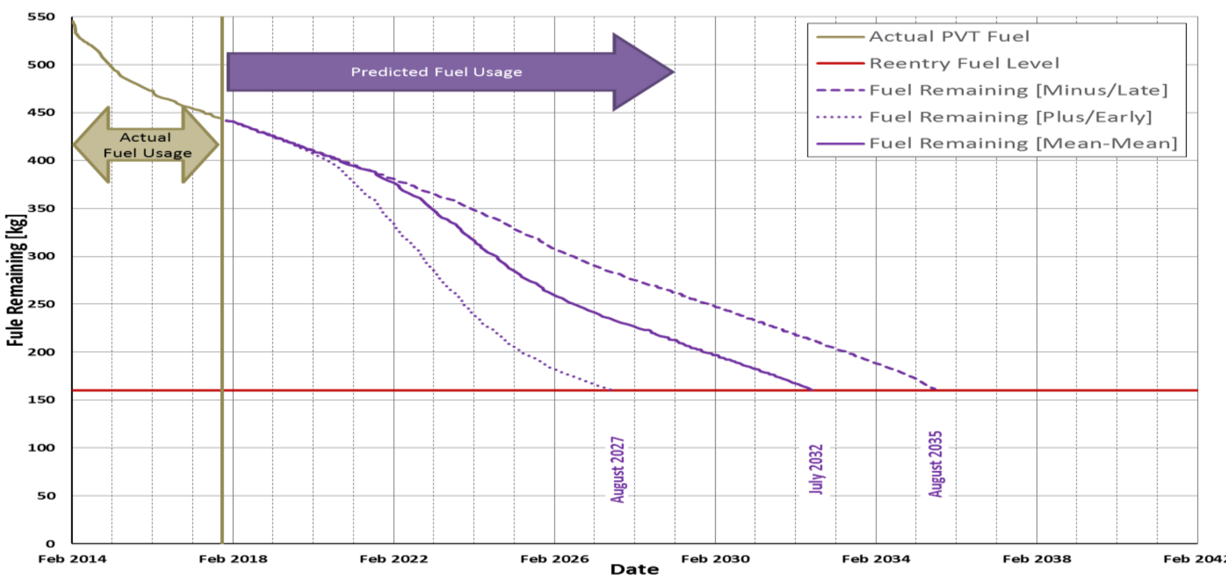

Fig. 3 Predicted Fuel Use for Lifetime Analysis.

G. Maneuver history leading up to solar minimum

Again, per pre-launch analysis, the mission was expecting to plan and perform orbit maintenance maneuvers as frequently as once a week during high solar activity, and as infrequently as every eight weeks during low solar activity. And indeed, for the first two years post-launch, maneuvers were performed once a week in the higher drag conditions as predicted. During the on-orbit check-out phase the senior engineers determined that the solar arrays performance was more than adequate to recharge the batteries and provide power to the bus, thus a few of the solar array feathering profiles were tested on board to optimize the input power and drag induced. After a few months of testing, the low drag profile know as Profile K was selected in August of 2014 and maintained since. This change, coupled with the solar flux dropping slowly as the mission months passed, allowed for the maneuver frequency to slowly change from once a week to roughly once a month.

With multiple successful maneuvers performed on orbit and the frequency cadency changing from once a week to approximately once a month there was one more additional maneuver test that was requested to be executed. With GPM only performing posigrade maneuvers the mission director requested that a retrograde maneuver be tested. The test would demonstrate two things. The first, would be that prior to end of mission where retrograde burns are required, the team demonstrates the maneuver capability successfully at least once prior to end of mission. The second point, would be that if test is successful then this type of maneuver could be used for Risk Mitigation Maneuver with other space objects. A retrograde maneuver would allow the team to use up more of the box during nominal burns, and if a conjunction occurred, a retrograde maneuver could be executed instead of a posigrade one. The test (a 15-second burn) was successfully executed in March of 2016, and a separate maneuver planning script was created to provide the capability to use a retrograde maneuver prior to end of life.

IV. Entering Solar Minimum

A. Period of Solar Minimum starting in mid-2016.

At this point, with the maneuver frequency following as predicted, the team was expecting the maneuver cadence to remain relatively stable throughout the solar minimum. GPM had performed 45 maneuvers as of February 1, 2017, with a variable maneuver frequency throughout the mission. However, during the period of solar minimum starting in mid-2016, and predicted to extend through 2020, the FDS engineers began to predict that the Drag Make-Up maneuvers (DMUs) required to maintain the SMA within tolerances were both too infrequent and of insufficient size to control the eccentricity. Figure 1 shows the solar flux (specifically the F10.7 cm radio flux) decreasing and reaching its minimum between 2015 and 2017.

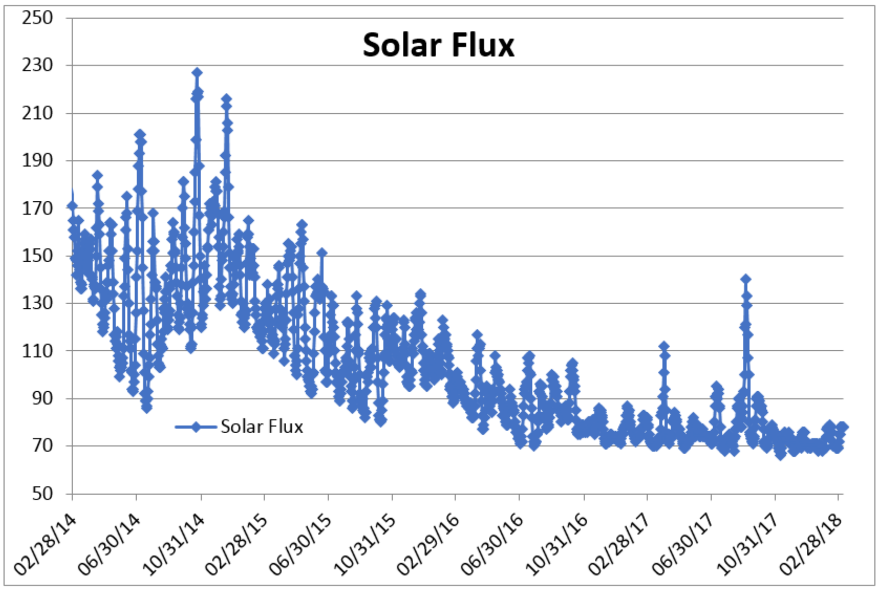

Fig. 4 Entry into Solar Minimum: F10.7cm Radio Flux Progression.

B. Observed Orbital Issue

The cause was determined to be due to the low drag environment which, according to the latest Schatten predicts, would last until 2021. Given the near-zero ECC at which GPM flies and the very low-drag environment, the ECC was growing over time. The spacecraft's minimum HGT was increasingly falling faster than its maximum HGT.

Figure 5 shows the evolution of atmospheric density and ECC over an identical time span, with GPM unable to control ECC within limits between 2017 and 2021. The low atmospheric density allows for more ECC growth between maneuvers, and for a given maneuver constrained by an upper HGT limit, the ECC cannot be reduced sufficiently. Instead, the maneuver achieves a small reduction in ECC, only to be outpaced by the increase. As it turned out, for the existing operational paradigm, a minimum threshold of drag was required to maintain the orbit. This situation was counter-intuitive, and not foreseen in any of the pre-launch analysis.

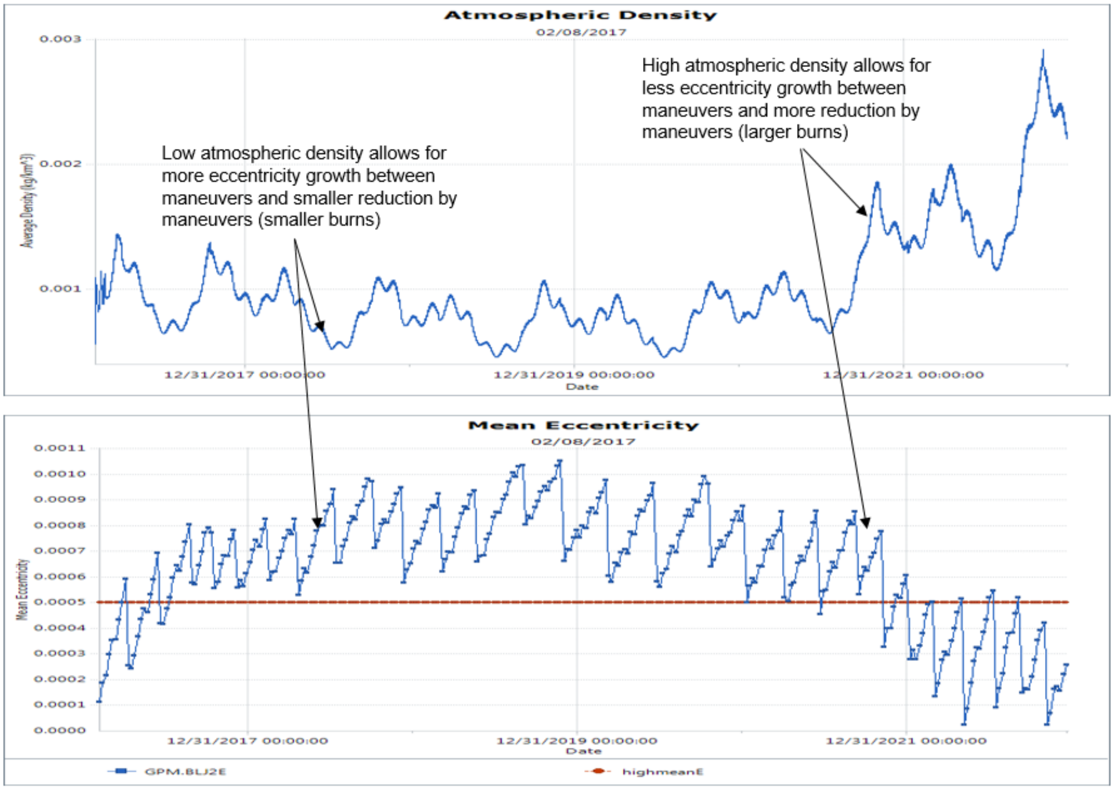

Fig. 5 Atmospheric Density and ECC: Evolution in Time.

More specifically, due to the low drag environment, the growth in ECC manifested as a steady increase in HGT range (minimum to maximum per orbit). This put GPM in a unique situation where the maximum HGT remained near the upper portion of the control box, while at the same time the minimum HGT was approaching the lower limit. As a result, performing any large DMU to reduce the eccentricity would cause a violation of the HGT requirements. The situation effectively "choked" GPM within its control box, meaning that a normal DMU would be unable to control the spacecraft within either the ECC or HGT requirements (which are of course correlated). Figure 6 shows GPM executing two normal DMUs before the scheme fails.

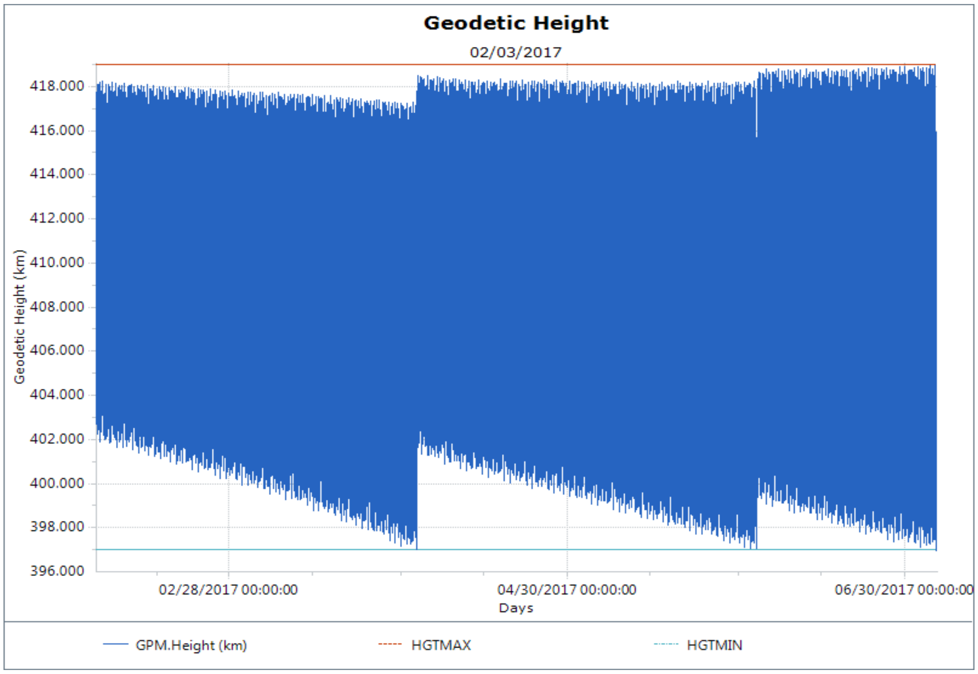

Fig. 6 HGT Evolution with Increasing ECC.

The FOT needed to develop an option that would allow GPM to control ECC growth without violating the HGT requirements, or at least one that would minimize loss of science for the remainder of the prime mission.

C. Initial Analysis to Change Current Maneuver Operations

The FOT analyzed three scenarios to help determine the best course of action. The first option was to change the maneuver cadence back to once every week. The idea was that smaller and more frequent maneuvers might decrease the eccentricity faster. The pros for this scenario was that no change to routine operations and procedures would be required to implement this option. The cons would be that maintaining a one-week cadence could result in short burn durations of less than 10 seconds which would be a violation of FOT constraints. The results showed that a maneuver every week will cause a violation of both the geodetic height and eccentricity requirement within 2 months.

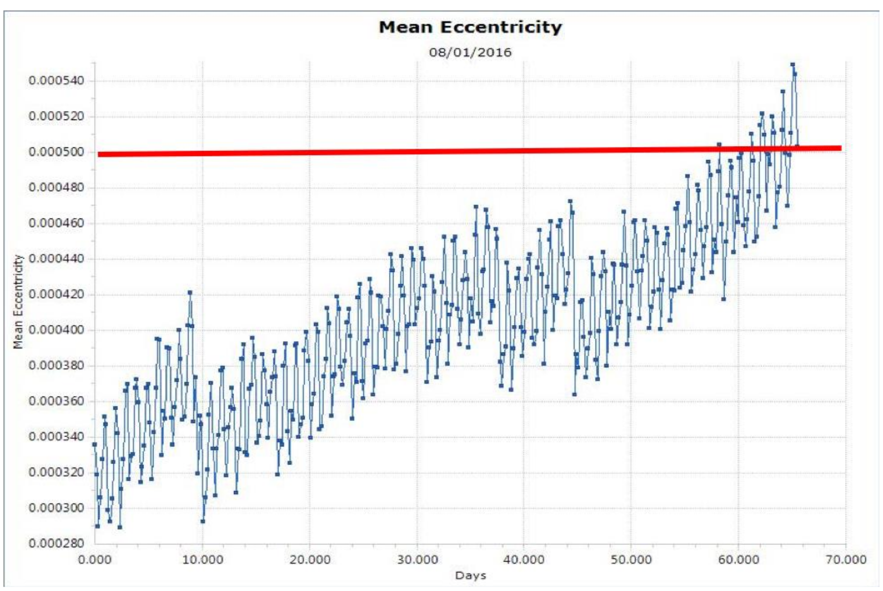

Fig. 7 Option 1: One Week Maneuver Cadence.

The second scenario analyzed was to perform a retrograde maneuver similar to the one tested 5 months prior. The idea was that the retrograde maneuver could provide a cushion at the top of the control box, which would allow for a longer Drag Make-Up maneuver (DMU) to be executed in order to trim off the excess eccentricity and still maintain the geodetic height. Analysis showed that a minimum retrograde burn duration of 15 seconds was sufficient enough to accomplish the desired outcome if the maneuver was followed up by a normal posigrade DMU. While the solution worked, Figure 7 shows that this trend of retrograde burn followed by a DMU would need to be repeated to prevent a future violation. The team was concerned that if multiple retrograde maneuvers were needed to maintain orbital requirements during the solar minimum, then mission life would be shortened dramatically due to fuel lost prior to even entering the next solar maximum.

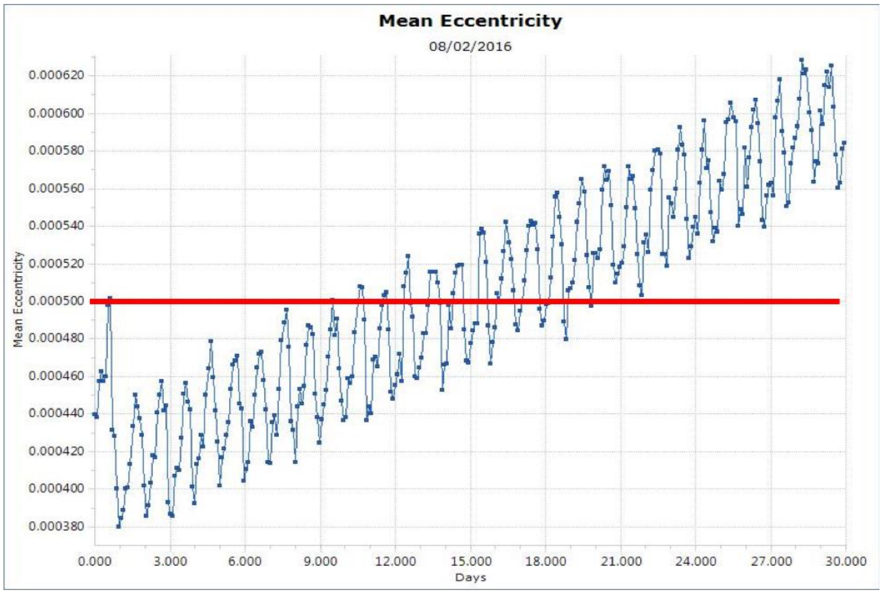

Fig. 8 Option 2: Retrograde Maneuver.

The third scenario proposed was to increase GPM's drag area profile through the use of unfeathering the solar arrays panels. Similar to how the array profile was changed during early orbit check out to reduce drag, the FOT could change the array profile to one that could create sufficient drag needed to lower the spacecraft's geodetic height faster than the growth of the eccentricity. The benefit would be that no additional maneuvers would be required to maintain orbit requirements. The predicted analysis showed that using the largest drag profile, profile G, the eccentricity requirement could be maintained for several months as depicted in Figure 8.

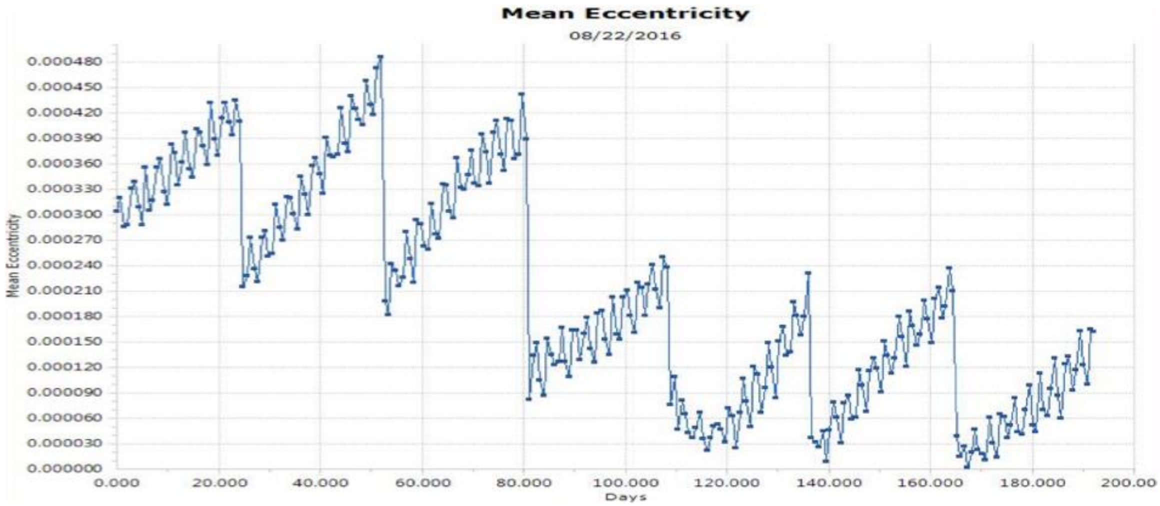

Fig. 9 Option 3: Switch to High Drag Solar Array Profile (Profile G).

V. Initial Orbital Maintenance Solution

A. Increase Drag with Solar array

In August 2016, after discussion the decision was made to utilize option 3. The main reason was that no additional maneuvers were needed to maintain the orbit and when a maneuver needed to be executed the minimum burn size requirement would not be violated. In addition, the power engineer was consulted to verify that there would be no concern about the excess power generation if the spacecraft switched to profile G and remained there until the solar minimum had passed.

B. Solar Array Drive Hardware Concern

After the switch to profile G was made the FOT trending revealed a concern that was not evaluated in the initial decision process. When using Profile G, trending was showing the SA profile induced additional cycles on the SA gimbals, thus putting an unnecessary strain and risk to the spacecraft. Pre-launch analysis predicted that 3-years into the mission the Solar Arrays would cycle (out and back) around 18,000 times per wing. Due to the switching from the profile G to the profile K control table early after launch the +Y gimbal had only reached just under 5000 cycles, and the -Y gimbal had reached just under 9,000 cycles. While the FOT trending of the systems shows no signs of motor degradation or slippage, the concern for staying on Profile G indefinitely was that the result in a large number of cycles could potentially lead to a solar array drive failure before the fuel projected mission end of life.

The concern was prompted from lessons learned from GPM's predecessor TRMM. As a preventive measure, TRMM parked one of their Solar Arrays for the remainder of the mission to prevent the solar array being stuck in a non-optimal position as a result of a potential drive failure. Returning to the G profile to increase drag was resulting in a faster increase in the number of cycles which increases the chance of solar array drive failure before fuel runs out. The rate can be observed in Figures 9 and 10, where the orange trend represents the number of cycles that would have been encountered if Profile G was used since launch and the green trend is what was actually used when the FOT switched from G to K.

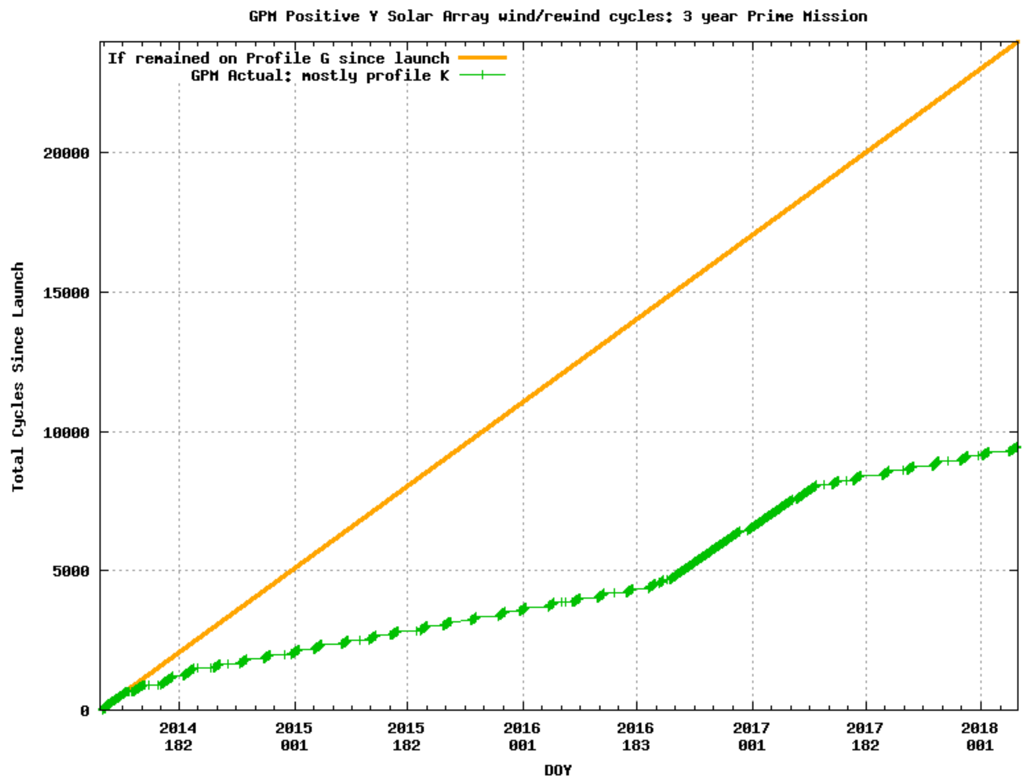

Fig. 10 Plus Y Solar Array Cycles: Profile G vs Actual.

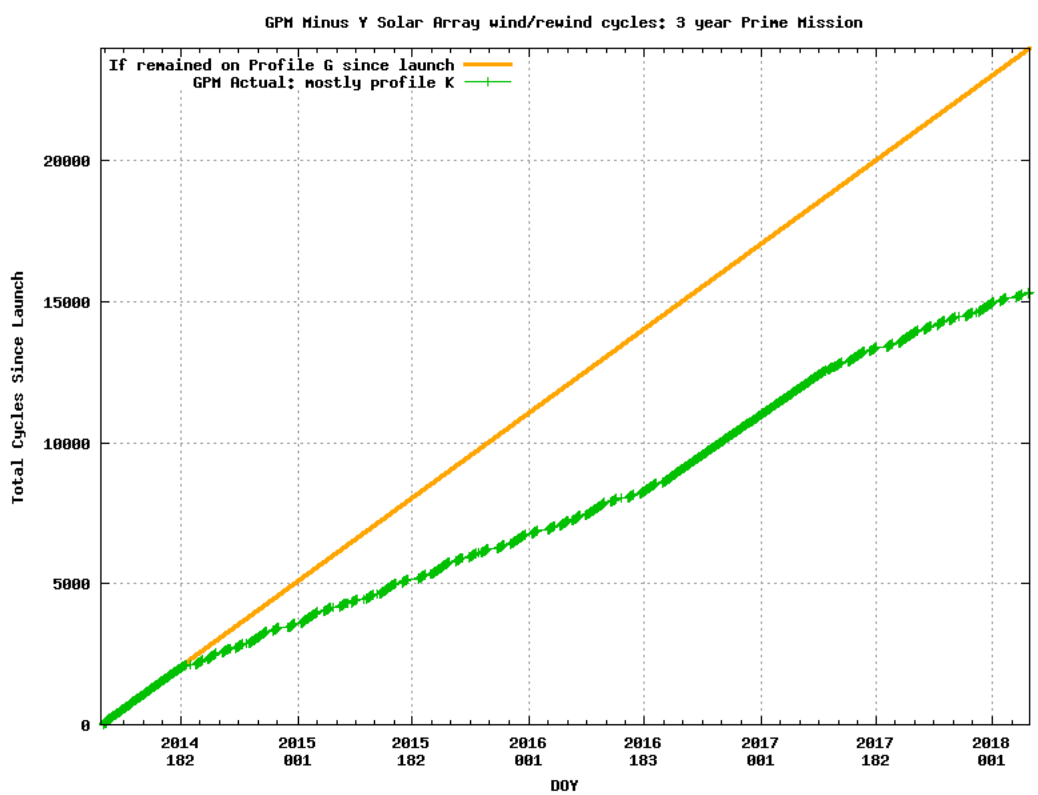

Fig. 11 Minus Y Solar Array Cycles: Profile G vs Actual.

While the orbit requirements were being maintained under this profile, in addition to the increased number of cycles Profile G was discovered to cause hardware concerns with the solar arrays at certain beta angles. As a result, the FOT began looking into using other profiles that would increase drag and minimize cycles. In the meantime, the spacecraft was flown off of both profile G and K where profile K was swapped in only during the problematic beta angle region. The objective was to find a profile that would have the drag qualities of profile G and the minimum array cycle qualities of profile K. If found, the new profile would be used for the remainder of the duration of the Solar Minimum cycle and then Profile K would be returned when drag was sufficient enough, thus optimizing the mission lifetime in fuel and hardware. The team continued to investigate other Solar Array profiles as a viable option until Solar Activity demonstrated that no current profile onboard would be sufficient to handle the requirements.

C. Increased Drag insufficient to last through Solar Minimum

The decision to move away from this profile was finally aided by the fact that while the increase in drag helped in maintaining the requirements for the first eight months after implementation, future predictions showed that the continual drop in solar activity would ultimately result in repeated violations of the mission requirements starting in early spring of 2017.

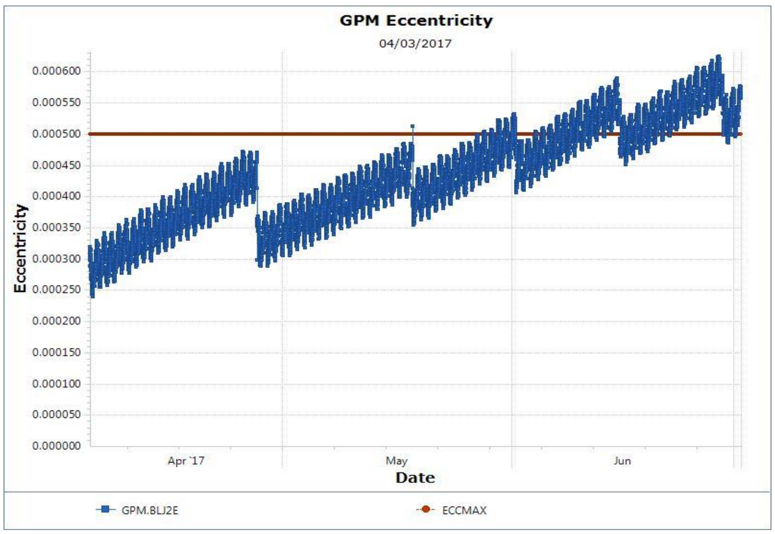

Fig. 12 ECC for Continued Swapping of Profile G and K.

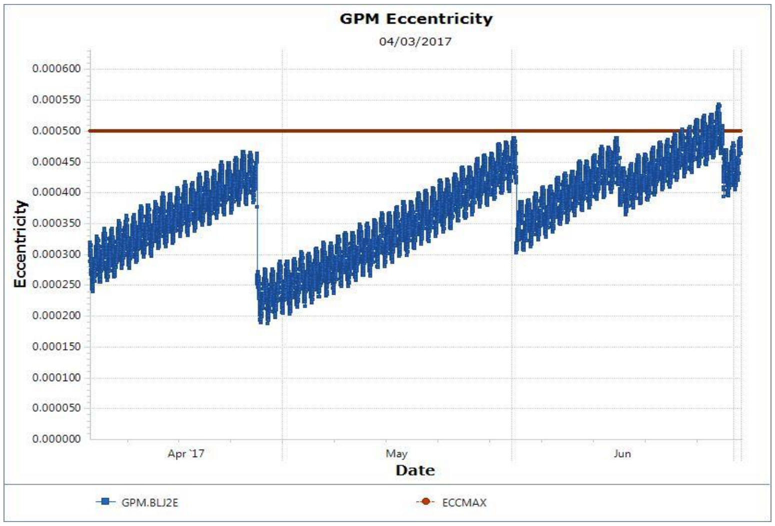

Fig. 13 ECC if Proceeding with Profile G Only.

Regardless if the spacecraft was flown on the continued swapping between profile G and K or if profile G was used indefinitely the eccentric requirement would be violated and the top of the geodetic control box would be reached. The consensus of the team was that the immediate response was to perform a retrograde burn to stay within the required orbit. A new maneuver maintenance plan with the use of Delta V maneuvers needed to be developed as the concept of self-induced drag with the Solar Arrays could no longer sustain orbital requirements. Not only would a new maneuver approach need to be determined but updates to the lifetime script would have to be incorporated to properly plan out the maneuvers through the entire Solar minimum.

VI. Maneuver Operations Analysis

A. GPM Lifetime Analysis Tool

The FDS engineers conduct a formal analysis of the GPM lifetime on a biannual basis, typically in April and November when the new Schatten atmospheric models are published. The analysis is performed using an autonomous script that reads an initial state from an input ephemeris file and propagates that state indefinitely into the future until a minimum fuel limit is reached. That limit is governed by a conservative estimate of the fuel required to perform a controlled reentry at the mission end-of-life. The fuel is consumed over time by DMUs that are modeled to maintain the orbit within the drag environment predicted by Schatten, and a basic blowdown model is leveraged to estimate the pressure drop in the fuel tank over that same time period.

Any maneuver targeting scheme implemented in the script must ultimately succeed in maintaining the orbital requirements, while constraining burn sizes within the operational limits of the spacecraft. And since the script targets autonomously, the scheme must follow a repeatable pattern with an objective set of rules. Further, GPM introduces two additional complications: first, yaw flips are performed at a solar beta angle of zero, meaning a thruster set with a different thruster scale factor and associated duty cycles may be used for any given maneuver; and second, the use of different solar array configurations impacts the effective drag area.

By manipulating the maneuver targeting scheme, as well as implementing a general criteria for modifying effective drag area, the lifetime analysis script can be leveraged as a testbed for evaluating options to address the problem of low-drag ECC growth. This approach was used to assess and eliminate single-solution candidates such as SMA-limit based maneuvers (in which the triggering and targeting is based solely on SMA), HGT-limit based maneuvers, and reduced maneuver cadence. The first (SMA) has the functional benefit of being able to continue executing maneuvers throughout the mission lifetime, as the targeting is not dependent on the actual constrained parameters (HGT and ECC). And although the scheme fails to maintain the orbital requirements as a result, it at least allows for years-long propagations such as the one for ECC back in Figure 5, and the one for HGT in Figure 14 below. Conversely, the second (HGT-limit based) fails to target maneuvers as soon as the orbital requirements can no longer be satisfied. The third (reduced maneuver cadence) has the same issue as described earlier for the one-week cadence option: the targeting fails when the generated burn durations fall below the operational limit of 10 seconds. Further, even if the lower limit on burn duration is ignored, the scheme generally causes the spacecraft to breach the ECC requirement even sooner than the other candidates.

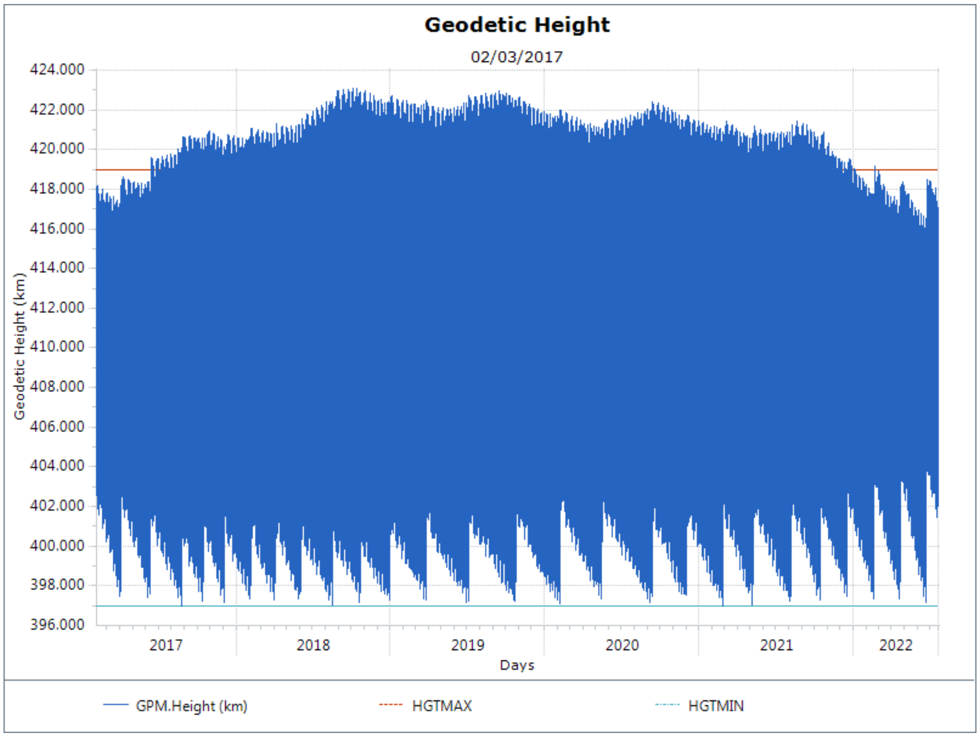

Fig. 14 HGT Evolution with SMA-Limit Based Targeting.

B. Incorporating Operational Schemes

Per the Local Operating Procedure (LOP) for DMU planning exercised by the FDS engineers, a maneuver is triggered by a minimum HGT condition, targeted to achieve a result in SMA, and then potentially replanned based on predicted maximum HGT outcome. For example, if the maximum HGT is predicted to be less than 418.5 km over the first 24 hours after execution, the DMU is replanned by increasing the SMA target by 0.1 km (e.g. 6777.94 km). Conversely, if the maximum HGT is predicted to be more than 418.6 km over the first 24 hours after execution, the DMU is replanned by decreasing the SMA target by 0.1 km (e.g. 6777.74 km). Since this presents an objective set of rules for scheduling a DMU, it was decided to implement the LOP scheme in the lifetime analysis script. This would serve to verify that it would encounter the same problem maintaining the control box, and within the same timeframe, as the other candidate solutions. And indeed, it did; the outcome was the same as that described back in Figure 6. In fact, most schemes that did not artificially manipulate the cadence were failing in the summer 2017 timeframe.

Regarding GPM's solar array configuration, the lifetime analysis script initially modeled a transition between Profile K and Profile G (the higher drag presentation) based on a threshold of atmospheric density. If the density was above a specified value, the drag area associated with Profile K would be used, and vice versa. However, GPM was operationally spending almost all of its time in Profile G, leading the lifetime model to underestimate the overall drag and thus predict an earlier date at which targeting would begin to fail. When the model was updated to more closely reflect what was happening in practice, the predictions were much closer to reality.

As an approximate rule of thumb for GPM's orbit, the ECC limit has been reached when the spread between minimum HGT and maximum HGT is 19 km (out of a control box size of 22 km). During periods of normal to high drag, this size of spread is generally not seen. However, it is a more common occurrence for low-drag periods. What this means is that it is possible for the ECC limit to be reached before the minimum HGT condition is reached (i.e. the normal trigger for the LOP maneuver targeting scheme). Thus, it became necessary to account for the ECC limit in the script. As it turns out, the addition of ECC as a second target adds little value, since it is tightly coupled to maintaining the HGT limits. In general, if a targeting algorithm is provided with multiple targets to achieve, it will be beneficial for convergence if those targets are mostly de-coupled. The correct approach in this circumstance was to make the ECC limit a trigger condition for the maneuver. To be clear, this did not change the big picture in terms of the LOP scheme ultimately failing to target, and in some cases caused that failure to occur sooner, but it ensured that both orbital requirements would be maintained.

C. Additional Hybrid Options

Leveraging the upgraded lifetime analysis script, which implemented the LOP maneuver scheme and added an ECC trigger, two additional hybrid approaches were assessed: first, tightening the HGT control box to force more frequent maneuvers; and second, performing paired apogee and perigee burns on the same orbit, which was a TRMM maneuver scheme to control its eccentricity.

For the first hybrid approach (effectively shrinking the HGT swath), it was quickly determined that decreasing the upper bound of the control box was completely counterproductive, as it only served to eliminate "breathing room" for the maneuvers. Thus, the approach was limited to stepping up the lower bound of the HGT box (e.g., 398, 399, and 400). However, as was perhaps foreshadowed by the earlier experiments with maneuver cadence, smaller and more frequent maneuvers tended to hasten the failure of targeting, even if a larger number of smaller maneuvers were successfully targeted. The most successful modification to the bottom of the control box (an increase of 2 km to 399) only allowed targeting until early summer 2017, as shown in Figures 15 and 16.

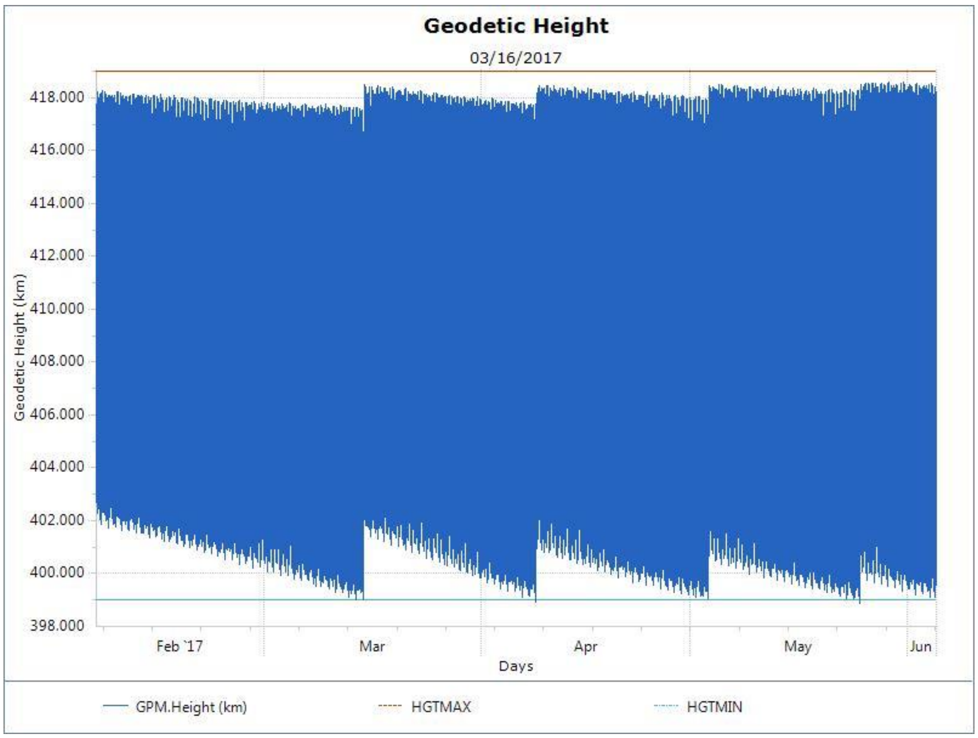

Fig. 15 HGT Evolution – Increase of Lower HGT Limit by 2 km.

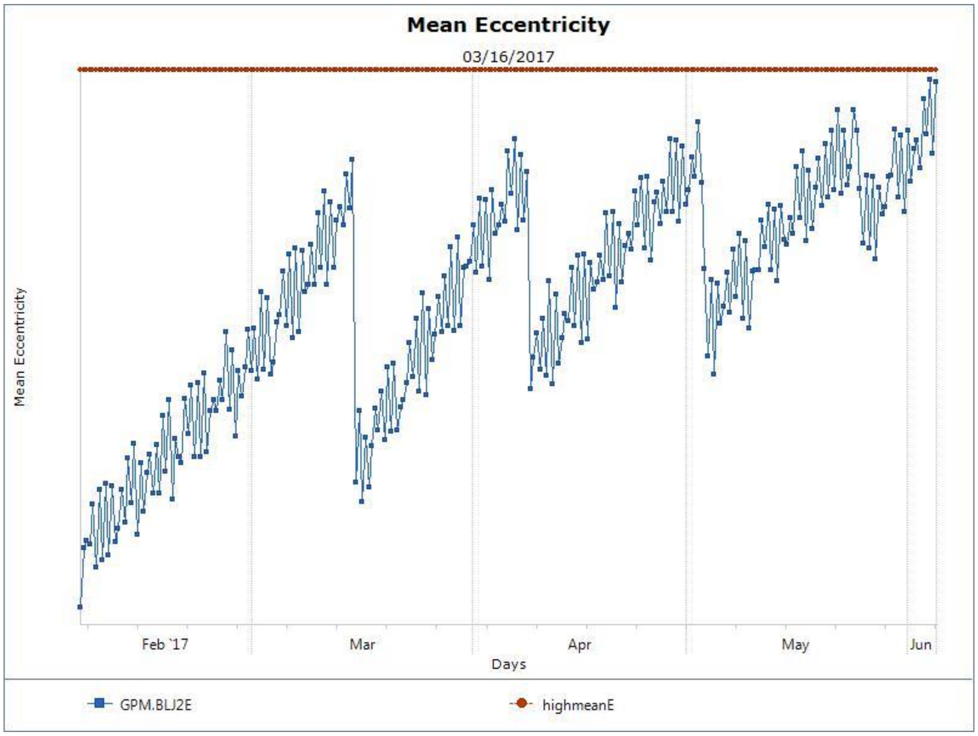

Fig. 16 ECC Evolution – Increase of Lower HGT Limit by 2 km.

Regarding the second hybrid approach (paired apogee and perigee burns), it became clear that this solution was a mismatch for GPM's problem. TRMM had targeted a specific non-zero value of ECC by performing a posigrade burn at both apogee and the following perigee, with appropriate relative sizing of the burns to achieve that objective. Conversely, GPM prefers to drive the ECC as close to zero as possible, and so it would actually be counterproductive to that goal to burn posigrade at perigee after the first burn at apogee.

D. Conclusion for Posigrade-Only Schemes

A relatively exhausting examination of options to address GPM's problem of eccentricity growth in a low-drag environment did not identify a successful solution that leveraged only posigrade maneuvers. Thus, under persistent conditions of lower solar activity, the conclusion was that the judicious use of retrograde maneuvers would be the only reliable means of satisfying the orbital requirements. To objectively weigh this against the potential impact to the overall GPM mission lifetime, an analysis would have to be performed that qualitatively measured the length of that lifetime with retrograde burns included in the model. Accordingly, logic to substitute a retrograde burn under a very specific set of circumstances would have to be added to the lifetime analysis script. And if approved for operations, that same logic would be incorporated in the operational DMU planning script.

E. Retrograde Maneuver Design

The earliest design decision associated with incorporating retrograde maneuver logic into the lifetime analysis script was related to the precise nature of the circumstances that would trigger it. Since it was logically assumed that the burn would be sized to be as small as necessary (and likely not much larger than the 15-second retrograde burn executed in March of 2016), it followed that the maneuver would have to occur in relatively close proximity timewise to either the preceding or following posigrade maneuver. In fact, an early concept attempted to pair a large posigrade and small retrograde burn in the same orbit, with the latter occurring at perigee (basically a modified TRMM concept). However, this was deemed as overly complex in terms of planning and execution, and entailed some risk in the event that one of the paired maneuvers had to be waived. Ultimately, the design settled on a standalone retrograde maneuver that would be sufficiently sized to allow for at least a week, and preferably two or three weeks, before a follow-up posigrade burn had to be executed.

Keeping in mind that a posigrade maneuver (of at least a minimum practical size) is always preferred, it made sense to engage the retrograde logic only as a "last resort", versus implementing a more nuanced logic to decide between the two every time a trigger limit (either HGT or ECC) was reached. The nominal LOP scheme ultimately fails because it cannot target a posigrade maneuver of at least the 10-second operational limit (without violating the top of the control box). Thus, upon a failure of that scheme to converge on a solution after a maximum number of iterations, the design defaults to the retrograde logic. The orbit is propagated forward from apogee to the following perigee, the opposing thrusters are initialized, and the targeting algorithm finds a burn solution that is sized to achieve a reduction in the maximum HGT. This creates room at the top of the control box for a larger posigrade burn to follow a small number of weeks later, and reduce the ECC even further.

Figures 17 and 18 show the HGT and ECC evolution over a two-year period with the retrograde logic implemented. They demonstrate that the design manages to maintain the orbital requirements well into the Solar minimum. In the ECC plot, the smaller dips result from the retrograde maneuvers, while the larger dips are caused by the follow-up posigrade maneuvers (note there are a couple of data points above the ECC limit; these are due to noise from the averaging method and the larger step size in the propagation). Also, since the retrograde logic is only engaged when the nominal scheme fails, there are of course instances of consecutive posigrade maneuvers.

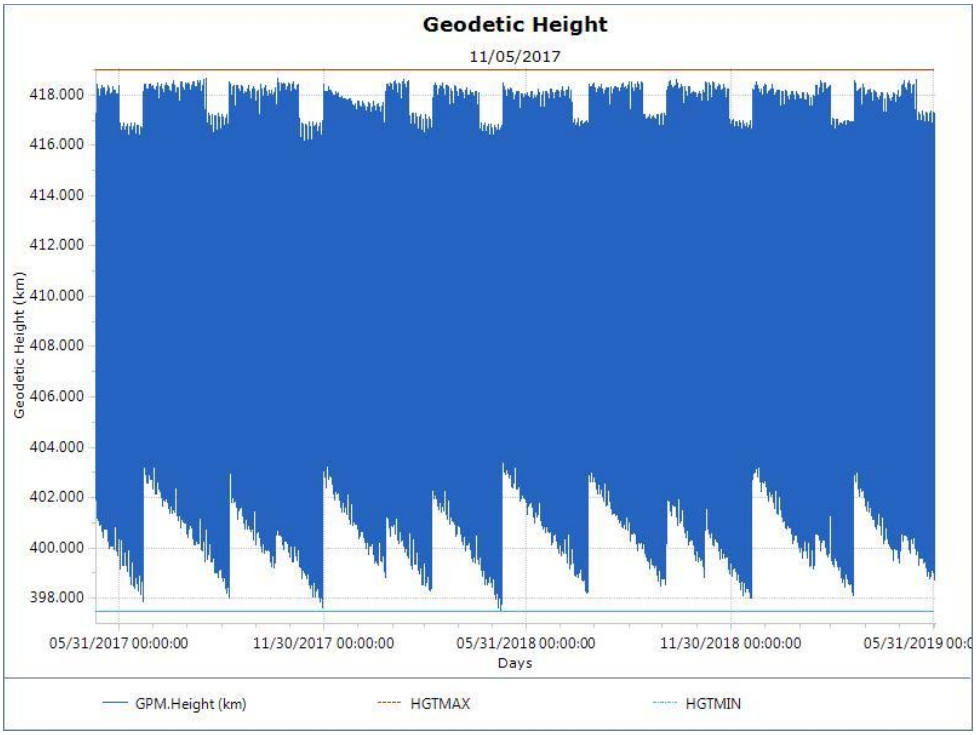

Fig. 17 HGT Evolution with Retrograde Maneuvers.

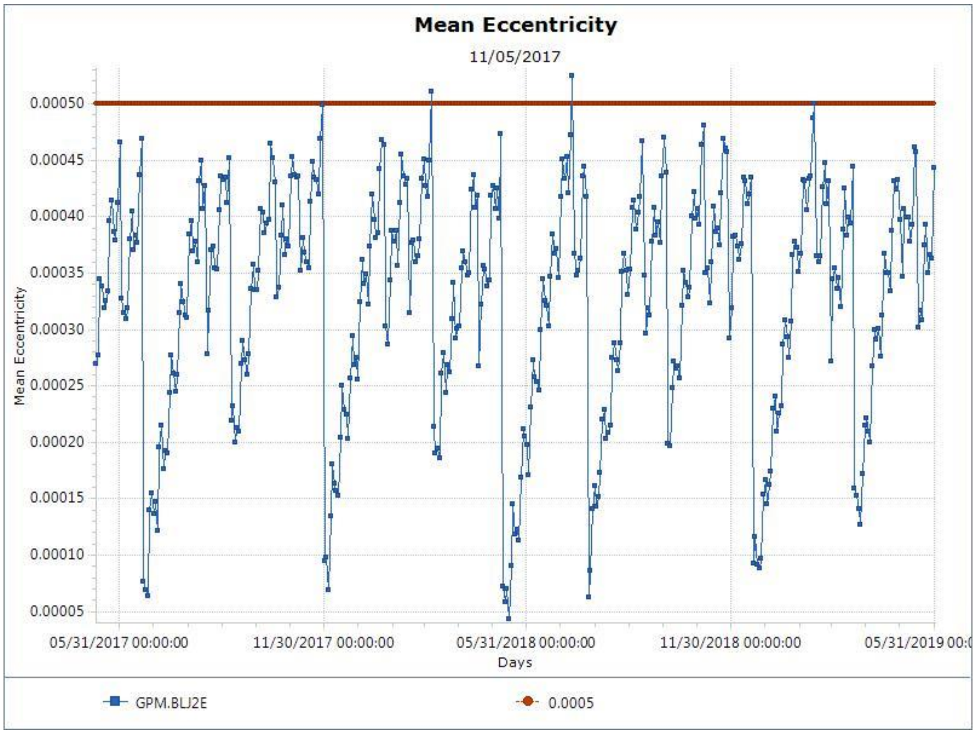

Fig. 18 ECC Evolution with Retrograde Maneuvers.

Finally, it is noted that these predictions assumed that the solar array configuration was in Profile K (the lower drag presentation) the entire time. The design that included use of retrograde maneuvers to maintain the orbital requirements did not rely on any use of Profile G, or any switching between the two configurations. This was yet another advantage, as the gimbal cycling concern associated with use of Profile G was alleviated.

VII. Full Lifetime Results

With an implemented maneuver targeting scheme that not only continued to execute maneuvers throughout the mission lifetime, but also maintained the orbital requirements over the entire period, the lifetime analysis script could now be used to qualitatively assess the impact of using retrograde maneuvers during the low-drag periods. Previous estimates had projected the mission lifetime to last through 2035 based on the remaining fuel, although that fuel was originally only budgeted for performing maneuvers that would raise the spacecraft height (i.e. posigrade). That said, the upgraded script represented a much more comprehensive analysis. In addition to more realistic maneuver modeling in the changing drag environment, the script accounted for yaw flips at a solar beta angle of zero, distinct scale factors and duty cycles for the thruster sets, and a modeled pressure blowdown over time in the propellant tank.

Figures 19, 20, and 21 show the HGT, ECC, and SMA evolution, respectively, for the full lifetime run. Note the significant dip in the average values of ECC and SMA during the solar maximum (2023-2028), as the high drag keeps GPM closer to the bottom of its control box and allows ECC to remain well-controlled. The top level result, using the Schatten atmospheric model for April 2017, was that the end of mission life would occur in mid-2033.

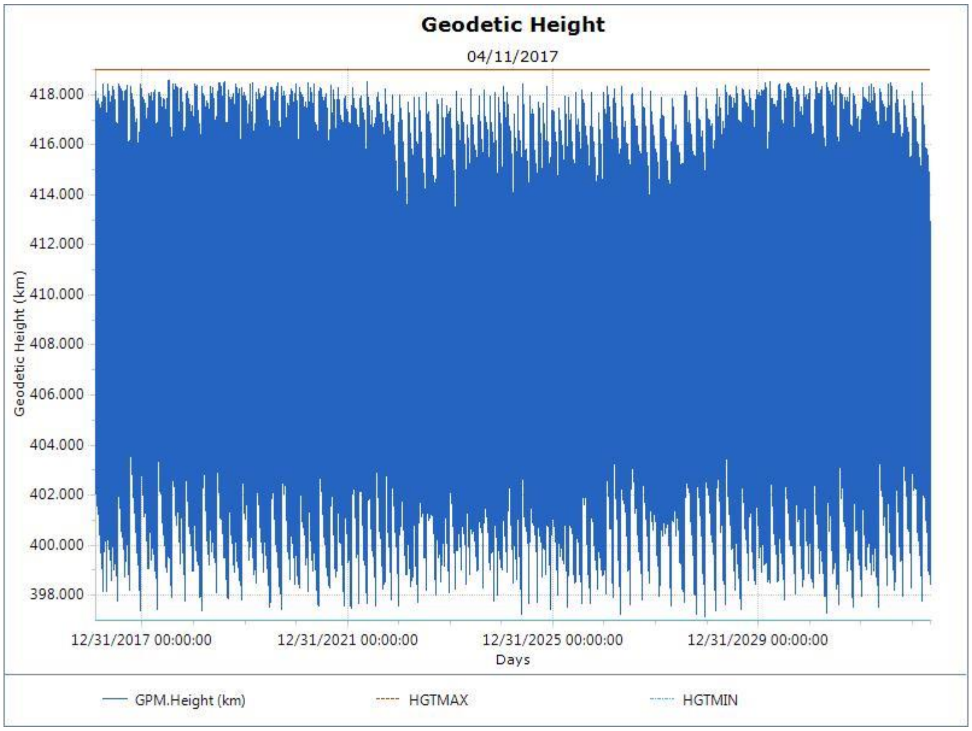

Fig. 19 Lifetime HGT Evolution Allowing for Retro Maneuvers.

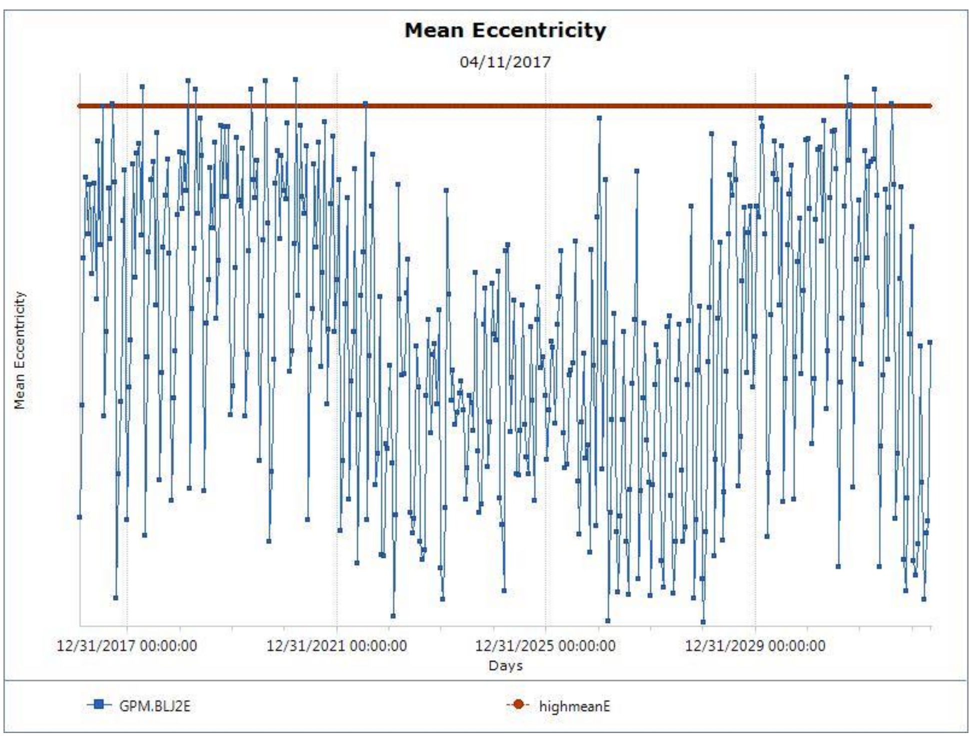

Fig. 20 Lifetime ECC Evolution Allowing for Retro Maneuvers.

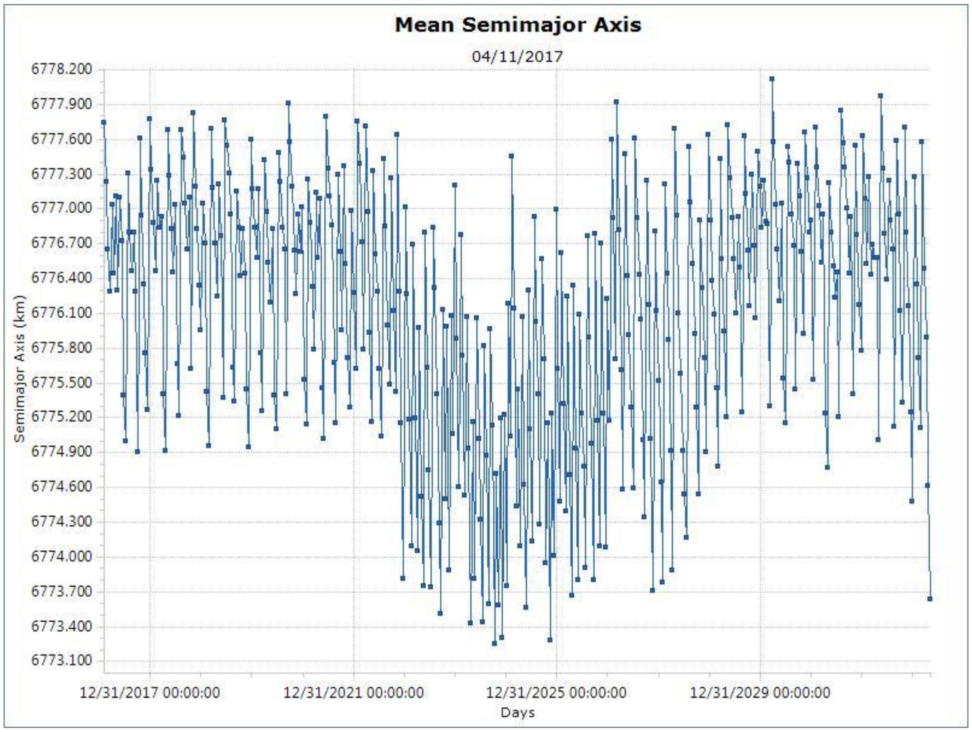

Fig. 21 Lifetime SMA Evolution Allowing for Retro Maneuvers.

These results indicated that the updated lifetime fuel usage, allowing for retrograde maneuvers to control eccentricity growth during periods of low drag, would not significantly impact the expected date at which the project would need to begin decommissioning activities.

This conclusion may seem non-intuitive, but there are multiple factors to consider. First, the original lifetime estimate was the result of a much more simplified analysis, and thus any comparisons with the results of this model may require qualification. Second, the period of relatively high drag (2023-2028) dominates fuel consumption over the remaining spacecraft lifetime; see Figure 22 for a lifetime prediction of the atmospheric density. All of the maneuvers during this period are posigrade, and with durations at or near the 90-second operational limit. Per the Mean-Nominal Schatten predictions, this timeframe will account for over 60% of the remaining fuel usage. Conversely, the low-drag periods in which retrograde maneuvers come into play account for much less than 40% of the remaining fuel usage. Thus, they have an accordingly lower impact on the bottom-line fuel usage. Third, the pre-launch analysis predicted one (orbit-raising) maneuver every eight weeks during periods of very low solar activity. The operational reality now generally consists of a relatively small retrograde maneuver, followed three weeks later by a posigrade maneuver, and then a six to seven week gap until the next retrograde maneuver. It may be that the difference between these two scenarios is actually not all that large in terms of fuel usage.

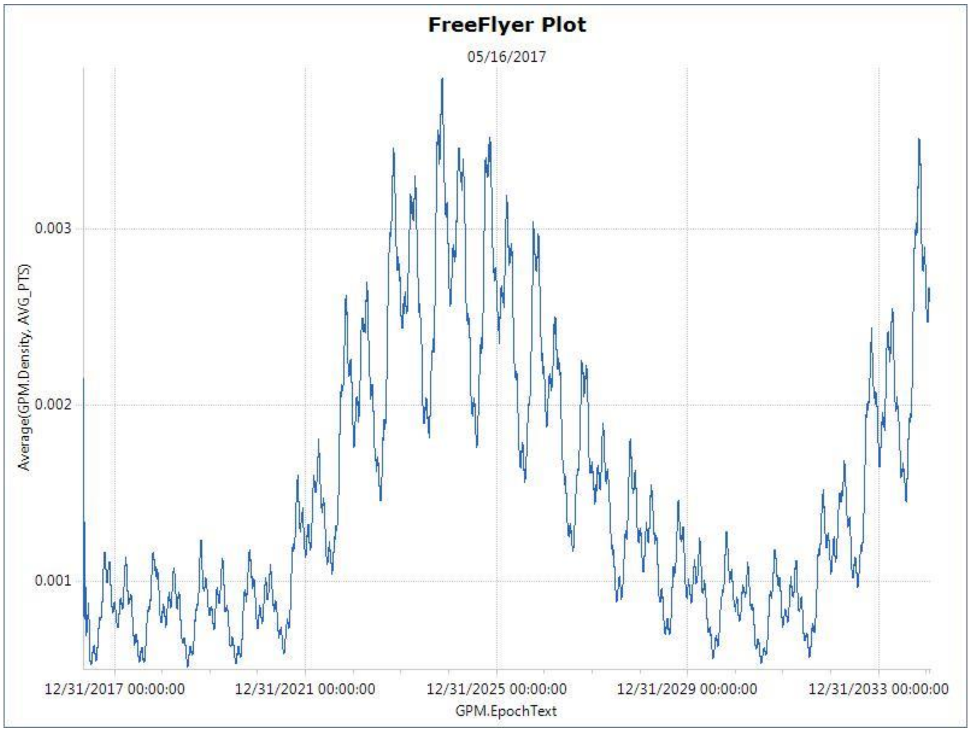

Fig. 22 Lifetime Prediction of Atmospheric Density.

Based on the lifetime analysis results, it was determined that the importance of maintaining orbital requirements throughout the solar minimum, as well as reducing mechanical cycles on the solar array hardware, clearly outweighed the apparent limited impact on the life of the mission. As a result, the use of retrograde maneuvers to control eccentricity growth during the solar minimum was accepted and implemented for operational use.

Before implementation, a modification was made to the algorithm to simply allow for a fixed retrograde duration. The reason for this was that only one prior retrograde maneuver had ever been executed, and the FOT was more comfortable starting out with a consistent duration. A value of 25 seconds was chosen, as near-term projections showed that it resulted in slightly lower fuel usage over time than the other analyzed options (15 and 20 seconds), and was sufficiently large to provide a three-week gap until the follow-up posigrade maneuver. This gap size is desirable, as it avoids the scenario of routinely tracking two maneuvers within the span of the daily predicted ephemeris generated by the FDS engineers. That said, longer-range analysis has shown there are periods of very low drag (2019-2020) where even the 25-second duration does not achieve the desired gap after the burn, and so the FOT may either accept a two-week gap in those cases, or implement a temporary hike of a second or more in the fixed duration.

Later analyses to determine if there was a more optimal retrograde burn duration demonstrated that the GPM fuel usage was remarkably insensitive to retrograde sizing, as long as it fell within reasonable limits (i.e. between 21 and 35 seconds). This implied a balancing act of sorts between the retrograde burn and its follow-up posigrade maneuver. Even the prior approach of variable retrograde duration (i.e. to achieve a reduction in HGT), in which the burn is effectively sized by the immediate drag environment, did not yield a statistically significant improvement in fuel performance. Given these results, there was not a compelling reason to modify the existing operational approach.

VIII. Conclusion

The operational use of retrograde maneuvers (instead of just for RMM activities or decommissioning) to control eccentricity growth in a low-drag environment was unforeseen, but turned out to be an effective solution to an otherwise intractable problem. The approach allowed for consistently reliable maneuver targeting throughout solar minimum without a significant impact to mission lifetime. Further, fuel usage during periods of routine retrograde maneuver operations was notably insensitive to retrograde sizing, assuming reasonable limits. To this date, the approach has been extremely successful in maintaining GPM's orbit requirements with no violations. Thus, it is recommended that other spacecraft in GPM's orbital regime, and with a retrograde capability, consider this approach to manage eccentricity growth during periods of low solar activity.