

Precise Orbit Control for the RADARSAT Constellation Mission

Chris Patterson^{a*}, Matthew Bourassa^b, Greg Hammel^c, Michal Jagodzinski^d, Oana Nica^e, Casey Lambert^f

^a MDA Space, chris.patterson@mda.space

^b Calian Ltd., matthew.bourassa@calian.com

^c Calian Ltd., gregory.hammel@calian.com

^d Calian Ltd., michal.jagodzinski@calian.com

^e MDA Space., oana.nica@mda.space

^f MDA Space., casey.lambert@mda.space

* Corresponding Author

Abstract

The RADARSAT Constellation Mission (RCM) is an Earth Observation constellation of three (low Earth orbit) LEO satellites with Synthetic Aperture RADAR (SAR) payloads, launched by the Canadian Space Agency in June of 2019. Building on the strong heritage of Canadian SAR missions including RADARSAT and RADARSAT-2, RCM was designed with much stricter orbit control requirements than its predecessors. This calls for all three spacecraft to follow a tight circular orbital tube with a radius of 120 m and a repeat cycle of 12 days. This ensures that any region on the Earth's surface that is observed by the SAR payload, will have another SAR payload passing within 120 m every four days, which can be used to produce reliable Coherent Change Detection (CCD) products. To achieve the mission requirements, a reference orbital tube was derived based on a frozen sun-synchronous orbit with an altitude just under 600 km.

The performance of the orbit control strategy has been excellent during for the first five years of mission operations, and an analysis of the results will be presented. As the drag environment evolved from a solar minimum at launch to a near solar maximum five years later, the automated orbit control strategy performed remarkably well with the number of manoeuvres increased from one or two per week per spacecraft, to almost one per day. The percentage of time spent each month within the 120 m orbital tube was above 96% for the first few years of the mission but decreased as solar activity increased.

With the higher solar activity in 2023 and 2024, new challenges have arisen for orbit control. One challenge is responding to unpredicted drag increases as a result of large solar storms. The effects of such a storm with regards to precision orbit control will be presented.

Keywords: Orbit Control, constellation, RADARSAT

Acronyms/Abbreviations

CCD – Coherent Change Detection

CME – Coronal Mass Ejection

CSA – Canadian Space Agency

FD – Flight Dynamics

GT – Groundtrack

LEO – Low Earth Orbit

LTAN – Local Time of Ascending Node

RCM – RADARSAT Constellation Mission

SAR – Synthetic Aperture RADAR

1. Introduction

The RADARSAT Constellation Mission (RCM) is an Earth Observation constellation of three LEO satellites with Synthetic Aperture RADAR (SAR) payloads, launched by the Canadian Space Agency in June of 2019. Building on the strong heritage of Canadian SAR missions including RADARSAT and RADARSAT-2, RCM was designed with much stricter orbit control requirements than its predecessors. This calls for all three spacecraft to follow an orbital tube, fixed in the Earth-Fixed frame, with a circular cross-section with a radius of 120 m and a repeat cycle of 12 days. This ensures that any region on the Earth's surface that is observed by the SAR payload, will have another SAR payload passing within 120 m every four days, which can be used to produce reliable Coherent Change Detection

(CCD) products. To achieve the mission requirements, a reference orbital tube was derived based on a frozen sun-synchronous orbit with an altitude just under 600 km. To achieve this level of precise orbital tube flying, active control in both in-plane and out-of-plane directions are required.

A summary of RCM’s orbit is provided in Table 1.

Table 1. RCM Orbit and Constellation Parameters

Constellation Geometry	
Number of Orbit Planes	1
Satellite Separation	120°
Orbit Geometry	
Groundtrack Repeat Cycle	12 days
Nominal Altitude	593 km
Orbit Type	Sun Synchronous, Frozen
LTAN	18:00
Orbit Parameters	
Orbital Period	5785 sec
Inclination	97.74°
Semi-Major Axis	6965 km
Eccentricity	0.00106
Argument of Perigee	90°

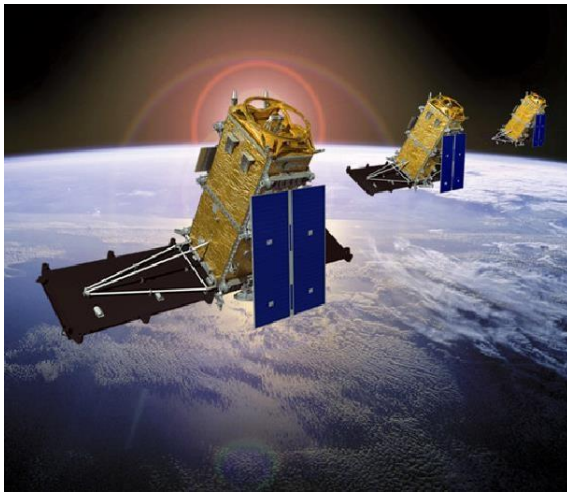


Figure 1. RCM constellation; shown in configuration prior to orbit acquisition with 120 degrees spacing. The figure on the right was taken from orbit with NEOSat. NEOSat imagery © Government of Canada (2019)

Orbit control requirements for SAR missions have become more precise in the decades since the original RADARSAT-1 mission, which maintained the groundtrack at the Equator to within 5 km of the reference orbit. This was later reduced to 2 km. For RADARSAT-2, the equatorial groundtrack error was reduced to 150 m. TerraSAR-X adapted an orbit control strategy based on staying within an orbital tube with a 250 m radius [1]. Sentinel-1A was launched with an ambitious target of maintaining the orbit within a 50 m radius tube [2], but during operations the tube requirement was relaxed to a dead-band of +/- 120 m [3]. Starting in 2014, ALOS-2 controlled its orbit to within 500 m with an autonomous on-board navigation system [4].

2. Orbit Control Method

An automated orbit control method has been developed that maintains the RCM spacecraft near the reference orbit. The automated orbit control process has been used since the beginning of the mission, however, in the early phases, each manoeuvre was first inspected by a flight dynamics analyst on the ground before planned on the spacecraft. This manual inspection process continued for over a year into the mission before enough confidence was gained and unsupervised automation was adopted in 2021.

Each spacecraft is controlled independently, and each is controlled to the same limits around the same reference orbit. Each is in the same orbit plane. The three spacecraft maintain the same separation from one another in that plane throughout the mission.

2.1 The Reference Orbit

The reference orbit itself is defined by the generation of an ephemeris propagated with forces that include a high order gravity model and lunisolar gravity perturbations. The reference orbit was optimized such that it exactly repeats on itself in an Earth Fixed frame every 12 days. No non-conservative perturbations (drag, SRP) could be included in the generation of the reference. In determining whether the spacecraft are still in the tube around the reference, the nearest point in the reference orbit ephemeris to the spacecraft location is found and then compared for radial and cross-track errors, relative mean orbital elements, and relative groundtrack errors.

2.2 Spacecraft Attitudes

To perform SAR imaging, the spacecraft must keep the payload antenna directed towards the ground with prescribed roll, pitch, and yaw angles. Disruptions of this imaging attitude are detrimental to mission performance. So the spacecraft propulsion system is designed to perform most of its manoeuvres, specifically the GT manoeuvres, in this SAR imaging attitude. GT manoeuvres generally provide most thrust in the along-track direction and thus raise the semi-major axis but they also have off-axis components to their thrust which must be accounted for the orbit control algorithms.

2.3 Automated Manoeuvre Planning

Once per day, the Flight Dynamics (FD) system in the RCM Ground Segment performs orbit determination (OD) and prediction for each RCM spacecraft. An automated manoeuvre planning process examines the prediction for the following day and determines if there is any violation of limits of groundtrack or inclination in the orbit prediction during the time window roughly 12 to 36 hours after the OD.

The system uses space weather data predicted into the future in determining atmospheric drag estimations. Therefore, accuracy of predicted space weather is a significant factor in manoeuvre planning. The impact of the manoeuvre is expected to improve orbit performance for several days into the future. It is not uncommon for significant errors in space weather predictions, as well as likely imperfections in drag modelling, to cause significant variations between the predicted burn outcome at time of manoeuvre planning and the actual orbit.

2.3.1 Automated Groundtrack Control

Automated groundtrack control focuses on maintaining the groundtrack at the ascending node only. Drag lowers semi major axis and causes groundtrack to drift West. GT manoeuvres are planned automatically to raise the semi-major axis and cause the groundtrack at the node to drift East.

Figure 2 shows the groundtrack at the ascending node and the semi-major axis in the presence of GT manoeuvres.

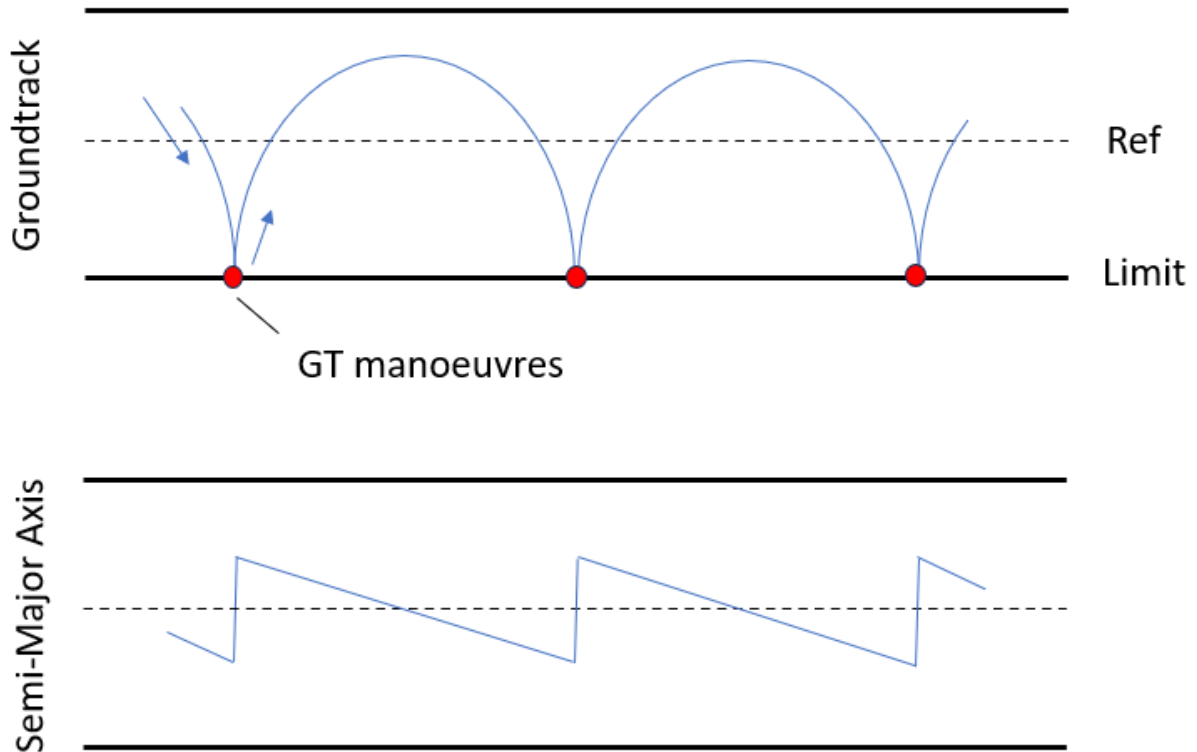


Figure 2 Groundtrack and Semi-Major Axis during GT Manoeuvres

2.3.2 Automated Inclination Control

Inclination is controlled such that the mean inclination relative to the mean reference inclination remains within an upper and lower bound. Dedicated inclination manoeuvres are planned whenever the FD system determines that the relative mean inclination will cross one of the bounds.

The inclination manoeuvres are expensive in terms of fuel because such manoeuvres tend to be large, but also require long outage times since they require the spacecraft to slew to align thrusters with the orbit normal direction. The goal for inclination control strategy then is to perform these manoeuvres as seldom as possible.

Figure 3, which is representative only and not based on flight data, shows relative mean inclination (that is mean inclination relative to the reference) changing with time. This is in the propagated orbit prediction, up to 14 days into the future. The dominant perturbing forces driving this inclination variation are the third-body gravity perturbations caused by the Moon and Sun. The variation itself is roughly sinusoidal in the medium term with a period of 14 days, a period influenced by the Moon, and other larger-amplitude and longer term effects influenced by the Sun.

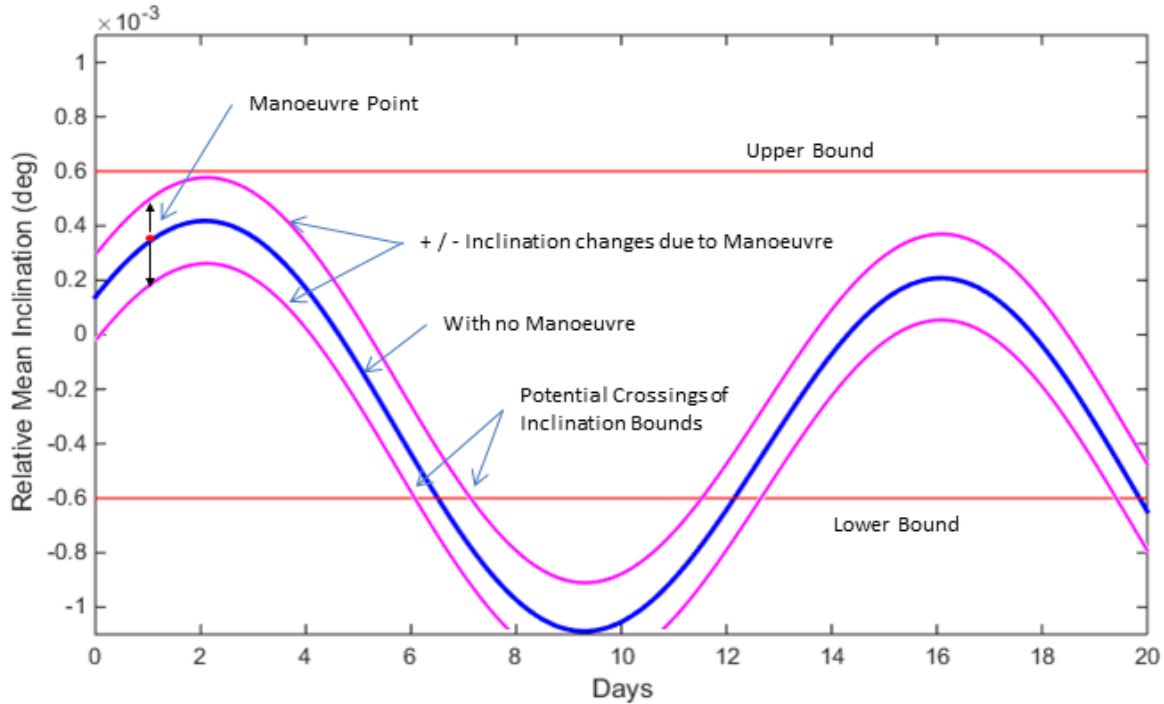


Figure 3: Relative Mean Inclination Variations with Effects of Manoeuvres

A positive or negative change in inclination has the effect of shifting the medium term (~14 day) trend up or down without changing the shape of the curve. This is because, after the manoeuvre, the largest effects on inclination perturbations are still the third-body effects, and the manoeuvre itself is not large enough to significantly alter how those perturbations effect the orbit. In the figure, the relative mean inclination is shown alongside two alternative curves that represent the effects of the potential cross-track components of a GT manoeuvre. GT manoeuvres are configured such that their impact on inclination maximizes the amount of time that passes before the next time that relative mean inclination crosses a boundary.

When inclination manoeuvres are necessary, they are selected to make the appropriate change to the curve so that the maximum amount of time passes before the next time that relative mean inclination crosses a boundary.

2.3.3 Frozen Orbit Control

To fully maintain the orbit within the reference tube the radial error must also be considered. Part of that radial error is generated by semi-major axis errors relative to the reference, which is controlled by GT manoeuvres already that are repeatedly making up for the effect of drag lowering the semi-major axis. Another part of the radial error is generated by errors in the eccentricity and argument of periapse, the frozen orbit parameters.

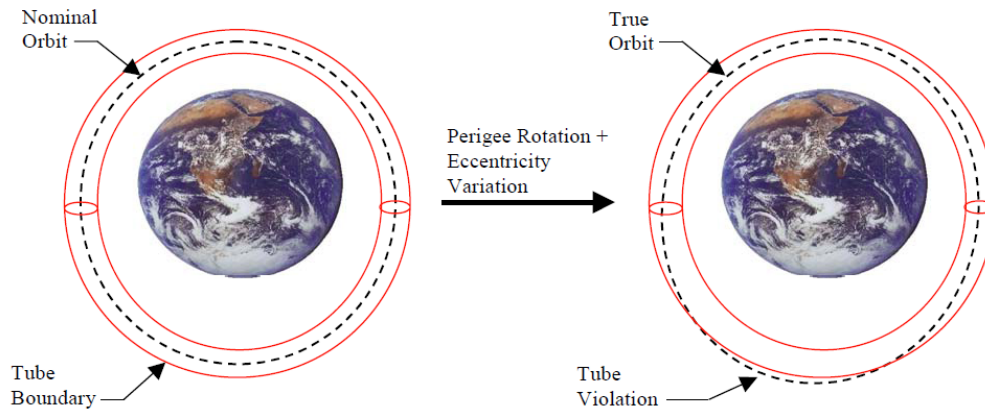


Figure 4 Effect of Eccentricity and Argument of Periapse Errors

Orbit control here relies on the fact that the reference orbit itself is a frozen orbit, so natural variations in eccentricity and argument of periapse generally remain small. Further control is still provided by the placement of the GT manoeuvres in orbit. Since the thrust is mostly along-track, they can provide some improvement in eccentricity and argument of periapse, though this is limited and the size of the GT manoeuvres is always set to meet groundtrack control needs first.

2.4. Automation Parameters in Practice

At the start of the mission, in June 2019, the orbit tube was intended to be 100 m radius. In 2020, the radius was increased to 120 m as an evaluation of the imaging products was made and the mission determined a slightly larger tube would still accomplish the required imaging goals.

As the solar activity increased from solar min in 2019 towards solar max in 2025, the groundtrack control became generally less accurate as will be discussed below. Control parameters were adjusted to mitigate the difficulty in predicting groundtrack performance. Groundtrack and inclination limits have been adjusted several times, generally tightening the band in which groundtrack is allowed to drift in the predicted orbits as solar activity increases.

3. Performance and Impacts of Solar Cycle

3.1 Analysis of Lifetime Performance

RCM was launched in June 2019, a few months before solar cycle 25 began in December 2019 [6]. As the cycle progressed towards solar maximum, significant effects on the overall orbit control performance of RCM began to occur due to increased solar activity. Figure 5 below shows the daily solar flux measurements over the mission duration.

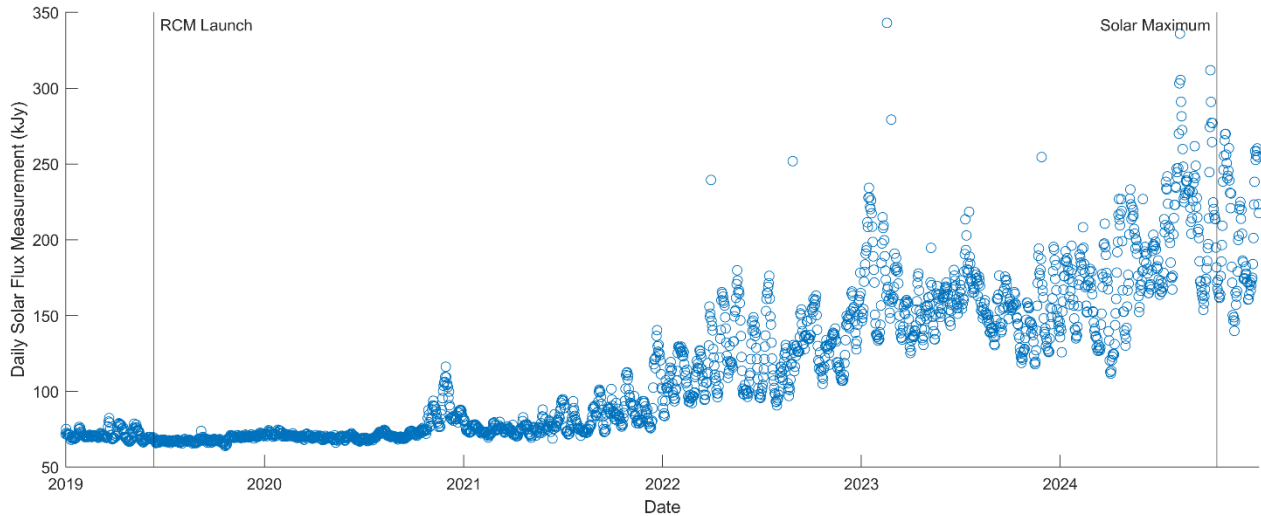


Figure 5: Mean Weekly Solar Flux over RCM Mission Duration

Due to increased atmospheric drag resulting from high solar activity, the number and magnitude of routine orbit control manoeuvres increased. Figure 6 shows the average weekly Δv of groundtrack and inclination control manoeuvres over the course of the mission.

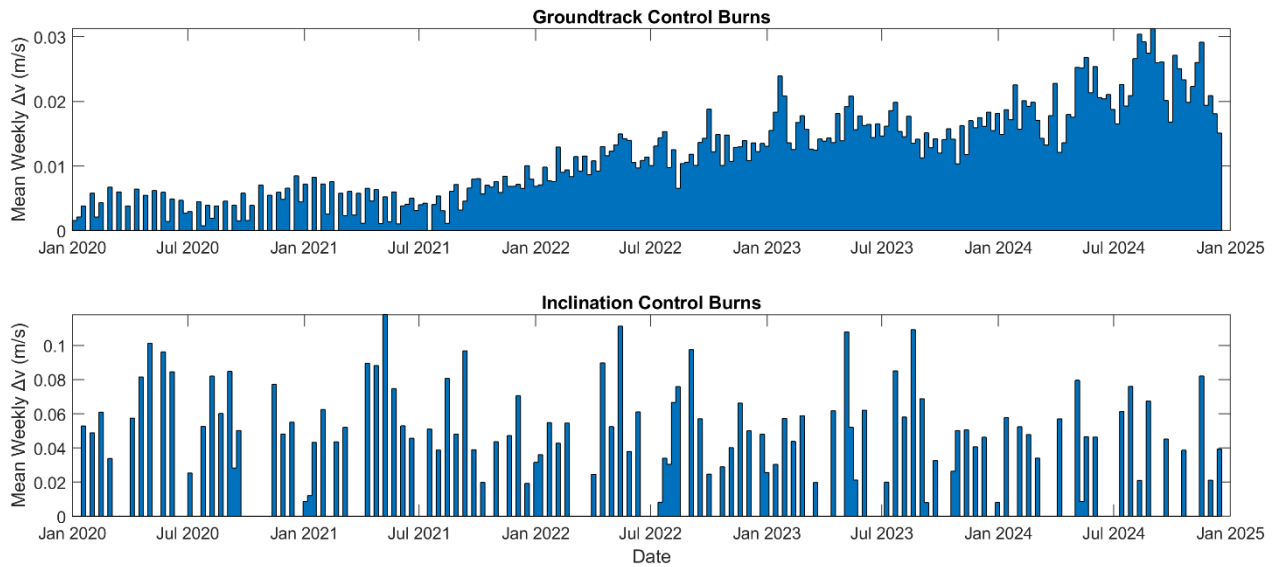


Figure 6: Mean Weekly Δv of Groundtrack and Inclination Control Manoeuvres over Time

As can be seen, the average size of groundtrack control manoeuvres has increased steadily as solar activity increased. For inclination control manoeuvres however, the required average Δv did not change much over the course of the mission. In Figure 7, there is a clear linear correlation between weekly groundtrack control manoeuvre magnitude and weekly mean solar flux. For inclination control manoeuvres, there is no easily identifiable correlation.

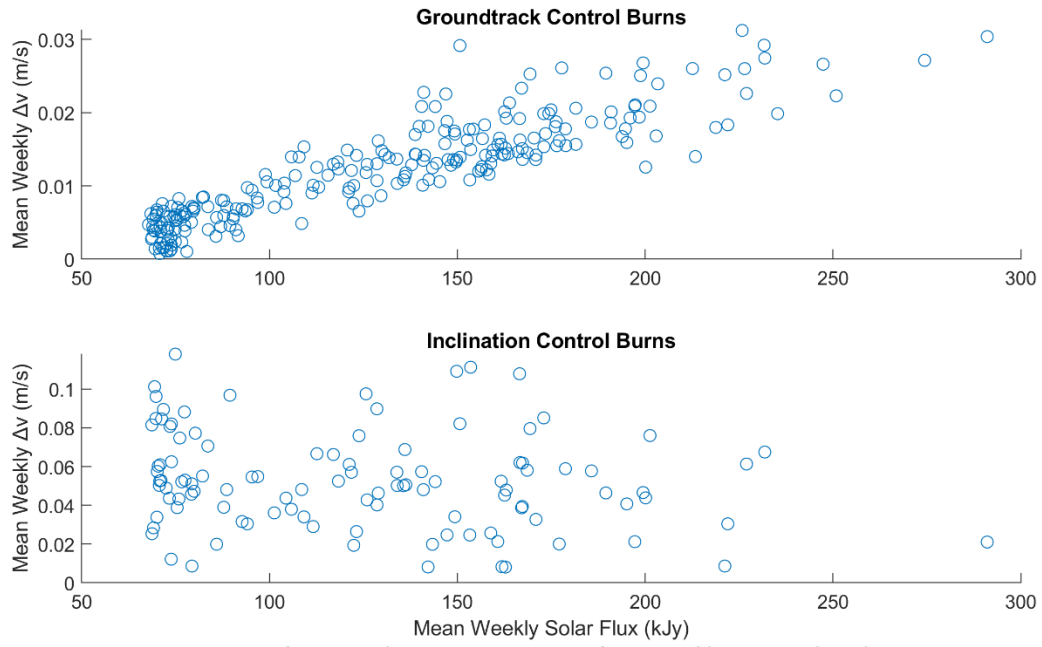


Figure 7: Orbit Control Manoeuvre Magnitude vs. Weekly Mean Solar Flux

Table 2 below summarizes the overall increase in manoeuvre size from the beginning of the mission at the start of the solar cycle, and in the 2024-2025 period, which saw the highest solar activity and the start of solar maximum:

Table 2: Comparison of Groundtrack and Inclination Control Manoeuvre Magnitude from Start of Mission and Solar Maximum

Metric	Start of Mission (2020-2021)	Solar Maximum (2024-2025)	Percent Increase from Start of Mission to Solar Maximum
Mean Groundtrack Control Manoeuvre Δv (m/s)	0.005007	0.02038	307%
Mean Inclination Control Manoeuvre Δv (m/s)	0.06125	0.05266	-14%

While the size of groundtrack control manoeuvres increased significantly, the size of inclination control manoeuvres decreased slightly. Since groundtrack burns do provide some inclination control, this decrease in the required amount of purely inclination control is most likely due to the overall increase in amount of groundtrack control required.

An important metric used to evaluate the overall performance of the orbit control system is the amount of time an RCM spacecraft spent outside of its tube over a period of interest. Just like the average Δv required per week, the average time of the RCM spacecraft outside of the tube per week also increased with increased solar activity.

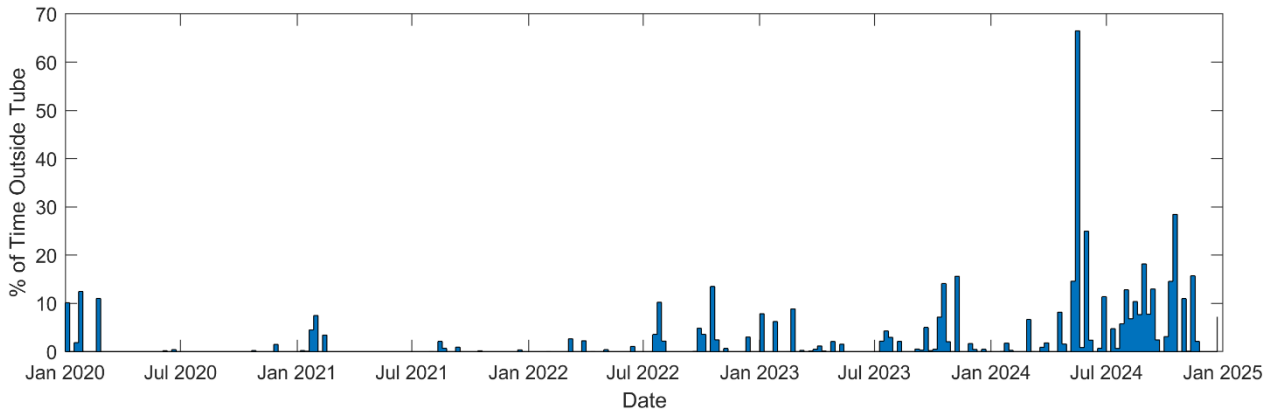


Figure 8: Mean Weekly Percent out of Tube over RCM Mission Duration

As the mission progressed into solar maximum, the average amount of time the RCM spacecraft spent outside the tube increased and the exits became more frequent. The largest spike in the figure above, where the RCM spacecraft spent almost 70% of the week outside of their tubes, was due to the significant May 2024 geomagnetic storm.

Table 3 below summarizes the number of weeks and the average percent of time outside of the tube for each year between 2020 and 2025.

Table 3: Yearly Overview of Tube Exits

Year	Weeks with Tube Exits*	Weekly Mean Percent Time out of Tube (%)
2020	9	8.74
2021	12	4.04
2022	19	4.23
2023	31	4.60
2024	37	10.40

*Denotes the number of weeks in the year with at least one RCM spacecraft outside of its tube

As can be seen, as the mission progressed, both the number of weeks with tube exits and the size of the tube exits increased. During the first year of the mission, the orbit control algorithm was not tuned properly at this stage, which

resulted in the 8.74% mean percent out of tube. The following three years all had around 4%, as the orbit control algorithm was optimized, and performed consistently. While the size of tube exits remained steady, the number of tube exits did increase year after year. The period from 2024 to 2025 showed a dramatic increase in the average weekly time out of tube, not seen since the start of the mission.

Histograms that show the counts of weeks with tube exits against the percentage of time spent out of tube on those weeks from 2020 to 2024 can be seen in Figure 9. The distribution of these tube exits between 2024 and 2025 can be seen in Figure 10. Note that the histograms sum up the tube exits of all three RCM satellites for the year, meaning the total count of weeks with tube exits can be greater than 52 in a year.

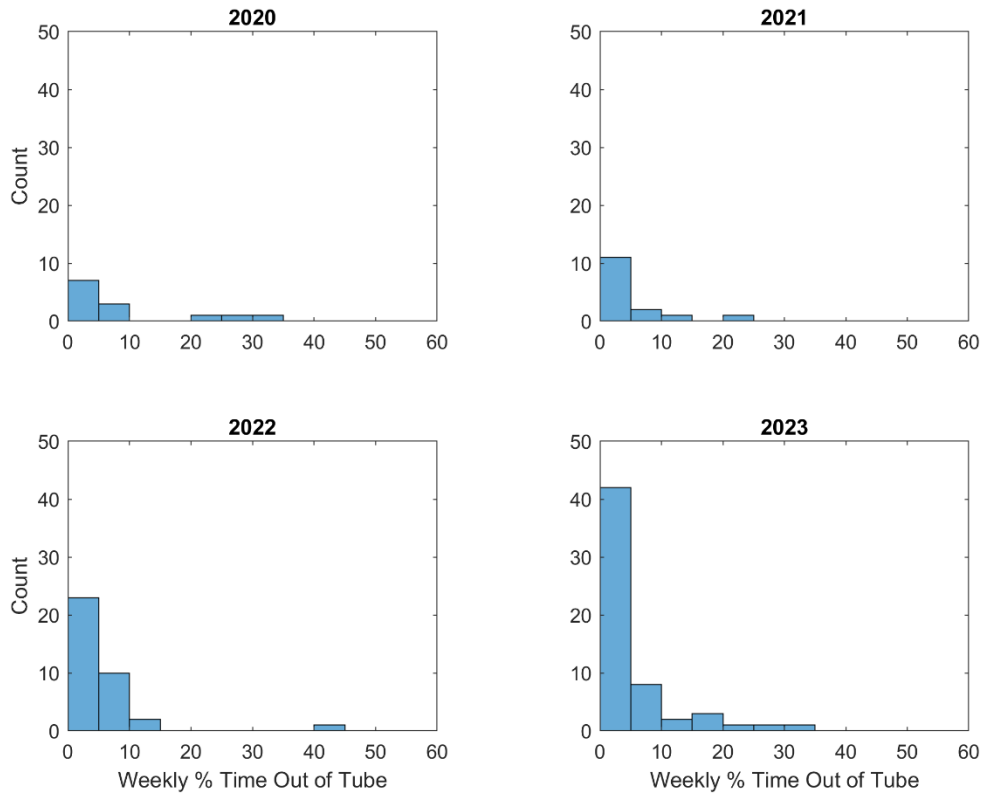


Figure 9: Distributions of Weekly Tube Exits From 2020 to 2024

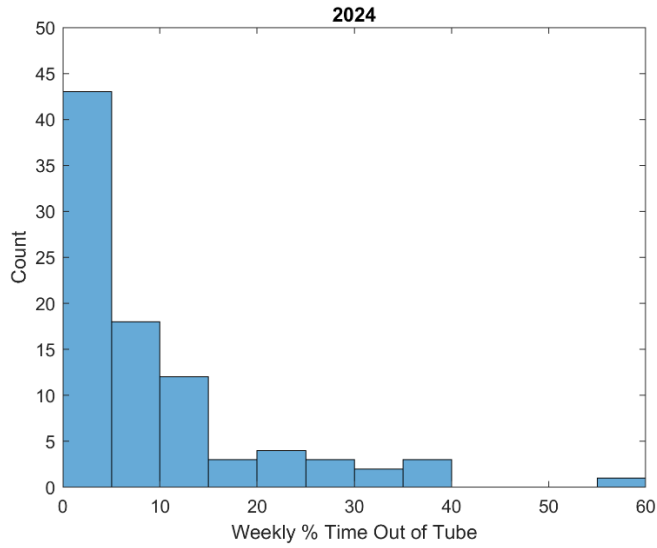


Figure 10: Distribution of Weekly Tube Exits between 2024 and 2025

The increase in the size and number of tube exits cannot solely be attributed to an increased magnitude in solar activity. Solar maximum also brings increased variability in activity as well, making predictions less accurate. This increase in variability in solar activity will be described in detail in the next section.

3.2 Impacts of Solar Maximum

One notable challenge has been the onset of Solar Cycle 25. As of the writing of this paper, it is outpacing pre-solar maximum predictions by nearly 50% and is stronger than Solar Cycle 24 by the same margin.

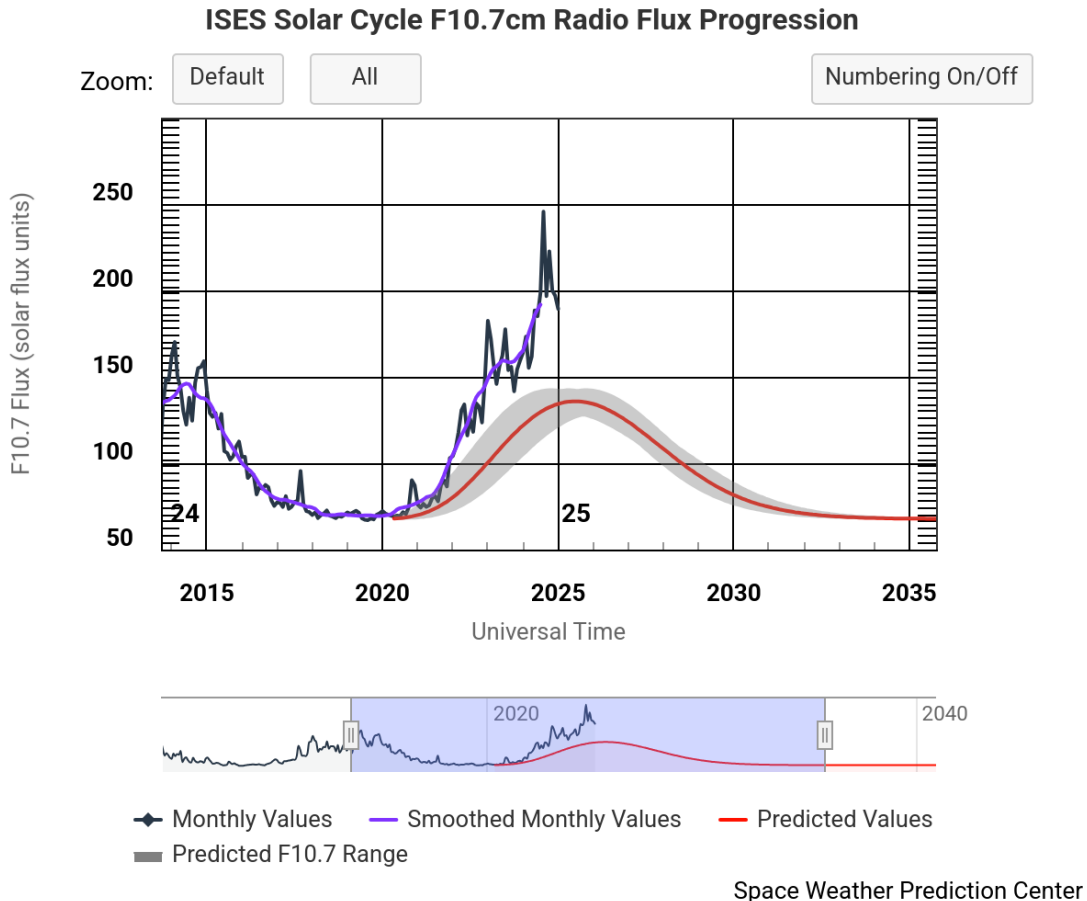


Figure 11: Solar Cycle 25 Predicted vs. Observed F10.7 Flux [7].

Not only is the increased activity a challenge to satellite operations, but the increased uncertainty in the near-term predictions is also an issue. In truth, if predictions were accurate, then increases in solar and geophysical activity would not significantly contribute to uncertainty in orbit predictions (aside from mismodelling) as the fluctuations in solar activity would be known ahead of time. However, what is more difficult to account for is the fact that changes can occur quickly and without advanced warning, causing predictions of atmospheric density (and therefore drag force) to be inaccurate at the time of manoeuvre planning.

These inaccurate predictions can occur as either over-estimations or under-estimations in solar activity (which also impact geomagnetic activity). Over-estimations often will result in manoeuvres planned too large, as the increased size is expected to counteract the expected increased drag. Under-estimations are also an issue as manoeuvres are not planned to be large enough, when the solar activity and/or geophysical activity increases without warning.

Solar and geophysical activity are linked by the Earth-Sun connection of the solar wind. Increased solar activity injects more energy into the atmosphere due to the increase in solar electromagnetic output, as measured by the 10.7 cm radio flux output of Sun.

Additionally, and often more difficult to predict, are the impacts on Earth's geomagnetic field. Often a coronal mass ejection (CME) can result from a solar flare. This material is ejected from the Sun and sent hurtling through space sometimes in the Earth's direction. When the constituent particles (electrons, protons and alpha particles) interact with the Earth's magnetic field, there is a transfer of energy which can result in increased geomagnetic activity (as measured by the planetary A_p or K_p indices) that then results in increased precipitation of these charged particles trapped in the geomagnetic field to enter to deeper levels of the Earth's atmosphere. The increased particle inflow and geomagnetic activity causes increased heating in the atmosphere raising densities at satellite altitudes. While the existence of a CME is generally observed 2-4 days prior to its impact on the Earth, the extent of that interaction, or even if the CME hits the Earth at all, are sometimes only known if and when the CME impacts the Earth.

To understand the impact of poorly predicted solar activity, one must remember that for East-West tube maintenance the most important perturbation on the satellite is that of the drag force. Accurate predictions of solar flux and geomagnetic activity are critical to achieving the desired result when planning a groundtrack manoeuvre.

The case of under-predicted drag, that is when the actual solar or geomagnetic activity is higher than expected, will cause the satellite to drop more quickly, resulting in the satellite exiting the eastern edge of the tube sooner than was predicted. For a mission with a relaxed groundtrack restriction or at a higher altitude where drag is not as significant, this can be a minor issue at best. If a mission needs to execute a drag make-up manoeuvre once every week, say, in order to maintain its groundtrack control grid, then executing a manoeuvre one or two days earlier than anticipated is not necessarily a significant change to operations.

However, for RCM, as manoeuvres are planned almost daily at solar maximum, having to execute a subsequent manoeuvre earlier than planned can often mean missing the opportunity to stop the eastern drift before it exits the groundtrack. There is one manoeuvre planning per day session (coordinated with the orbit determination and orbit event prediction sessions), occurring at roughly 12 UTC each morning. The execution period for any manoeuvre that is planned during that session is over a 24 hours period starting at 03 UTC the next day. These manoeuvres are always planned with the most up-to-date space weather information available at the time.

If the space weather is high, but well predicted, it is possible that a second manoeuvre will need to be planned before the end of the planning period. However, if the space weather activity ends up being high, but not well predicted, it is possible that the FD software will believe only one manoeuvre is required, when in actuality a second one would be needed. In this case, the state of the groundtrack would only be observed after the fact and while a manoeuvre would be planned as soon as is possible, it would necessarily occur while the satellite was outside the groundtrack limits. It should be noted that even in this case, the system is still predicting the groundtrack location for nearly 15 hours until the next manoeuvre execution period, which can add even more error to this projection, worsening the situation before the planned manoeuvre executes.

When a planned manoeuvre occurs as soon as the planning period allows, but after the groundtrack has exited the limit at the eastern edge, the impact on the missions is doubled in terms of time outside of the mission groundtrack limits – for every hour spent outside the groundtrack heading eastward, one hour will be spent heading westward back to the groundtrack. And because this occurs at the end of the groundtrack curve, the rate at which the satellite is moving East is the greatest of the whole period, which can result in large excursions. Depending on the size of the excursion, this could impact the mission’s ability to make reliable imaging products.

Figure 12 shows the groundtrack for the month of October 2024. Note the magenta line is the groundtrack at the ascending nodes only. The black line marks the groundtrack throughout the orbit, even away from the ascending nodes. The boundaries shown include the +/-120 m limit in a solid red line that marks the edge of the tube itself as well as the limit in a dashed red line, much smaller at +/- 30 m, that marks the desired extent of the groundtrack of the ascending node. Triangles mark the time of GT manoeuvres (red) or inclination manoeuvre (blue). Note the case from October 1st to 5th. On Oct 1st a manoeuvre was planned to correct the groundtrack while the spacecraft was already below its minimum groundtrack limit due to issues predicting atmospheric drag. The Oct 1 manoeuvre, however, was unable to reach its target groundtrack as shown since a new manoeuvre was required on Oct 2 and the groundtrack was still unable to reach its target value. This was caused by an under-prediction of atmospheric drag; the predicted solar flux and geomagnetic activity when the manoeuvre was planned was greater than what the spacecraft experienced. As a result, the manoeuvre was under-sized. This under-prediction issue persisted for multiple consecutive days until the Oct 4th manoeuvre was able to approach its target and the groundtrack error reached +15 m.

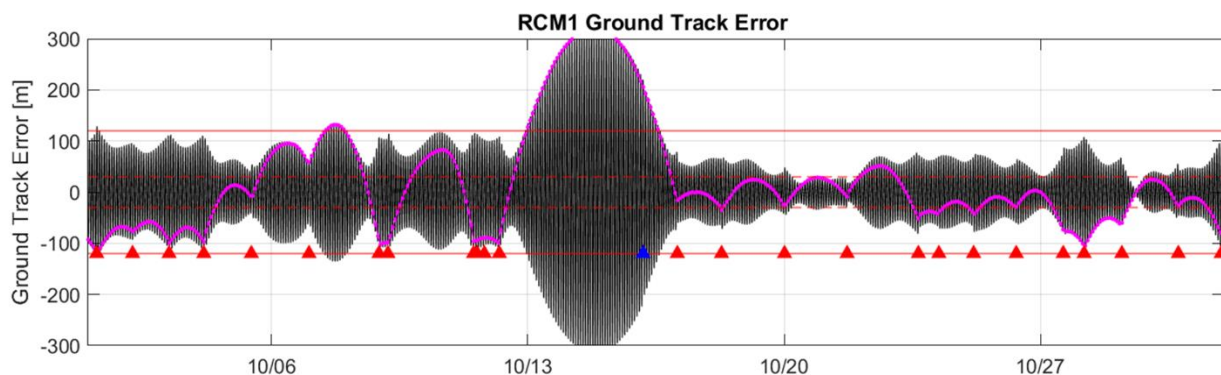


Figure 12: Monthly RCM-1 Ground Track Error Plot for October 2024.

Conversely, over-prediction of drag will result in a manoeuvre planned too large (to compensate for the anticipated increase in drag) and result in an excursion of the western edge of the tube. This in many ways is worse in terms of mission impact than the case of under-predicted drag. In the case where the resulting drag is significantly less than expected, the planned manoeuvre ends up being too large for the environment as the satellite actually experiences it.

In the case of a too large manoeuvre, the result is an excursion of the western edge of the groundtrack limits. The reason for this is due to the nature of a drag make-up manoeuvre. On average, 50% of the magnitude of a drag make-up manoeuvre is simply to arrest the eastward drift of the satellite on the groundtrack, preventing an excursion of the eastern edge. This portion raises the satellite to its nominal semi-major axis, the value used to define the groundtrack at the start of mission. The rest of the manoeuvre imparts a western drift on the groundtrack, the result of which can be approximated to a parabola, where the slope of the curve is a function of the altitude above (or below) the nominal value, and the second order derivative is proportional to the rate of decay of the semi-major axis, averaged over the period between manoeuvres.

So, estimating the drag (or more precisely the rate of decay of the semi-major axis due to drag) is critical to sizing the manoeuvre. Estimating too little decay (as in the previous case) and the parabola is too small, and the next excursion is too soon. Estimating too much decay, as in the case where drag predictions over perform the eventual situation, and the parabola is too large and there is an excursion at the western edge of the groundtrack.

The western excursion is more severe, in terms of operations, than the eastern excursion for two reasons. The first is that, as the groundtrack is approximately a parabola, significantly more time is spent outside the western edge of the groundtrack at the peak of the parabola than an eastern excursion. This means that any impact on the mission is extended while waiting for drag to bring the satellite back into the groundtrack control grid.

The other reason is that there is no non-disruptive means that can be taken to remedy the situation. With an eastern excursion, the immediate solution is to plan a drag make-up manoeuvre as quickly as possible to reverse the groundtrack drift and send the satellite back into the groundtrack control window. As mentioned above, these drag make-up manoeuvres are performed in the nominal imaging attitude and aside from the short period during which the manoeuvre executes (which is less than 100 s), there is no interruption of mission activities.

For an excursion of the western edge of the groundtrack, the only means to quickly correct the orbit (*i.e.* not waiting for drag to bring the satellite back East) is to perform a retrograde manoeuvre, which requires a slew of the spacecraft to point thrusters in the positive in-track direction. This type of manoeuvre can quickly lower the semi-major axis of the satellite, either stopping or reversing the western drift. Timing is also critical; if the manoeuvre occurs prior to the western exit, one only needs to apply enough thrust to stop the western drift, which equates with lowering the semi-major axis to the nominal value. If, however, the manoeuvre can only be executed once a significant excursion has already occurred, then it is necessary to reverse the groundtrack drift by dropping the semi-major axis below the nominal value (the larger the drop, the quicker the return) which will bring the satellite back to the nominal groundtrack more quickly. At this point (when it nears the eastern edge) a routine drag make-up manoeuvre can be performed by the automated manoeuvre planning software at the eastern edge of the groundtrack getting the satellite back into its normal cadence of manoeuvres to maintain tube flying.

Because retro-manoevres require a re-orienting of the attitude of the satellite, this activity creates an imaging outage of significant duration which would impact mission operations as the SAR is no longer pointing in the desired direction. The impact of this re-orientation means that the decision to perform a retro-manoevre is not an automatic decision. The extent of the western excursion, including the amount of time that will be spent outside the window must be considered and weighed against the imaging outage that would be created by the execution of a retro-manoevre, before one is planned. In the end, not all western excursions are deemed severe enough to warrant a retro-manoevre, as they do not go out too far. There is no hard and fast rule regarding this, and it is often decided on a case-by-case basis.

On Oct 12, a groundtrack manoeuvre was planned on RCM-1 after under-estimating the atmospheric drag on Oct 11 which resulted in the groundtrack curve not reaching its desired target (Figure 12). A geomagnetic storm was predicted to hit the Earth [8] before the manoeuvre had been planned but the effects of the storm on the atmospheric drag was over-estimated. As a result, the size of the Oct 12 manoeuvre was too large and the groundtrack overshot and reach a maximum west of over 300 m.

4. Conclusions

To achieve mission requirements, all three RCM spacecraft need to fly within a tube of circular cross-section with a radius of 120 m defined about an Earth-Fixed reference trajectory. To achieve precise tube-flying, two types of manoeuvres can be generated automatically by the Flight Dynamics system: groundtrack manoeuvres that provide

mostly along-track thrust to counteract the Eastward drift due to drag but that also provides a cross-track thrust component that can be leveraged to give some control over inclination, and dedicated inclination correction manoeuvres that require a slew and therefore increase the SAR imaging outage required. The goal for the orbit control strategy is thus to have to perform the latter as little as possible.

Flight results for more than five years of operations have been presented. As the solar cycle progressed towards solar maximum, the average size of groundtrack control manoeuvres has scaled up with solar flux, reaching an increase of 307% from start of mission as of 2025, while the size of the inclination burns has decreased slightly.

The increased solar activity has also been accompanied by an increased uncertainty in the near-term predictions. This uncertainty causes a real challenge to orbit control as it can lead to both under-predicting and over-predicting the drag, resulting in larger and more frequent tube excursions.

The automated orbit control method used by the RCM Flight Dynamics system has been proven to work remarkably well to achieve precise tube-flying at the start of the solar cycle and was able to keep the weekly mean percent time out of tube under 5% after some initial tuning. Even with the additional challenge of increased solar activity variability near solar maximum, the Flight Dynamics system continued to perform reasonably well, keeping this figure under 10%.

Acknowledgements

- RADARSAT is an official mark of the Canadian Space Agency
- <https://www.asc-csa.gc.ca/eng/satellites/radarsat/access-to-data/public-user-license-agreement.asp>
- Image of RCM taken by NEOSSat is Based on data from the NEOSSat satellite, a joint mission of the Canadian Space Agency (CSA) and Defence Research and Development Canada (DRDC), with contributions from Microsat Systems Canada Inc. (MSCI), the University of Calgary, Bishop's University, and the National Research Council of Canada (NRC).

References

- [1] Kahle, R., D'Amico, S. The TerraSAR-X Precise Orbit Control – Concept and Flight Results, International Symposium on Space Flight Dynamics (ISSFD), May 2014.
- [2] Serrano, M.A.M., Shurmer, I., Marc, X. Sentinel-1: Operational Approach to the Orbit Control Strategy, International Symposium on Space Flight Dynamics (ISSFD), May 2014.
- [3] Pinheiro, M. Increase of Sentinel-1A Orbital Tube: Impact on Interferometry, ESA Tech note, ESA-EOPG-EOPGMQ-TN-2024-12, April 8, 2024.
- [4] Arikawa, Y., Yamamoto, T., Kondoh, Y., Akiyama, K., Itoh, H., Suzuki, S. Autonomous Precision Orbit Control Considering Observation Planning: ALOS-2 Flight Results, AIAA Journal of Guidance, Control, and Dynamics, April 2016.
- [5] David A. Vallado, Fundamentals of Astrodynamics and Applications, 2nd ed., Microcosm Press, El Segundo, 2001
- [6] “Hello Solar Cycle 25.” *National Weather Service*, <https://www.weather.gov/news/201509-solar-cycle>. Accessed February 21, 2025.
- [7] “Solar Cycle Progression.” *NOAA/NSW Space Weather Prediction Center*, <https://www.swpc.noaa.gov/products/solar-cycle-progression>. Accessed March 6, 2025.
- [8] “G4 (Severe) Storm Watch for 10-11 October.” *NOAA/NSW Space Weather Prediction Center*, <https://www.swpc.noaa.gov/news/g4-severe-storm-watch-10-11-october>. Accessed March 6, 2025.