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Covariance analysis, orbit determination and other operational challenges inside the Martian sphere: the contribution of CNES FD to MMX mission

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Abstract

MMX is a sample return mission by the Japanese exploration agency (JAXA) to be launched in 2026 and aimed at exploring the Martian moons. A cooperation agreement was established between the French space agency and JAXA on MMX at the early phases of the project. This collaboration is organized around three different axes: the delivery of an infrared spectrometer (MIRS), the development and operation of a rover for Phobos surface exploration (a joint effort with the German space agency DLR) and expert support to JAXA teams on trajectory design and flight dynamics related issues inside the Martian sphere. The current paper is focused on this last item: an overview of all the activities performed by CNES Flight dynamics team in the frame of MMX mission will be presented, including the preparation of the operational work packages. Then, the details of CNES contribution in terms of covariance analysis and orbit determination will be elucidated. The main objective of our work for this project is to provide JAXA teams with expert support and cross-validation of key analyses by independent methods and tools, in order to help MMX stand up to the challenges raised in the vicinity of the Martian moons. Besides, our work is also intended at assisting other CNES teams involved in MMX when needed. This contribution helps consolidating CNES as a privileged partner for small body exploration, proximity operations and landing, following other past or on-going collaborations in projects such as Rosetta, Hayabusa-2 and Hera.

Keywords: Mars exploration, flight dynamics, covariance

Nomenclature

$\mathbf{a}$: Vectors
$\mathbf{A}$: Matrices
γ: Scalars
$\boldsymbol{A}^{\boldsymbol{T}}$: Transpose
$\boldsymbol{A}^{-\mathbf{1}}$: Inverse
$\boldsymbol{\Delta}$: Represents change or correction
$\|\cdot\|$: Norm of vector, matrices
$\mathbf{Ax}$: Matrix multiplication

Acronyms/Abbreviations

CNES	Centre National d'Etudes Spatiales (French space agency)
CoM	Center of mass
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German aerospace center)
DRO	Distant retrograde orbit
ESA	European Space Agency
FD	Flight dynamics
GiNS	Geodesy by simultaneous numerical integrations
GRGS	Space geodesy research group
GSST	Geodesy sub-science team
IMCCE	Celestial mechanics and ephemeris computation institute
JAXA	Japan exploration agency
LSS	Landing Site Selection
LSSWT	Landing Site Selection Working Team
LTE	Time-Space Laboratory
MIRS	MMX Infrared spectrometer
MMX	Martian Moons Exploration
POD	Precise orbit determination

1. Introduction

MMX, or the Martian moons exploration mission, is a chemical-propulsion sample return mission currently under development at JAXA, to be launched in 2026. MMX is expected to go to the Martian system, explore the Martian moons Phobos and Deimos, and return pristine samples from the surface of Phobos to the Earth ([1]). A collaboration between JAXA and the French space agency (CNES) was established at the early phases of this mission. The French contribution to MMX is organized around three different axes:

1. The delivery of an infrared spectrometer (MIRS).
2. The provision of the rover IDEFIX©, developed with the German space agency (DLR) and aimed at exploring the surface of Phobos.
3. Support to JAXA teams concerning trajectory design and flight dynamics related issues.

The present paper has to be read in the context of item number three of the list above. The activities of CNES-FD team in terms of trajectory and flight dynamics issues for MMX expand in time from the preliminary design phases of the project in 2017 and up to the exploitation phase more than 10 years later, especially concerning proximity operations around the Martian moon Phobos. Furthermore, in addition to the work that CNES-FD engineers perform with MMX teams at JAXA, we obviously also embrace the needs of the other French teams involved in the project (that is to say, MIRS and the Rover) whenever flight dynamics expertise is called for.

It is worth mentioning that in the last decades, CNES Flight dynamics division has become a privileged partner for space agencies when it comes to proximity operation and exploration of small bodies. For instance, CNES was involved in the preparation and execution of the landing of Philae module on the surface of the comet Churyumov-Gerasimenko in November 2014, as part of the European comet chaser mission Rosetta. Moreover, our team was also in charge of the flight dynamics operation of the Mascot lander, that the Japanese probe Hayabusa-2 released on the surface of the asteroid Ryugu on October 2018. Currently, in addition to our participation in MMX project, we are also preparing the proximity operations of the two cubesats on board of Hera, the recently launched ESA mission aimed at the binary asteroid system Didymos. In this context of small body exploration, CNES can provide its know-how, its up-to-date analysis tools and ground segment products, along with dedicated control rooms and privileged relationships with internationally recognized research groups (GRGS, LTE…).

2. Trajectory scenario design and flight dynamics contribution of CNES to MMX

MMX plans to stay in the Martian sphere for 3 years, nominally. Designing trajectories to allow for such a long observation and science campaign of planetary moons is not an easy task. In this case, the characteristics of the couple Mars-Phobos make the keplerian motion around Phobos impossible. Quasi-Satellite Orbits are a type of distant retrograde orbits (DRO) suitable for Phobos exploration, as they offer a convenient means to orbit the moon in the sense of relative motion in the three body dynamics. MMX plans to make extensive use of QSO trajectories during its several years stay in the vicinity of the moon. Despite having been frequently mentioned as potential location for Phobos exploration missions since the 1980s, these orbits have only been briefly flown in reality by *Phobos 2* Russian probe. This is why building orbital scenarios including QSOs with different characteristics and exhibiting the best trade-off in terms of scientific return, manoeuvre cost and operational risk constitutes a major challenge. See Table 1 for more details on the QSO chosen for MMX nominal mission, including high, middle and low (H, M and L respectively) altitude QSOs.

Table 1 Characteristics of the QSO trajectories around Phobos for MMX mission ([2])

Orbit	Distance from Phobos CoM [min, max] (km)	Period (h) Phobos fixed	Period (days) Inertial
QSO-H	101 x 202	7.59	32
QSO-M	50 x 96	7.13	4.3
QSO-LA	33 x 56	6.15	1.3
QSO-LC	20 x 27	3.97	0.38

CNES-FD team was initially invited to participate in MMX preliminary phases with the purpose of helping perform the best choice of QSO trajectories, in addition to tackling the mission analysis and operational problems deriving from their trajectory design (transfers, station-keeping, eclipse avoidance, descent to Phobos…). However, our contribution became subsequently wider, both in terms of tasks and in terms of duration, as explained in the following subsections.

2.1 CNES Flight dynamics team tasks during mission preparation phases

2.1.1 Orbital scenario design and crossvalidation

As already mentioned, the design of a trajectory scenario using QSO trajectories around Phobos is a major challenge, not only from a mathematical point of view, but also operationally. Trajectories have to be designed in such a way that they are as stable as possible in realistic dynamics, meaning that they are robust to existing uncertainties on the physical and dynamical environment of Phobos. The operational feasibility and cost of the mission strongly depends on this mission analysis choice.

Several reference altitudes of QSO trajectories were established, from far away distances at which the effect of Phobos gravitational pull is barely noticeable, down to only a few km from the surface of Phobos. In this way, the more knowledge about Phobos is accumulated in higher altitude trajectories, the closer and trickier trajectories can be undertaken by the spacecraft, at a reduced risk. CNES-FD contribution in this particular topic helped confirm the stability of some of the chosen QSOs and lead to a slight change in the amplitudes of one of the low-altitude trajectories, to avoid falling in the amplitude zone recognized to be the most instable, both from a theoretic and numerical perspective. Moreover, complementary analysis performed by our team in collaboration with JAXA-FD allowed for a potential inclusion of three dimensional QSO-like motions in the nominal scenario. These spatial motions can increase the scientific return by allowing for a better observation of latitudes far from the equator, but its actual use in the real operations of MMX will have to be confirmed during the in-flight phase.

The work of CNES-FD in the topic of QSO design and analysis was intense during the early phases of the project ([3], [4]) and it is still on-going. Currently, our work is oriented towards the crossvalidation of the trajectory scenarios designed by JAXA engineers, and the analysis of these scenarios to make sure they are adapted to MIRS and IDEFIX© rover needs. Even though a big part of this work is performed internally, research contracts have also been established with other research institutions on topics such as the design of 3D QSO or the station-keeping strategies.

2.1.2 Precise determination of Phobos gravity model and ephemeris

Improving the accuracy of the existing models for Phobos gravity field, as well as its shape and precise trajectory around Phobos, is one of the objectives of MMX mission. The GRGS is internationally recognized as a reference group for space geodesy studies and gravity determination of celestial bodies. JAXA was interested from the beginning in having these experts on board. The CNES geodesy engineers participate in the technical studies for evaluating MMX trajectory scenario from the gravity determination point of view ([5]), but they also belong to the GSST (Geodesy sub-science team), an international scientific group in charge of updating Phobos shape and gravity models using in-flight data from MMX.

Moreover, the former IMCCE (currently part of the French LTE) is also involved in the project through CNES-FD, with the assignment of updating the currently available ephemeris of the Martian moons by taking into account available data from recent missions (before actual MMX data is received).

2.1.3 Support for the definition and execution of the Landing site selection procedure

MMX being a sample return mission, several landings of the probe on the surface of Phobos are foreseen. IDEFIX® Rover will be deployed from a low altitude above the moon surface during the rehearsal for the first landing. Close approach, descent and landing on the moon are among the most critical operations that the spacecraft will have to undergo. Therefore, careful preparation of these activities is mandatory. One of the keys to a successful landing is a meticulous landing site selection process. This process shall put all the relevant actors into play in a highly constraint timeline, in order to choose the target landing sites presenting the most attractive scientific features, while guaranteeing a robust descent, a safe landing and a successful on-surface mission. For the particular case of MMX mission, given that the Rover and the probe must land on the same Phobos region separated only by a few tenths of meters, the LSS process becomes even more complicated.

The support of CNES teams for the definition, implementation and execution of all the LSS related activities was agreed with JAXA at the beginning of the collaboration. This is the second time that JAXA and CNES/DLR teams join forces for selecting a landing site, as the LSS of Hayabusa-2 and Mascot was executed in 2018.

2.1.4 Navigation and orbit determination around the Martian moons

Even though they have been observed by several other Martian missions, a high degree of uncertainty exists concerning the dynamical environment around the Martian moons and their precise physical characteristics. In addition to the physical unknowns, spacecraft behavior can also be a source of in-flight errors, that should be predicted in the most accurate way possible in order to guarantee that the mission objectives can be fulfilled. It is in this frame that the navigation and covariance analyses are of the utmost importance: to accurately determine the order of magnitude of the differences that can be expected between the real state of the spacecraft (position, velocity and attitude) and the state that can be computed on-ground from the telemetry readings. Despite being a classical task for orbit determination and flight dynamics teams, these estimations are particularly tricky for an interplanetary mission such as MMX, due to the novelty of the framework. Orbital and pointing errors to be expected have a strong impact on the observation plans of the payloads, as well as on the safety and optimality of the routine spacecraft activities.

Regular exchanges between JAXA and CNES orbit determination teams take place. More technical details and results on this part of the cooperation are the object of the second part of this paper, starting from §3.

2.2 Operational activities of CNES-FD team

2.2.1 Operational work packages

The aforementioned tasks of the CNES FD engineers for MMX are the object of continuous work. We hold an expert support and crosscheck role when requested by JAXA. All of these activities will continue during the in-flight phases. In particular, the operational contribution of CNES FD will be organized around the following tasks:

- Operational trajectory analysis crosscheck, for nominal scenario and also in case of contingencies. This includes the constraint check and risk assessment of trajectory scenarios, especially during critical activities (orbital transfers, first orbit acquisition for each QSO altitude, landing rehearsal and execution…). Moreover, if requested by JAXA teams, additional checks can be performed and recovery strategies can be explored by CNES teams in case of contingency.
- Crosscheck of operational orbit determination. The contribution of CNES teams to support the precise orbit reconstruction around the Martian moons involves the sharing of the necessary in-flight data, and therefore the existence of an interface control document independent from the Rover and MIRS ground segment ICDs. This exercise will be beneficial for both teams. On the one hand, for JAXA and the MMX project it will allow for an independent validation of the orbit determination under perturbed dynamics and complex operational processes. On the other hand, for CNES orbit determination experts, whose proficiency is well proven for POD of Earth orbiting missions, it will provide real data and the first hands-on experience in orbit reconstruction in an interplanetary environment.
- Preparation and execution of the landing site selection process. As already mentioned, any sample return mission is highly concerned about the safety of the landing strategy and the suitability of the chosen target site. The overall feasibility and success of the mission as well as the quality of the collected samples is strongly driven by the LSS. The probe should be operated in a safe way all along the approach and descent phase, to ensure that landing and sample collection are performed with no damage to the platform, and to preserve the reentry capacity of the return capsule. On the basis of a recent collaboration between CNES/DLR and JAXA for the LSS process of Hayabusa-2 and its lander MASCOT, a work package related to the preparation of the LSS was agreed as early as beginning of phase A of the project. Later on, collaboration between the agencies on this topic has been naturally extended up to operational preparation and execution of the LSS trainings, and the actual LSS after Martian orbit insertion. The role of CNES FD in collaboration with the Rover team is to assist JAXA LSSWT in the definition and implementation of the LSS process, as well as generating the products to support the choices and quality rankings established by the Rover team for IDEFIX landing.
- Determination of Phobos gravity field from in-flight data. This activity, of a scientific nature, will be performed by the GSST including two CNES engineers belonging to GRGS. Moreover, the use of GiNS software, developed and maintained by the Geodesy team at CNES, has been chosen to be used operationally by the GSST.

2.2.2 Contribution of Flight dynamics team to CNES ground segments of MIRS and Rover

In addition to the specific operational activities described in detail in the previous subsection, the Flight dynamics team at CNES is also invested in the implementation and validation of ground segment software. In particular, the SIRIUS FDS product line ([6]) developed by CNES has been adapted for use in the frame of interplanetary projects. SIRIUS FDS for MIRS and Rover IDEFIX© are being customized from the standard SIRIUS FDS taken from the shelf. The FDS will allow the consumption and processing of trajectory and attitude products coming from JAXA ground segment and the accurate computation of events (such as eclipses and Earth stations AOS/LOS, for instance) as requested by the instruments. This means, of course, a tight collaboration between ground segment teams, scientific teams and the flight dynamics engineers. For instance, the Flight dynamics products, to be consumed and produced, must be included in the ICDs that establish the rule for communicating between different mission and control centers. Moreover, CNES-FD team participation in the technical and operational qualification tests of the CNES ground segment components of MIRS and Rover is also expected.

3. Covariance analysis

Covariance analysis is a fundamental tool in orbit determination and navigation, particularly for missions operating in complex dynamical environments like the Martian system. The primary goal of covariance analysis is to quantify the uncertainties associated with the estimated orbital parameters and predict their evolution over time. By doing so, it provides a statistical framework for assessing the reliability of orbit solutions and planning corrective maneuvers when necessary.

For the MMX mission, covariance analysis serves several critical purposes:

- Uncertainty Quantification: It enables mission analysts to characterize the expected errors in position and velocity, helping to identify potential navigation risks.
- Mission Planning: By propagating covariance over time, it becomes possible to predict the degradation of orbit knowledge and optimize tracking schedules.
- Operational Decision-Making: Covariance results guide maneuver planning, ensuring that corrective actions are taken before uncertainties exceed acceptable limits.
- Cross-Validation of Orbit Solutions: Since CNES contributes to the MMX navigation strategy alongside JAXA, covariance analysis serves as a means of independent verification, ensuring consistency between different orbit determination methods.

Covariance analysis is particularly important for MMX due to the unique challenges posed by Phobos' weak and irregular gravitational field. Small perturbations can lead to significant deviations over time, making it essential to anticipate uncertainty growth and implement robust navigation strategies. By leveraging covariance-based techniques, CNES supports JAXA in refining orbit determination approaches, enhancing the mission's overall robustness and reliability.

The covariance analysis software used in this study was created by the CNES orbit determination team and was based on Patrius, Ficus, and Lotus libraries. A few modifications were required, such as the incorporation of new measurements functions, which will eventually be merged into the library, as Lotus and Ficus were primarily created

Developed in CNES, Patrius is a C-critical Java Flight Dynamics library. This extensive collection of features spans several mathematical levels, from basic matrices, rotations, and integrators to comprehensive models and tools for describing the orbital environment, such as orbit extrapolation, event detection, attitude laws, and so on.

Lotus and Ficus are also C-critical Java libraries based on Patrius. Lotus that includes multiple features needed to precisely represent, model, and use measurements for satellite navigation, including:

- The measurement models

- The theoretical measurements and residuals computation,
- Partial derivative computation in relation to dynamical and measurement parameters,
- Measurement manipulation using statistical methods,
- Assessment of measurement quality,

Ficus provides several tools to develop and use filters needed for orbit determination procedures such as least squares or Kalman filters, including:

- The representation of normal equations,
- Measurements weights,
- Constraints equations,
- Least-squares orbit determination and parameters estimation

3.1 Orbit determination using least-squares

The Weighted Least-Squares Method, as written by Bryson [7], is widely used in the process of orbit determination and covariance analysis. If we write the measurement model as:

$$m = H(x) + \nu \tag{1}$$

With x, the spacecraft state, H the non-linear function and ν the measurement error, usually:

$$p(\nu) = N(0, \sigma^2) \tag{2}$$

Since a closed-form solution of the equation cannot be found, a linearization should be done assuming that an a-priori estimated state x_0 is known. Taylor expanding the equation around x_0, we can compute the measurements residuals:

$$\Delta z = m(x) - m(x^0) \tag{3}$$

which can be rewritten in a matrix form:

$$\Delta z = A(x - x_0) = A\Delta x$$

with A the normal matrix, composed of partial derivatives of the observations with respect to the state vector elements, x the actual state vector and x_0 the a-priori state vector at the beginning of the propagation.

If the number of measurements is equal to the number of states, the equation can be solved by inverting A directly. number of measurements is equal to the number of states, the equation can be solved by inverting A directly. If it is not the case, we multiply both sides by the transpose of A. In practice, the number of measurements is much higher than the size of the state vector, which means that A is not directly invertible:

$$A^{\mathrm{t}}\Delta z = A^{\mathrm{t}}A\Delta x$$

The optimal solution is given by:

$$\Delta x = (A^{\mathrm{t}}A)^{-1}A^{\mathrm{t}}\Delta z$$

This equation is called the least-square equation and must be solved iteratively to estimate the state. The measurements must be weighted for their residual to contribute to the state correction. If we define the weight matrix W containing all weights for each measurement:

$$W\Delta z = WA\Delta x$$

$$A^{t}W^{t}W\Delta z = A^{t}W^{t}WA\Delta x$$

thus:

$$\Delta x = (A^{t}W^{t}WA)^{-1}A^{t}W^{t}W\Delta z$$

To modify these equations to account for considered parameters, we need to introduce an additional term or matrix representing the considered parameters. One common approach is to introduce a stochastic model for the uncertainties.

If we note Γ, the vector of the nΓ considered parameters (non-estimated), the measurement model with consider parameters can be written as:

$$m = H(x) + \nu + G(\gamma)$$

where:
- m is the measurement vector.
- H(x) is the non-linear function of the spacecraft state x.
- ν is the measurement error, usually modelled as $p(\nu) = N(0, \sigma^2)$.
- γ is the error on the consider parameters.

Assuming an a-priori estimated state x_0 is known, we perform a Taylor expansion around x_0 to get the measurement residuals:

$$\Delta z = m(x) - m(x_0) + \nu + K\gamma$$

where:

$$K = \partial m/\partial \Gamma$$

The above equation can be rewritten in matrix form:

$$\Delta z = A(x - x_0) + \nu + K\gamma = A\Delta x + \nu + K\gamma$$

To solve for Δx considering the weights and uncertainties, we modify the normal equations. When the number of measurements is not equal to the number of states, we proceed by multiplying both sides by the transpose of A:

$$A^{t}\Delta z = A^{t}A\Delta x + A^{t}\nu + A^{t}K\gamma$$

Applying the weight matrix W:

$$W\Delta z = WA\Delta x + W\nu + WK\gamma$$

Multiplying by the transpose of W:

$$A^{t}W^{t}W\Delta z = A^{t}W^{t}WA\Delta x + A^{t}W^{t}W\nu + A^{t}W^{t}WK\gamma$$

Solving for Δx:

$$\Delta x = (A^{t}W^{t}WA)^{-1}A^{t}W^{t}W(\Delta z - \nu - K\gamma)$$

The covariance matrix of the estimation error Δx_0 can be adjusted to:

$$Px_0 = \zeta((W^tW)^{-1} + KP\gamma K^t)\zeta^t$$

These modified equations account for both the measurement weights and the uncertainties in the parameters, providing a more robust state estimation in the presence of uncertainties.

3.2 Dynamical model

In this section, the dynamical model taken into account in the covariance analysis is presented. The spacecraft's properties and the forces it will experiences, both from mars, Phobos and other environmental factors, are essential for accurately modeling its trajectory and operational behavior. The spacecraft's characteristics, including its mass, radius, and surface properties are critical in understanding its response to external forces such as Solar radiation pressure (SRP). The subsequent description of forces acting on the spacecraft includes gravitational attraction from Mars, Phobos, and the Sun, as well as additional forces such as solar radiation pressure and empirical accelerations as well as manoeuvers errors.

Spacecraft Properties:

- Mass: 2100 kg
- Radius: 26.5 m2
- Cr: 1.3

Forces Applied:

- Gravitational Attraction:
  - Mars:
    - GM: 4.282837566395650E13 m3/s2
    - Spherical harmonics 10x10
  - Phobos, treated as third body because the integration is made in Mars ICRF reference frame:
    - GM: 0.711E6 m3/s2
    - R_ref: 11.12592363 km
    - Spherical Harmonics 8 x 8

  - Sun: Third-body gravitational attraction
    - GM: 1.32712440041279419E20 m2/s3

- Solar Radiation Pressure (SRP) Reference SRP at 1AU: Solar constant = 1350 W/m2
- Empirical Forces 2.0E-11 km/s2 at 1-σ
- Thrust Errors:
  - Modelled as constant thrust errors with uncertainties in direction and magnitude
  - Uncertainties include a percentage of the manoeuver norm (4% at 1-1-σ) and depointing.

Table 2: State vector

Parameter	Status	σ
Position	Estimated	1 km
Velocity	Estimated	0.1 $m \cdot s^{-1}$
Maneuver Error	Estimated	1.67% norm, 0.67° depointing
SRP Parameter	Considered/Estimated	5%
Phobos Central Parameter	Estimated	1.3% of GM
Phobos Potential Coefficients	Considered	20%
Empirical Acceleration (RTN)	Considered	1e-10 $km \cdot s^{-2}$
Two-Ways Doppler Bias	Estimated	0.0005 * frequency / speed of light
Two-Ways Doppler Noise	Estimated	0.0005 * frequency / speed of light

4. Results

The crosscheck between CNES and JAXA on trajectory propagation shown satisfactory results for the QSO-M to QSO-LC transition arcs provided by JAXA on June 25, 2024, as shown in Figure 1. These arcs, which form an essential part of the analysis, are accompanied by an OPM file, including the orbit determination results, the associated covariance matrix, and delta-v information computed by JAXA. Additionally, JAXA supplied what they refer to as "Error Information," which was derived from their own covariance analysis framework. These datasets provide critical insight into the uncertainties and errors associated with the trajectory, which is essential for validating the propagation results.

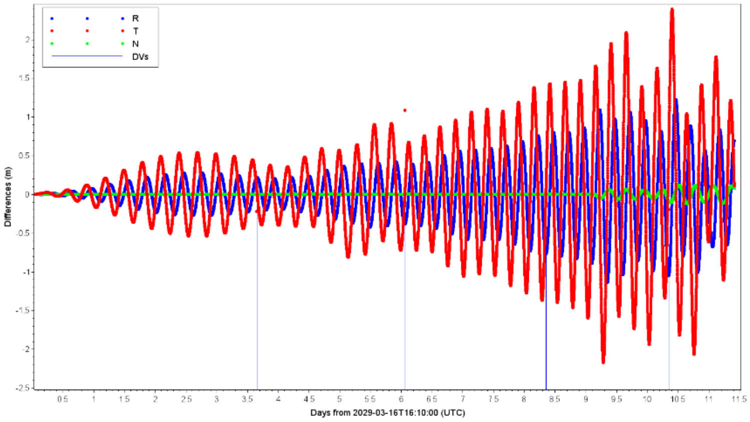

Figure 1: Trajectory comparison between JAXA and CNES

The primary objective of this analysis was to replicate the approach used by JAXA and to compare the propagated covariance for the QSO-M to QSO-LC transition arc data provided in their Excel files. By performing this comparison, we aimed to consolidate the results, ensuring consistency in the order of magnitude for both position and velocity at the conclusion of the covariance propagation.

The consideration of these intermediate transition arcs from the perspective of consider covariance analysis allows for a more thorough validation of the covariance propagation method. It provides a means to assess the accuracy of the models used in the propagation by checking if they align with the values derived from JAXA's datasets. Ultimately, this study aims at characterizing the error occurring during this transfer, ensuring that we reach the mission constraints. Some differences in the results are expected, because JAXA and CNES does not consider exactly the same dynamical model. Primarily, JAXA does not considers occultation from Mars and Phobos. Secondary, the empirical accelerations are applied in QSW in CNES, while JAXA apply these forces in ICRF. Finally, the modelling of manoeuvers in CNES may differ from that used by JAXA.

The transition from QSO-M to LC has been divided in 10 arcs, given by JAXA, with starting dates written in Table 3.

Table 3 Different arcs considered in the covariance analysis for the transition from QSO-M to QSO-LC

Arc number	**Starting date of propagation**
#0	2029-03-18T20:00:00.000000
#1	2029-03-21T20:00:00.000000
#2	2029-03-23T20:00:00.000000
#3	2029-03-25T20:00:00.000000
#4	2029-03-27T20:00:00.000000
#5	2029-03-30T19:50:00.000000
#6	2029-04-01T19:00:00.000000
#7	2029-04-03T19:00:00.000000
#8	2029-04-06T18:00:00.000000
#9	2029-04-08T16:00:00.000000

Figures 2 and 3 are showing the evolution of the covariance in position and velocity for the first arc. We can see in these Figures that they are showing the same pattern overall for both arcs, which is expected. Also, the order of magnitude in errors is the same for the position, while the velocity shows a difference in the order of magnitude, 2 times larger for CNES propagation. This cross-validation is considered satisfactory, given the expected differences coming from the variations in modelling approaches between CNES and JAXA.

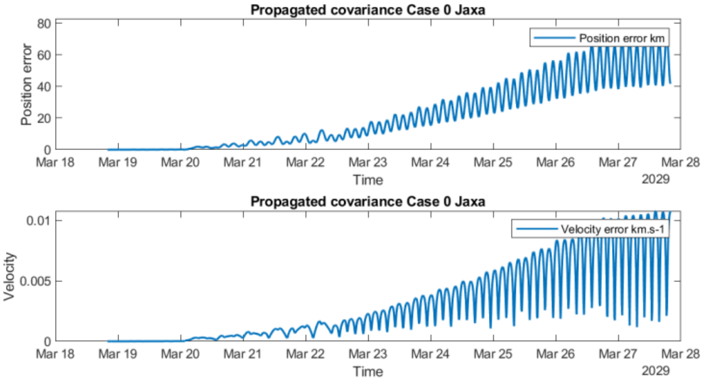

Figure 2: Propagated covariance from JAXA side, arc #0

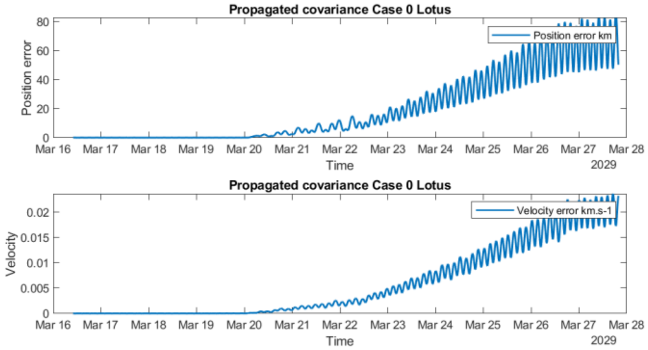

Figure 3: Propagated covariance from CNES side, arc #0

The covariance propagation for arc #1 is depicted in Figure 4 for JAXA and Figure 5 for CNES. Similar to the first arc, we can see consistent trends in the evolution of the covariance with respect to time, for both position and velocity. Again, for this arc, we have the same order of magnitude of error for the position, while the velocity error is approximately twice as large for CNES compared to JAXA. This discrepancy can be again attributed to differences in the modelling approaches between CNES and JAXA. Overall, these results are also considered satisfactory.

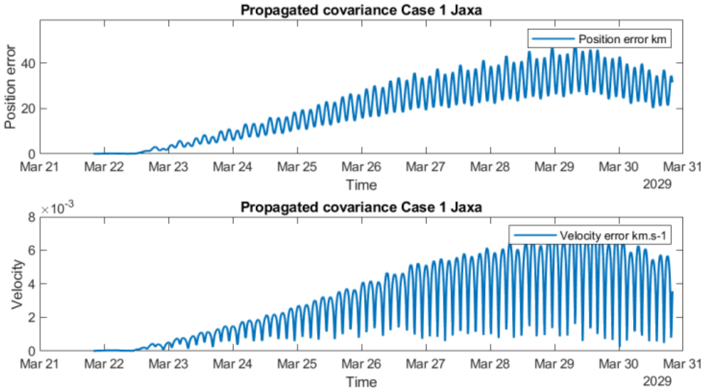

Figure 4: Propagated covariance from JAXA side, arc #1

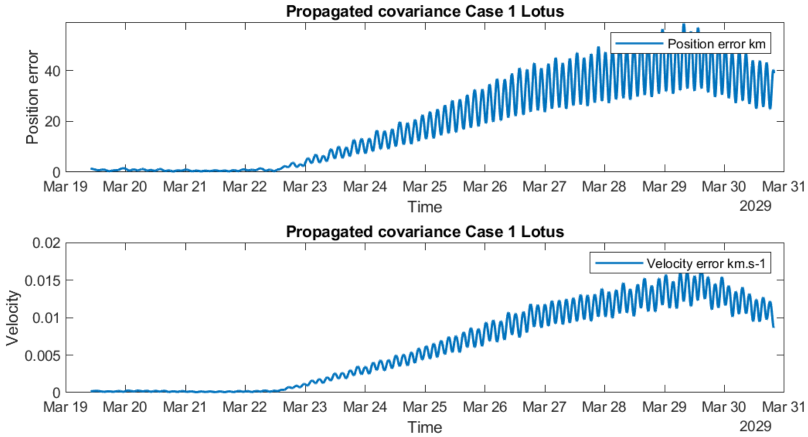

Figure 5:Propagated covariance from CNES side, arc #1

For arc #2, we can observe similar patterns for the covariance propagation, especially around April 01, where a significant manoeuver is impacting the covariance, as shown in Figures 6 and 7. This time, while the positions errors remain of the same order of magnitudes, the velocity errors now exhibits larger differences, up to three times the order of magnitude. This can be expected, since we have a differences in models for the manoeuvers.

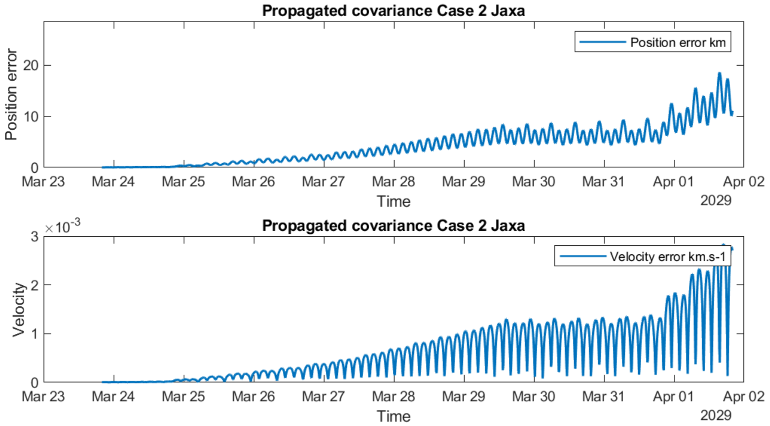

Figure 6: Propagated covariance from JAXA side, arc #2

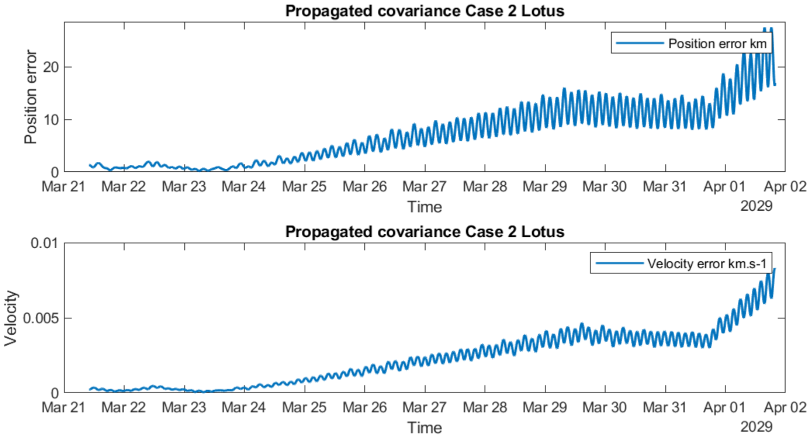

Figure 7: Propagated covariance from CNES side, arc #2

Figures 8 and 9 illustrate the differences in covariance propagation for arc #3. The evolution of the covariance over time remains consistent for both JAXA and CNES. The position errors continue to be of the same order of magnitude. However, the discrepancies in velocity errors have increased, with differences now up to four times in magnitude. These differences are expected but can be further investigated with JAXA to address and correct the remaining errors between the two propagations.

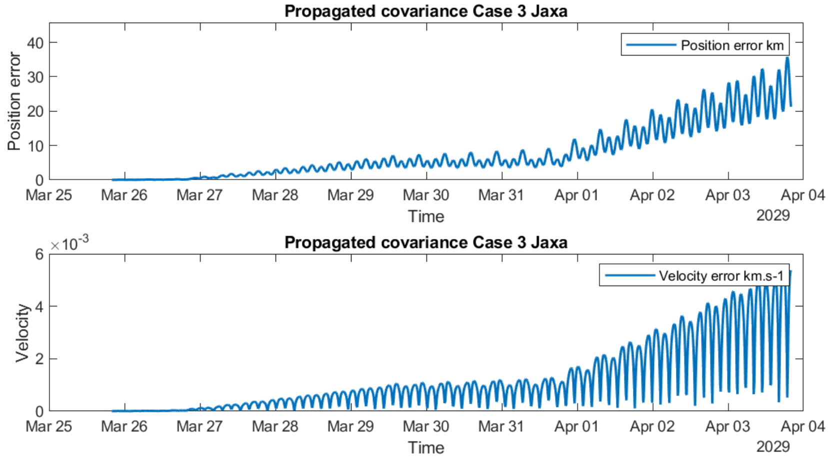

Figure 8: Propagated covariance from JAXA side, arc #3

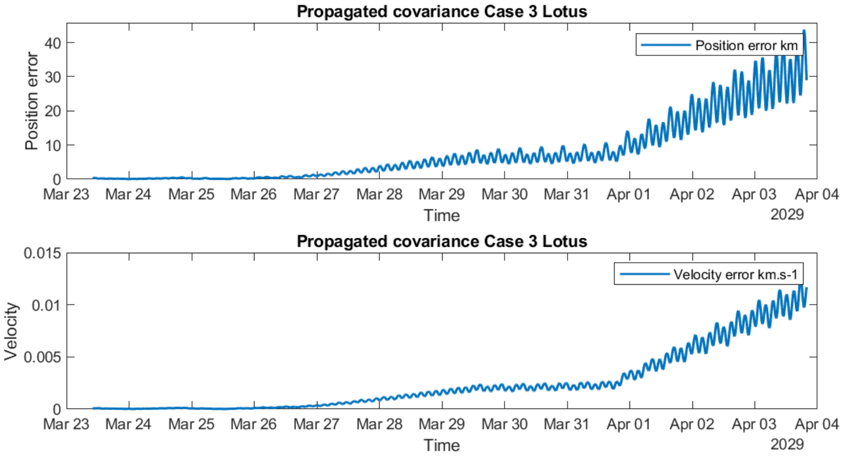

Figure 9: Propagated covariance from JAXA side, arc #3

In Figures 10 and 11, we can see that for arc #4, the error growth pattern for JAXA and CNES propagation is consistent with the other arcs. Again, the position errors remain of the same order of magnitude. However, the velocity errors show some differences. For this arc, the difference in velocity is reduced to two times the error for CNES propagation.

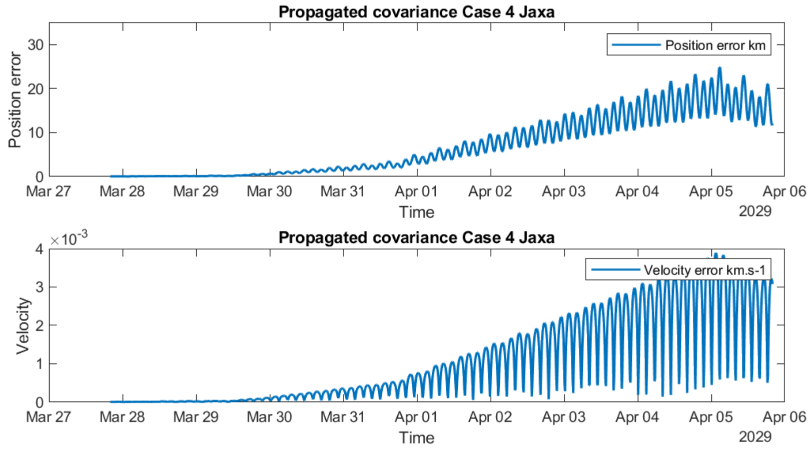

Figure 10: Propagated covariance from JAXA side, arc #4

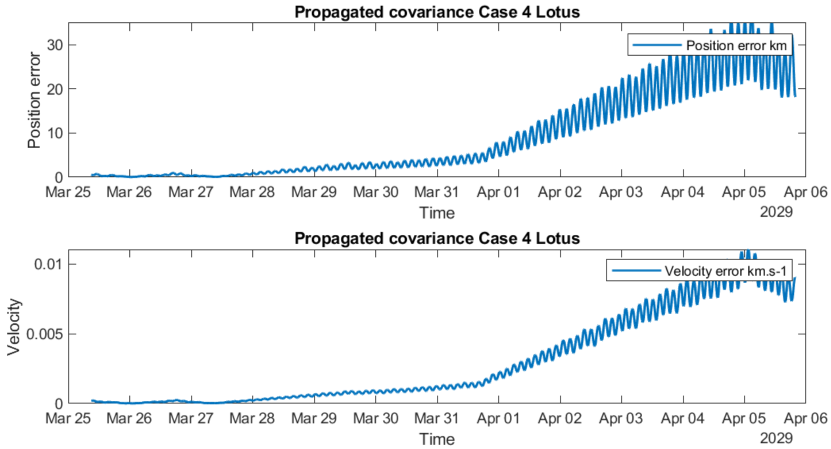

Figure 11: Propagated covariance from CNES side, arc #4

For arc #5, differences in the evolution of errors between CNES and JAXA are more noticeable compared to other arcs, as shown in Figures 12 and 13. Although both CNES and JAXA show an increase in covariance over time, we do not have the same pattern for the evolution of the covariance, neither for position or velocity. This can be attributed to the differences in the models between JAXA and CNES and must be investigated in the future. However, we still have the same orders of magnitude for the position which is considered satisfactory for this part of the cross validation.

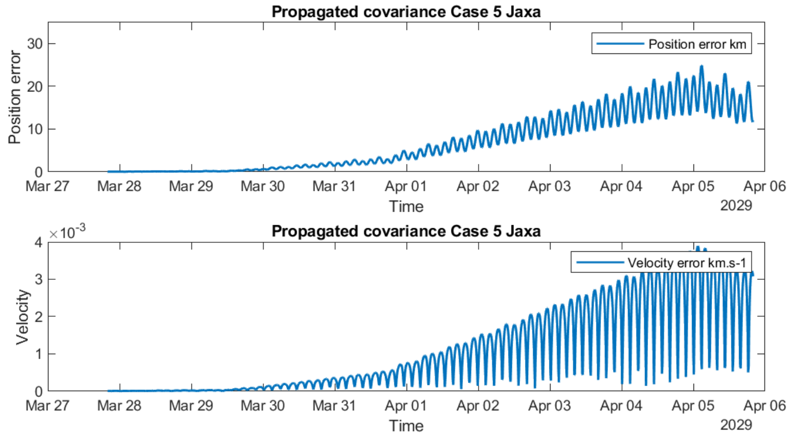

Figure 12: Propagated covariance from JAXA side, arc #5

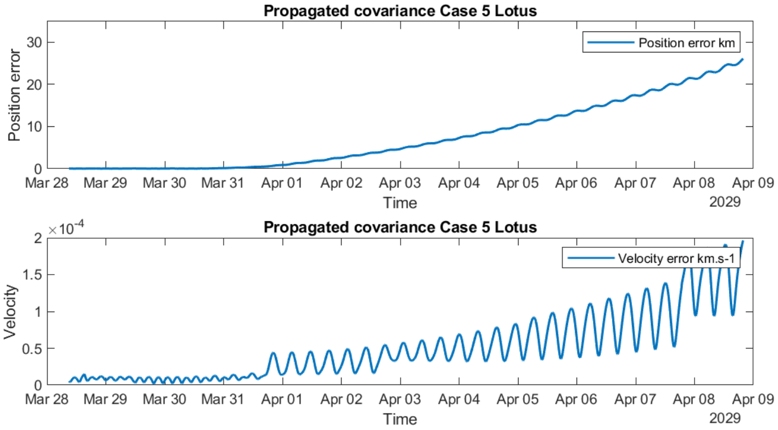

Figure 13: Propagated covariance from CNES side, arc #5

Figures 14 and 15 illustrate that for arc #6, the evolution of covariance for position and velocity follows the same pattern once again. This consistency highlights that arc #5 is unique, compared to the other arcs, and will require further investigation during the cross-validation process. Arc #6 demonstrates similarities in both the patterns and the orders of magnitude for position, and two times the order of magnitude for the velocity, which is encouraging.

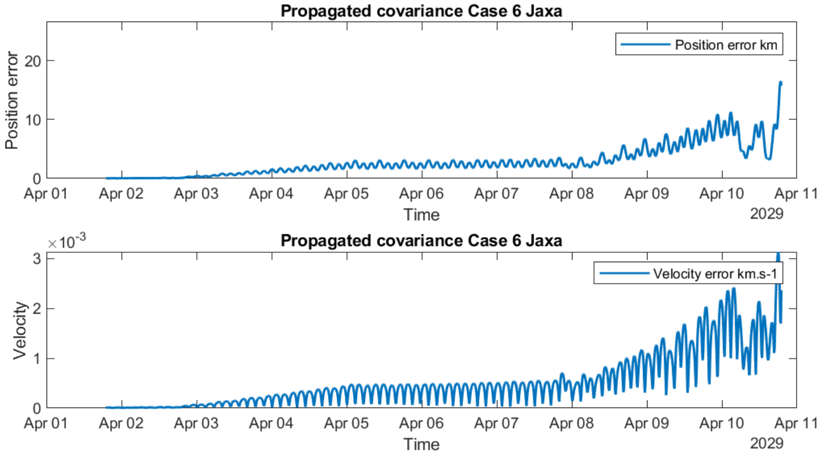

Figure 14: Propagated covariance from JAXA side, arc #6

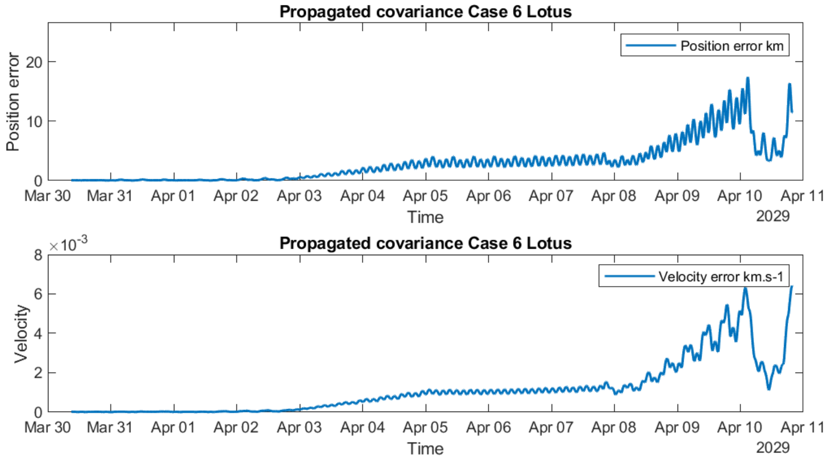

Figure 15: Propagated covariance from CNES side, arc #6

Arc #7 is again showing the same trends for the evolution of the covariance in position and velocity, as shown in Figures 16 and 17, with an event occurring around the 10th of April which reduces the covariance. Again, we have minor variations in velocity but the same order of magnitude for the position error. It is considered acceptable and can once more be attributed to the variations in models.

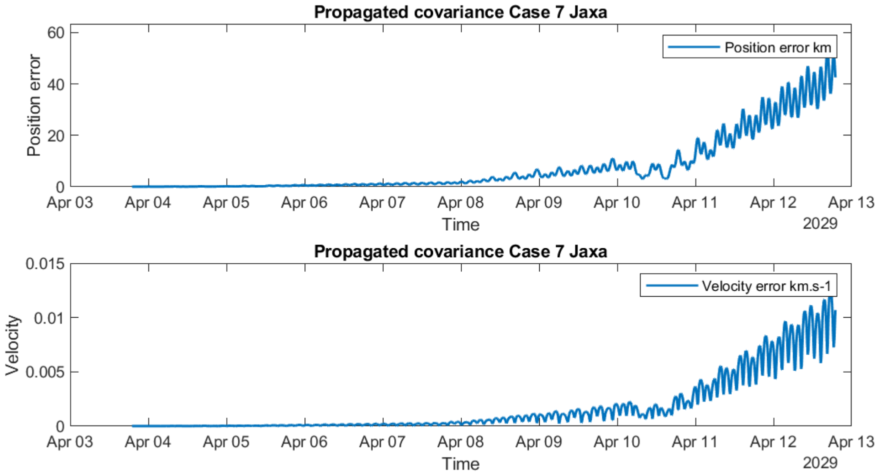

Figure 16: Propagated covariance from JAXA side, arc #7

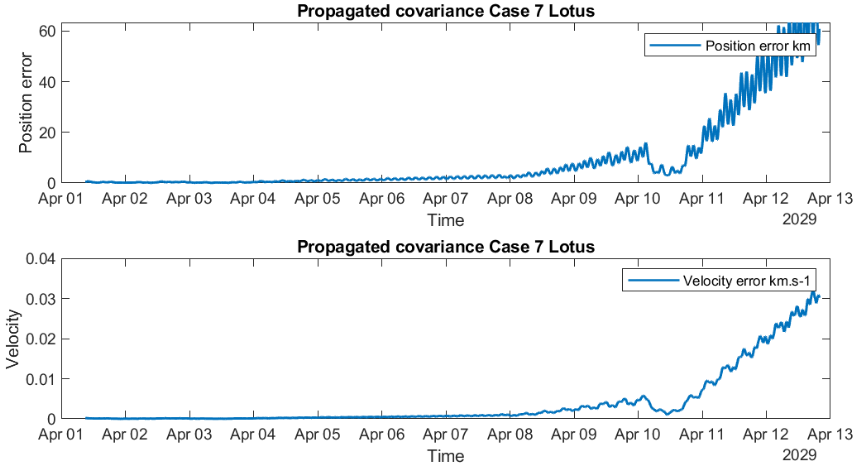

Figure 17: Propagated covariance from CNES side, arc #7

Arc #8 is also an acceptable case where we have the same trends in the evolution of the covariance, as illustrated in Figures 18 and 19. The Figures are showing an event occurring around the 10th of April, as expected in the last scenario. The same order of magnitude is displayed in the position error, while once more, the CNES velocity error is close to two times the velocity error of JAXA.

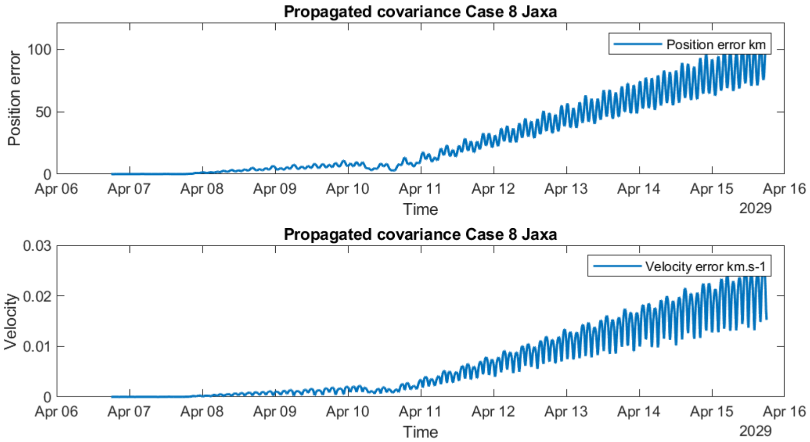

Figure 18: Propagated covariance from JAXA side, arc #8

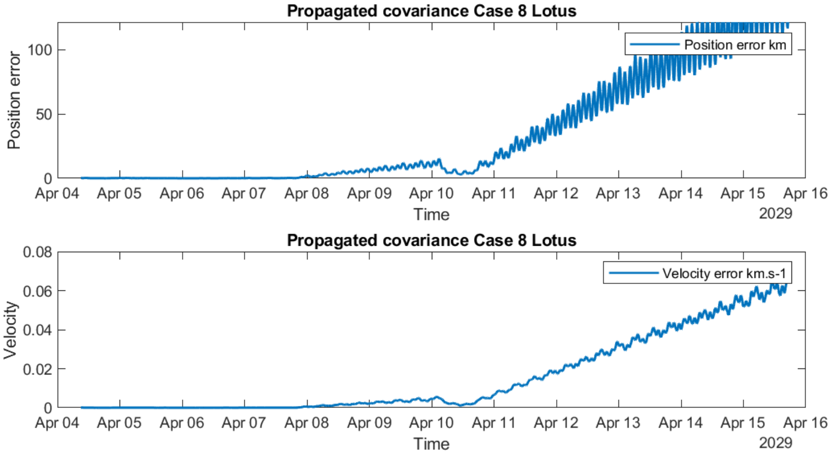

Figure 19: Propagated covariance from CNES side, arc #8

Figures 20 and 21 illustrate the final scenario, arc #9, which is the closest in terms of orders of magnitude. The CNES propagation exhibits almost the same behaviour than the JAXA propagation. The position errors as well as the velocity errors are of the same order of magnitude. Which is considered more than acceptable for this cross-validation.

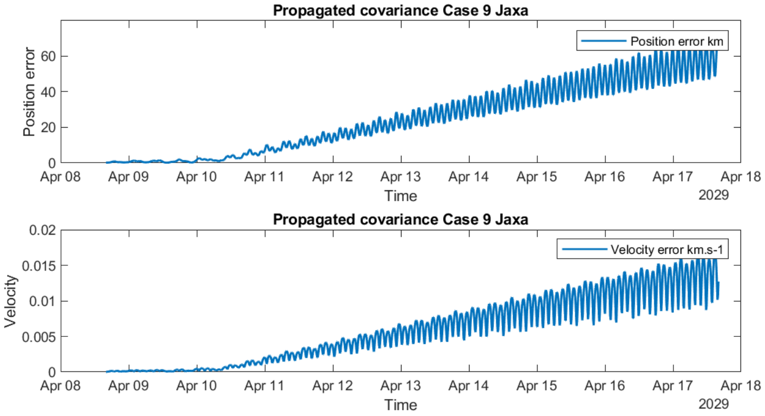

Figure 20: Propagated covariance from JAXA side, arc #9

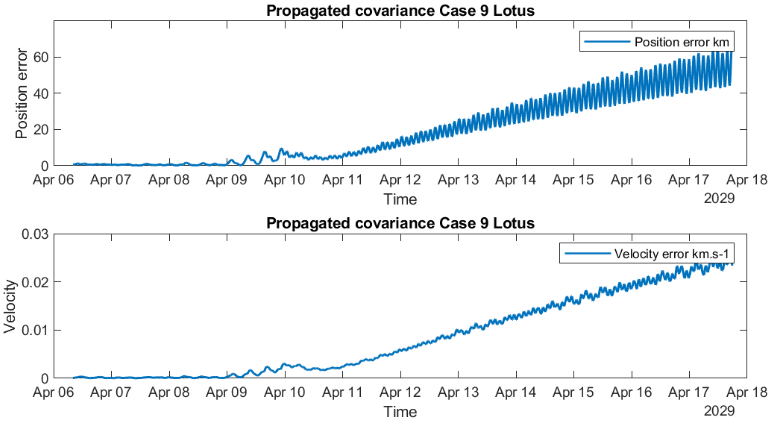

Figure 21: Propagated covariance from CNES side, arc #9

5. Discussion

As highlighted in the results section, the cross-validation of covariance propagation between JAXA and CNES was successful, confirming the reliability of the analyses conducted within the scope of the MMX mission.
The Figures are showing similar behaviours across the datasets, excepted for arc #5 which must be investigated further. This arc can be different due to a unique configuration that amplifies the differences between JAXA and CNES, resulting in greater differences in the results. Despite this, the position error evolution is consistent across all arcs, while variations in velocity errors appear in few orders of magnitudes only. These velocity differences can be largely attributed to the differences in the models taken into account in the propagation. For instance, the occultation of Phobos and Mars have not been taken into account in the JAXA study, which can lead to significant errors in the SRP thus explaining some of the observed discrepancies. Additionally, empirical forces are not applied in the same reference frame, which is QSW for CNES (Phobos centered) and ICRF for JAXA. This discrepancy is mainly due to software limitations and could be resolved in future studies. Last but not least, the modelling of the manoeuvers may differ between CNES and JAXA and this should be further investigated in subsequent work. While in this study we presented only the cross-validation of the transition arc form QSO-M to LC, other QSOs must be investigated in the future, to ensure consistency across all phases of the trajectory.

Overall, and despite these small differences, the cross-validation can be considered successful and serves to strengthen the confidence in the results. This collaboration underscores CNES's role as a key partner in supporting JAXA's MMX mission, particularly in trajectory design, flight dynamics, and covariance analysis. By providing expert support and independent validation of critical analyses with CNES tools, it contributes significantly to the mission's success, in this challenging Martian moons environment. This work further reinforces CNES's position as a trusted partner in small body exploration, proximity operations, and landing, building on past successes in missions such as Rosetta, Hayabusa-2, and Hera.

6. Conclusions

In this study, we performed a cross-validation of covariance propagation between CNES and JAXA for the MMX mission, focusing on the QSO-M to QSO-LC transition arcs. The results show satisfactory agreement between JAXA and CNES covariance propagations, with consistent trends in the evolution of position and velocity errors. The position errors generally exhibited the same order of magnitude for both CNES and JAXA, while velocity errors showed few variations, primarily due to differences in modeling approaches, including the handling of empirical forces, maneuver modeling, and the differences in SRP modelling.
The cross-validation was effective in determining the reliability of the covariance propagation methodology for both CNES and JAXA, while identifying areas for further investigation. Whereas the differences in velocity errors, particularly for specific arcs such as arc #5, highlights the need in further studies and model adjustments, the overall

consistency in position error evolution validates the consistency of the covariance propagation methods used between CNES and JAXA.

This work contributes significantly to the MMX mission by providing JAXA with independent cross-validation of key analyses, thus increasing confidence in the mission's trajectory planning and flight dynamics. It also highlights CNES's important role as a collaborative partner in small body exploration, reinforcing its expertise in flight dynamics proximity operations and landing, as demonstrated in past missions such as Rosetta, Hayabusa-2, and Hera.

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