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Correlated Atom Accelerometers for Mapping the Earth Gravity Field from Space

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ABSTRACT

The emergence of quantum technologies, including cold atom based accelerometers, offers an opportunity to improve the performances of space geodesy missions. In this context, CNES initiated an assessment study called GRICE (GRadiométrie à Interféromètres quantiques Corrélés pour l'Espace) in order to evaluate the impact of cold atom technologies to space geodesy and to the end users of the geodetic data. In this paper, we present a specific mission scenario for gravity field mapping based on a twin satellite concept. The mission uses a constellation of two satellites each equipped with a cold atom accelerometer. A laser link measures the distance between the two satellites and couples these two instruments in order to produce a correlated differential acceleration measurement. The main parameters, determining the performances of the payload, have been investigated. In addition, a preliminary study of mass, consumption and volume has been conducted to ensure the onboard feasibility of these instruments. A general study of the satellite architecture, including all the subsystems, has also been realized and is presented here.

Keywords: Geodesy, cold atoms, atom interferometry, gravity

1. INTRODUCTION

The knowledge of the gravity field, which reflects the mass distribution of the Earth, enables to investigate the internal structure of our planet and the dynamics of its external fluid layers (atmosphere, oceans, polar caps, hydrosphere). Observations on the gravity field thus contribute to the understanding of the geological and climatic evolutions of our planet. Meanwhile, the emergence of quantum technologies, including cold atom based accelerometers, offers an opportunity to improve the performances of space geodesy missions (e.g. GRACE and GRACE-FO, GOCE). In this context, CNES initiated an assessment study called GRICE (GRadiométrie à Interféromètres quantiques Corrélés pour l'Espace) in order to evaluate the potential contribution of cold atom technologies to space geodesy and to the end users of the geodetic data. This mission would map the temporal variations of the Earth's gravity field with a spatial resolution of about 100 km and a temporal resolution of about ten days. The envisioned mission lifetime is 5 years.

2. MISSION REQUIREMENTS AND END USER NEEDS

2.1 Applications of space gravity measurements

The Earth is a complex system composed of an internal structure (core, mantle, lithosphere) and its external fluid layers (atmosphere, oceans, polar caps, hydrosphere). This system is submitted to permanent interactions between its components over different temporal and spatial scales. Thus, the water cycle, ocean circulation or melting of the polar ice caps are followed by mass transfers in fluid envelopes. Besides, each part of the internal structure of the Earth presents a continuous evolution: the core is characterized by the magnetohydrodynamic motions, the mantle convects under the motion of tectonic plates, the lithosphere is permanently deformed, either extremely slowly, in response to the last deglaciation, or more violently during catastrophic events such as the recent major earthquakes (Sumatra, Tohoku).

Satellite gravimetry offers the only type of observation directly sensitive to mass transfers within the Earth's system. Thus it enables to investigate on one hand, the structure and dynamics of our planet and, on the other hand its external fluid layers evolution. Indeed, mass displacements mainly result from the global cycle of water between atmosphere, oceans, continental reservoirs and cryosphere, to which are superimposed signals derived from the dynamics of the solid Earth over time scales from the hour to the decade, even longer. This results in temporal variations of the gravity field, followed since 2002 with a global coverage by the GRACE mission [1], which comes to an end in 2017, and followed next year by

GRACE-FO. On the other hand, the undulations of the so-called "static" field, mapped by the GOCE mission [2], up to about 85 km of resolution [3] provide information on the internal distribution of the Earth's and its evolution on the geological scales. It also provides the horizontal reference surface, called geoid, to which the altitudes and the dynamic topography of the oceans relate.

Space gravimetry data are crucial in many areas of the geosciences as they provide information which are difficult to access by other means of investigation. For example, they enable to monitor groundwater and to evaluate the total available water reserve in continental areas. They also allow to understand the deep ocean circulation, which plays an important role in heat transport within the Earth's system.

2.2 Specificity of gravity gradient measurements

The use of the space gravimetry data is a real challenge because of the wealth of its signal. Indeed, its exploitation requires to identify the contributions of superimposed sources in the measurement of the field. The GOCE mission has shown the relevance of the gravity gradient measurement for the identification of the different sources based on their geometric characteristics. More generally, the used method for separating the superimposed contributions to the gravity field is based on the identification of specific spatial and temporal patterns. These are combined to observations and models on the individual components of the system (satellite data of soil moisture, altimetry, soil deformations, ...). It has been shown that these analyzes benefit from an increase of the spatial resolution. For example, remote sensing instruments in hydrology have a resolution between 15 and 35 km, a reduction of the gap in resolution based on spatial gravimetry is then needed. Such increases in resolution are particularly important to discriminate the deformations of the solid Earth from that of the water cycle in the fluid envelopes. It can also contribute to distinguish the signal of the postglacial rebound from that of the ice melt in the polar areas. An increase in spatial resolution also enables to reduce the “leakage" at the boundaries between areas of different variability, and therefore, to better estimate their mass balances.

2.3 End user needs

The end user needs, in terms of space measurement of the Earth gravity field, are first, the continuation of long-term observations, which are essential for the study of the climate system. Second, it is necessary to increase the spatial resolution of this kind of mission in order to close mass balances at all scales of time and space [4]. Finally, the end user community would benefit from a mission determining the temporal variations of the gravity field with increased performances compared to GRACE and GRACE-FO. This kind of mission seems more scientifically relevant than a mission dedicated to the improvement of the static field.

The needs of the end user community have been compiled in [4] and can be expressed as:

- Temporal continuity of observations, in order to estimate long-term trends and to distinguish them from interannual variations.
- Increased spatial resolution compared to GRACE (accuracy of 0.25 mm on geoid variation at 400 km), which is automatically linked to an increase in accuracy even at longer wavelengths.
- Increased time resolution up to a day, combined with a shorter latency; this would enable to develop real-time applications of space gravimetry.

3. INSTRUMENT

The main scientific needs, in terms of gravity field mapping from space, are related to an increase of the spatial resolution of the measurements. Moreover, stability and accuracy are needed for long time data treatments and combinations with other data types. Finally, the gravity gradient is the most relevant observable to increase the spatial resolution of the mission. In this context, the emergence of quantum technologies, including cold atom based accelerometers, offers an opportunity to improve the performances of space geodesy missions. Indeed, these instruments provide stable and accurate measurements and are particularly adapted to differential mode operations needed for the gravity gradient measurements. In this part, we describe the use of quantum technologies in a specific configuration that would enable an increase of the performances of space geodesy missions.

3.1 General description

Several mission scenarios have been studied in the frame of assessment phase [5, 6, 7]. One of them, inspired by the concept proposed in [6, 7], is based on a twin satellite concept and seems highly relevant for gravity field mapping. The instrument, depicted in Figure 1, is based on a composite gradiometric measurement. The mission uses a constellation of two satellites each equipped with a cold atom accelerometer placed at their center of mass. A laser link measures the distance between the two satellites and couples these two instruments in order to produce a correlated differential measurement. The combination of these acceleration data is eased by the absence of drift on the atomic measurements.

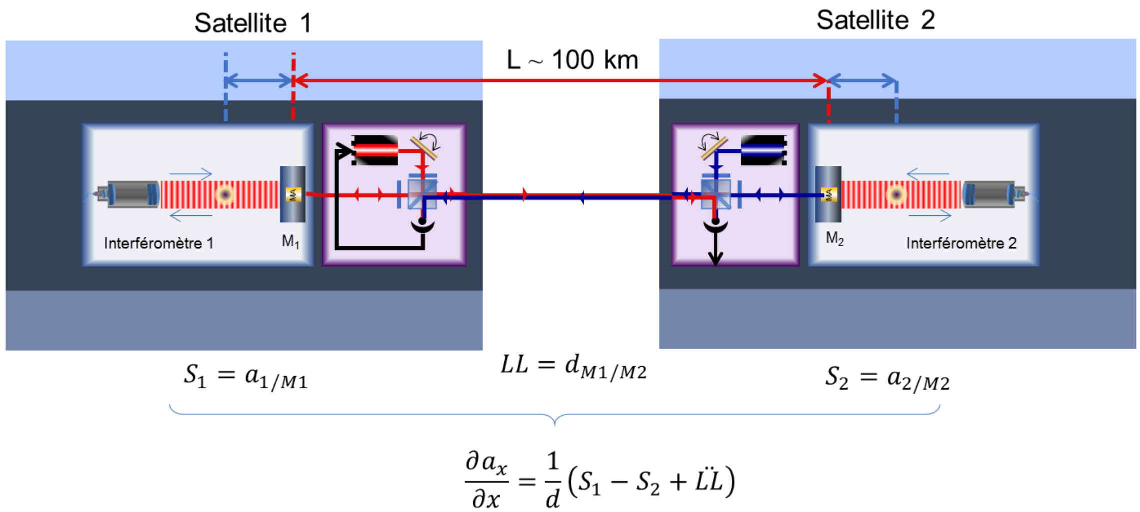

Figure 1. Mission scenario involving twin satellites each equipped with a cold atom accelerometer. A laser telemeter is used to monitor the distance between the two satellites and couples the measurements of the two atom interferometers. For details see text below and equations (2) and (3).

Each atom accelerometer measures the acceleration, S1 and S2, between an inertial frame, defined by the free falling atomic cloud, and the frame of its satellite, materialized by the retroreflection mirror of the Raman beam:

$$S_1 = a_{1/M1} \text{ and } S_2 = a_{2/M2}. \tag{1}$$

The laser link provides a telemetry measurement between the two frames of the satellites, i.e. between the two mirrors of the atom accelerometers:

$$LL = d_{M1/M2}. \tag{2}$$

The combination of these three measurements enables to determine the gradient of acceleration between the two distant atomic clouds along the track of the satellites:

$$\frac{\partial a_x}{\partial x} = \frac{1}{LL}(S_1 - S_2 + \ddot{LL}). \tag{3}$$

The gravity gradient measurement becomes more sensitive when the baseline of the instrument (i.e. the distance between the two accelerometers) increases. The present payload configuration, which distributes the atom accelerometers on two satellites, allows a significant increase of the baseline compared to an instrument that would have to stand on a unique platform. This instrument also enables to obtain interesting performances while limiting the impact of nadir pointing rotation of the constellation on the atom accelerometers.

3.2 Atom accelerometers

For this mission, we consider atom accelerometers using a source of laser cooled Rubidium atoms manipulated by Raman transitions (Figure 2). Rubidium atoms are first prepared from a vapor to form an ultra-cold sample, using atom chip techniques [8]. Then, the free falling rubidium cloud interacts successively three times with a unique pair of retro-reflected Raman beams, which acts on matter waves as beam splitters or mirrors. This creates an interferometer of 2T total interaction time. The atomic phase shift is then obtained from the population in each output port of the interferometer, which is measured by a fluorescence technique. The atomic phase shift $\Delta\Phi$ is given by:

$$\Delta\Phi = \Phi_1 - 2\Phi_2 + \Phi_3, \tag{4}$$

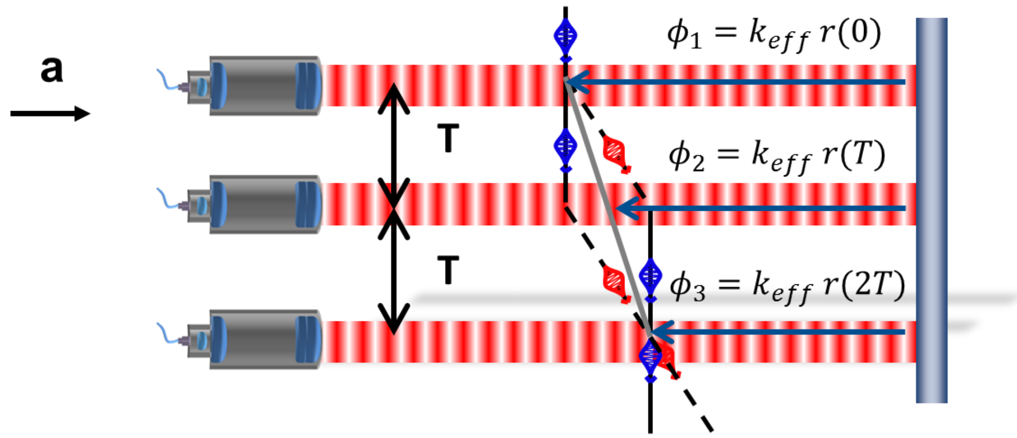

Figure 2. Scheme of a 3 pulses atom interferometer using Raman lasers in a retro-reflected configuration. The total interaction time is 2T. The interferometer is sensitive to the acceleration of the cold atoms with respect to the retro-reflection mirror in the direction of the Raman lasers.

where $\Phi_{1,2,3}$ is the local Raman laser phase seen by the atom along their classical path.

This phase shift is then related to the acceleration between the atomic cloud and the equiphases of the Raman laser, along its propagation direction, by:

$$\Delta\Phi = \mathrm{k_{eff}}\, \mathrm{a}\, \mathrm{T}^2, \tag{5}$$

where k_{eff} corresponds to the effective wave vector of the Raman beam.

In order to evaluate the atom accelerometer performances needed for this mission, we list the key parameters of the instrument. The sensitivity is related to the interaction time (T), the fringe contrast (C), and the dead time of the measurement cycle. In our study, we consider that the determination of the output phase shift of the interferometer is limited by the quantum projection noise [9], linked to the detected atom number (N_{det}) at the output of the interferometer. The fringe contrast depends on the atomic cloud temperature and decrease with the rotation of the satellite and the interaction time [10].

In the following table, we define a set of parameters, achievable by existing technologies, which enables to reach a sensitivity of 6 x 10^{-10} $m.s^{-2}$. $Hz^{-1/2}$ for the acceleration measurement.

Parameter	*Notation*	*Value*	*Unit*
Interaction time	T	0,5	s
Contrast	C	0,81	-
Preparation time	t_{prep}	1	s
Measurement cycle duration	t_c	2	s
Detected atom number	N_{det}	1 x 10^6	-
Atomic cloud temperature	T	5 x 10^{-11}	K
Initial size of the atomic cloud	σ_r	1 x 10^{-4}	m
Accelerometer sensitivity	σ_a	6 x 10^{-10}	$m.s^{-2}$. $Hz^{-1/2}$

Table 1. Main parameters of the cold atom accelerometer envisioned for the GRICE mission.

3.3 Laser ranging instrument

The laser ranging instrument is used to determine the relative displacement of the two atom accelerometers in order to retrieve the gravity gradient measurement along the track of the satellites. As the measurement is realized between the two retroreflection Raman mirror of the accelerometers, the gravity gradient measurement is insensitive to non-gravitational forces acting on the satellites. The laser ranging instrument considered in our study, is based on a heterodyne optical interferometer working at a wavelength of 1.5 µm. The principle of this instrument (Figure 3) would be similar to the one used on the GRACE-FO mission [11].

A first laser L1, onboard the satellite 1, is frequency locked on a spectroscopic signal coming from a saturated absorption setup [12]. This laser is sent to the satellite 2 after a retroreflection on the local Raman mirror. Onboard the satellite 2, the laser L1 is received and superimposed to a local laser L2 in order to form a beat note on a fast photodiode at a few tenth of MHz. This signal is used to lock the phase of the laser L2 onto the laser L1. The laser L2 is then sent back to the satellite S1 where its phase is measured with respect to the local arm of the laser L1 through a beat note technique. The intersatellite displacement is derived from the phase shift of the beat note:

$$\delta L = \frac{\lambda}{2\pi}\,\delta\Phi. \tag{6}$$

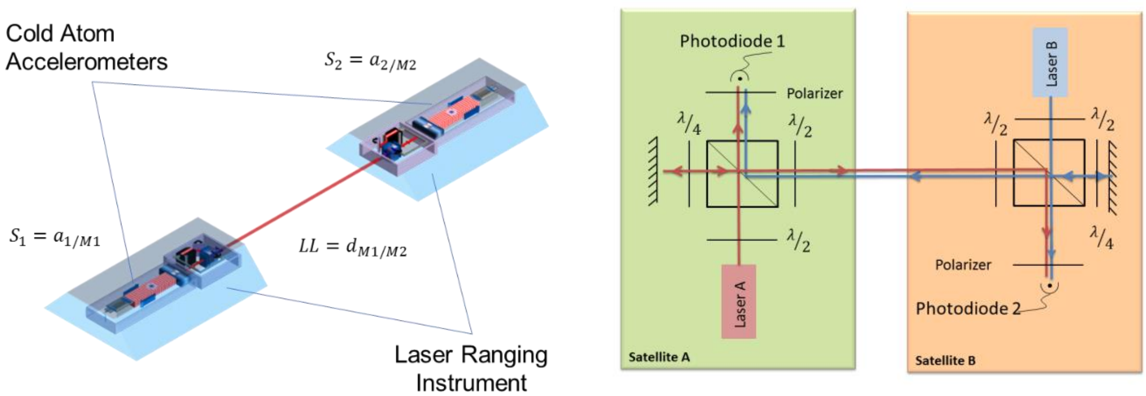

Figure 3. Left: Scheme of the twin satellite implementation including the two atom accelerometers coupled by the laser link. Right: Optical scheme of the heterodyne laser telemeter which enables to couple the acceleration measurements of the two accelerometers.

In the frame of GRICE mission, the requirements needed for this instrument are summarized in the following table:

Parameter	*Value*	*Unit*
Sensitivity	40	nm. $Hz^{-1/2}$
Intersatellite distance	≈ 100	km
Displacement range	±1	km
Relative velocity range	±0,5	$m.s^{-1}$
Relative acceleration range	±8 x 10^{-4}	$m.s^{-2}$

Table 2. Main requirements for the intersatellite laser ranging instrument.

3.4 Instrument performances

The gravity gradient measurement is retrieved from the combination of the acceleration data given by the atomic instruments and of the laser ranging instrument. The laser ranging instrument, which provides a distance measurement, is derived twice in order to give the relative acceleration between the two satellites. This derivation implies a high level of noise for the high frequency of the instrument. Indeed, the sensitivity of the instrument is limited by the atom accelerometers from 10^{-5} to 10^{-2} Hz and by the laser ranging instrument noise from 10^{-2} to 1 Hz. The sensitivity of the instrument to the gravity field gradient is reported of the Figure 4.

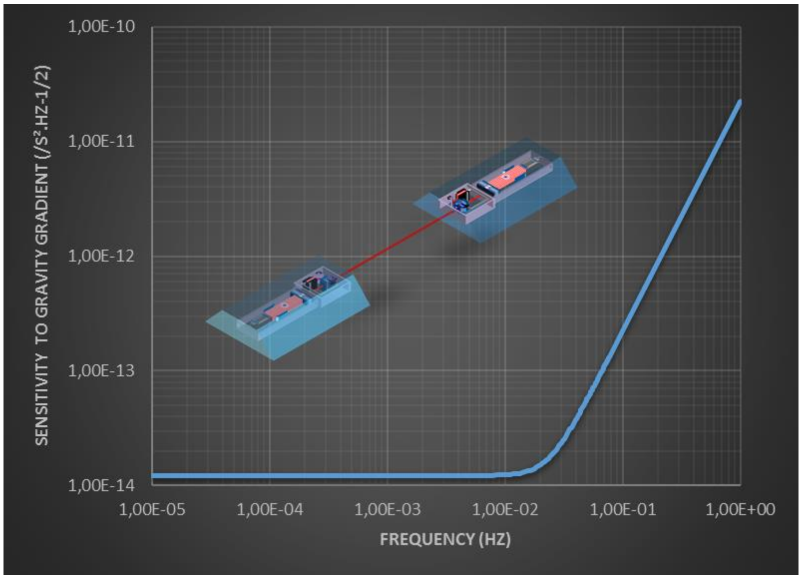

Figure 4. Power spectral density of noise of the complete instrument expressed in sensitivity to the gravity gradient along the track.

4. MISSION CONCEPT

4.1 Satellite constellation

The two satellites are planned to fly, separated by 100 km, on a polar orbit at an altitude of 370 km. This altitude is chosen to maximize the sensitivity of the constellation to the high spatial frequencies of the gravity field while limiting the effect of the residual atmosphere. Moreover, this orbit is optimized to obtain a homogeneous coverage of the Earth on different time scales (week, month, year). The orbit cycle is of 369 days, giving a ground track spacing of around 10 km. The chosen orbit has two sub-cycles of 28 days and 5 days which enable an optimal data treatment on these time scales.

4.2 Satellite architecture

A preliminary study of mass, consumption and volume was conducted to ensure the onboard feasibility of the instruments and an analysis of the satellite architecture, including all the subsystems, was also carried out. Several technical solutions for propulsion and attitude control have been investigated in order to guarantee optimal operating conditions (limitation of micro-vibrations, maximization of measurement time). A preliminary design of the satellite shape was performed maximizing the solar panel area available while maintaining its aerodynamics.

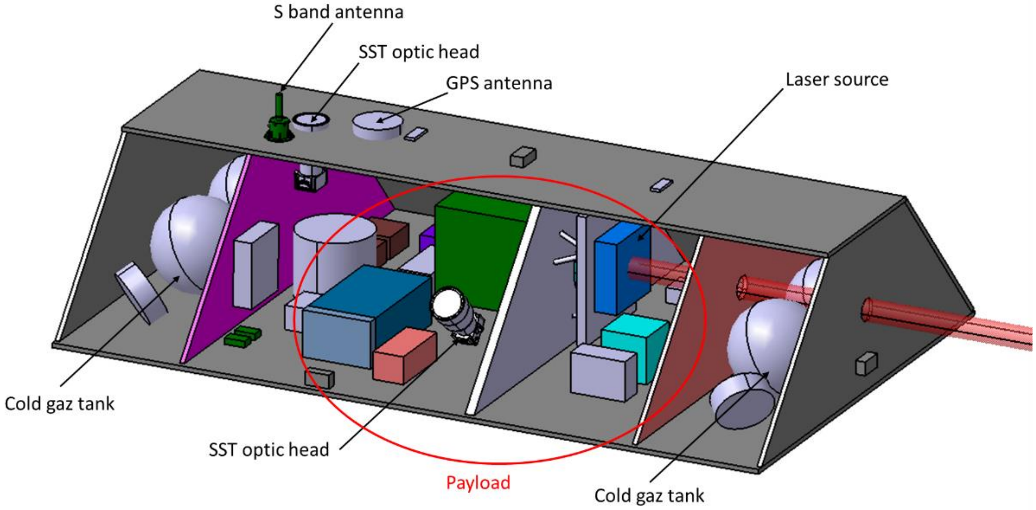

Figure 5. View of the GRICE platform

The envisioned platform (Figure 5) provides all the necessary housekeeping functions to achieve the mission goals: a payload support, electrical power, thermal control, command, data handling and storage, attitude and orbit control. The platform structure has a trapezoidal shape. Three faces need to support the solar cells coupled with a battery in order to provide the energy to the platform. A radiator is accommodated on the lower face for a thermal control. The different parts of the payload are accommodated on the lower panel near the middle of the platform. The sensor part of the payload is placed at the satellite center of mass and supported by a transversal bench. The platform is based on a 3-axes stabilization with nadir pointing. The attitude measurement is done by stellar sensor and gyrometers. For the control, two options are identified: reaction wheels or propulsion (cold gas) with magnetotorquers. At this stage of the study, the cold gas is the reference solution with eight thrusters placed on the velocity and anti-velocity faces of the platform associated with three magnetotorquers, one on each axe. The data handling architecture is based on a central computer (OBC). The housekeeping TM/TC (telemetry/telecommand) and the payload telemetry is realized in S band. For the precise orbit determination, a bi frequencies GNSS receiver and laser reflector are also integrated at the platform.

5. CONCLUSION

We have carried out an assessment study of a space mission for gravity field mapping involving innovative atomic technologies. A preliminary investigation has been performed in order to understand the end user needs. These needs are mainly linked to the improvement of the resolution on the temporal variations of the Earth’s gravity field. The related mission scenario involves a constellation of two satellites, each equipped with a cold atom accelerometer placed at their center of mass. A laser link measures the distance between the two satellites and couples these two instruments in order to produce a correlated differential measurement. This instrument enables to retrieve a gradiometric measurement along the track of the two satellites which is likely to increase the resolution of the high harmonics of the Earth’s gravity field. The main parameters of the instruments have been estimated in order to determine the final performances of the payload. To ensure an optimal temporal resolution, the mission orbit has been optimized to guarantee a consistent coverage over different time scales. Finally, a preliminary design of the platform has been realized. This design integrates all the subsystems which enable the satellite to operate at low orbit during 5 years, and demonstrates the technical feasibility of our concept.

Further work will be dedicated to simulate the gravity field recovery. For this, a specific data processing method will be developed taking advantage of the correlation between the two atomic accelerometers. This study will aim at validating the specifications of the instrument sensitivity and assesses the impact of other parameters on mission performances (knowledge of the variable field, orbit restitution).

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