METRIC: A Mission Concept for a Spacecraft Aimed at Upper Atmosphere Mapping, Gravitational Physics, and Geodesy

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Abstract We present a mission concept named Measurement of EnvironmenTal and Relativistic In-orbit pre-Cessions (METRIC) for a compact spacecraft to be placed in a low Earth orbit. Dedicated instrumentation to provide data useful for atmospheric science, fundamental physics, and geodesy will be placed on the platform to achieve the main scientific objectives of the mission: mapping the atmospheric density by in-situ acceleration measurements and by spacecraft tracking at altitudes of great interest for satellites deorbiting; fundamental physics tests and verification of the equation of motion for a well-characterized test mass; and providing an additional space-based node, to improve the tie among different space geodesy techniques. These three objectives need precise orbit determination and a well-calibrated space-based platform. GNSS, SLR instrumentation, and a VLBI beacon are planned to be installed on the METRIC spacecraft and metrologically referenced to one another. The potential contribution of METRIC to geodesy lies in the challenge of performing the co-location of the geodetic techniques in space to improve the International Terrestrial Reference Frame accuracy and stability. GNSS and SLR are space geodetic techniques that rely on satellite observations from the ground, but VLBI observations to satellites are not standard and are not performed routinely yet. In this work we introduce the METRIC concept as a whole and present some of the main requirements to observe the METRIC satellite by VLBI, regarding e.g. satellite visibility using legacy VLBI and VGOS networks and the characteristics of the signal that can be transmitted by the VLBI beacon.

Keywords Upper atmosphere, General relativity, Geodesy, VLBI, ITRF

1 Introduction

METRIC (Measurement of EnvironmenTal and Relativistic In-orbit pre-Cessions) [1] is a mission concept which foresees a small satellite in a polar or quasi-polar and highly eccentric orbit, with dedicated instrumentation in order to perform measurements for atmospheric science, fundamental physics, and geodesy. Specifically, its three main scientific objectives are:

- map the density of the upper atmosphere;
- verify the satellite equation of motion;
- implement a space-based geodetic node.

These objectives belong indeed to three different research areas, making METRIC a truly integrated mission in which selected high-precision instrumentation can work together in a compact platform that should be metrologically very well-calibrated. The basic idea is having a satellite similar to geodynamic ones (e.g., LAGEOS) but, unlike them, equipped with active instrumentation to allow precise orbit determination (POD). The key instrumentation should include Satellite Laser Ranging (SLR) retroreflectors, a Global Satellite Navigation Systems (GNSS) receiver, and a high-precision accelerometer; an add-on instrument would be a Very Long Baseline Interferometry (VLBI) beacon.

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The accelerometer, an evolution of the Italian Spring Accelerometer (ISA) instrument [2, 3], should measure the surface forces acting on the satellite. From these measurements, information can be extracted on the atmospheric drag and therefore on the local atmospheric density. The acceleration data can be used also to support the POD, providing an on-site estimate of non-gravitational perturbations. The POD itself is based on tracking data provided by SLR and GNSS (range for the first technique and pseudo-range and/or phase for the second). Having a precisely reconstructed orbit allows, in principle, to test for the satellite equation of motion, measuring e.g. the various precessional effects predicted by the theory of general relativity for a body around a massive object such as the Earth [4, 5, 6, 7, 8]. With this basic configuration, a third scientific opportunity emerges: indeed, such a satellite behaves naturally as a space-based geodetic node that could constrain the tie between different space geodetic techniques.

In the following, after an introduction to the mission science objectives and to the mission concept, particular attention is given to a discussion of the requirements of VLBI observations for METRIC. This option, though not in the baseline, will significantly augment the potentiality of a mission like METRIC for the geodetic sciences.

2 Science Objectives

The METRIC basic concept is to combine scientific measurements to contribute to open questions in Earth science, fundamental physics, and geodesy in a very effective way. One of the keys to this is having a very well-characterized spacecraft platform from the metrological point of view.

2.1 Upper Atmosphere Density Mapping

The accurate measurement of atmospheric drag in the 450–1200 km altitude range, where it affects satellite lifetimes, is an area which is still open to improvement [1]. Indeed, the knowledge of atmospheric density and its dependency on varying solar and geomagnetic activity is still affected by large uncertainties, especially in upper low Earth orbit (LEO) [9, 10, 11, 12]. In this altitude range, the atmospheric composition changes, also in response to varying solar activity: atomic oxygen, the dominant species in low LEO, progressively gives way to helium and atomic hydrogen. These varying dominant species interact in different ways with the satellite surfaces, leading to changing accommodation and drag coefficients.

It has to be noticed that satellites in this range of altitude may or may not violate the 25-year deorbit guideline depending on the ballistic coefficient and solar activity. Therefore, an improved knowledge of atmospheric density and its variability in LEO will benefit the estimate of satellites' lifetimes and the accuracy of conjunction assessments. Any progress in the field will lead to a reduction of collision avoidance maneuvers, saving propellant, improving safety, and mitigating the problems related to space debris. Improving the knowledge of accommodation coefficients, as a function of altitude and solar activity, by direct acceleration measurements, may lead to better drag coefficient estimates and more accurate modeling of the atmospheric drag perturbation. This in turn should lead to improved density models.

2.2 Fundamental Physics

A compact object in an elliptical orbit close to the Earth, such as METRIC, could in principle allow improvements in testing the relativistic equation of motion in a geocentric frame [13], especially in the case of a polar or quasi-polar orbit. Indeed, a high-inclination orbit would allow for a strong suppression of competing Newtonian gravitational signals, especially the quadrupole and the octupole (for a discussion of these issues see [14]). These Newtonian signals (due to the action of a non spherically symmetric Earth mass distribution on the orbit) cause secular precessions in the same orbital elements (longitude of ascending node and argument of pericenter) affected by general relativistic precessions. Such an orbital configuration would be beneficial especially for a direct measurement of the Lense-Thirring effect (due to the gravitomagnetic field generated by the rotating Earth) with just a single satellite, and not with a combination from multiple satellites as done up to now (for further details see [14]).

The POD for the fundamental physics measurements will be based on the tracking data provided by SLR and GNSS. It will be furthermore based on a complex set of models to describe the satellite dynamics. The accelerometer data should allow overcoming of the well-known limitations of analytical or numerical models in dealing with the non-gravitational, surface forces.

2.3 Geodesy

The contribution of METRIC to geodesy lies in the challenge of performing the co-location of the geodetic techniques in space to improve the accuracy and the stability of the International Terrestrial Reference Frame (ITRF). Four space geodetic techniques are regularly used to realize the ITRF: GNSS, SLR, VLBI, and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The origin of the ITRF is defined by the SLR, sensitive to the Earth's center of mass; the scale is defined by an average of the SLR and VLBI scales and realized by knowledge of coordinates and velocities of the ground stations obtained by the combination of the four techniques' observations. The SLR and VLBI play an important role for ITRF determination, but their co-locations on Earth are limited (fewer than ten sites) and poorly distributed, see Figure 1.

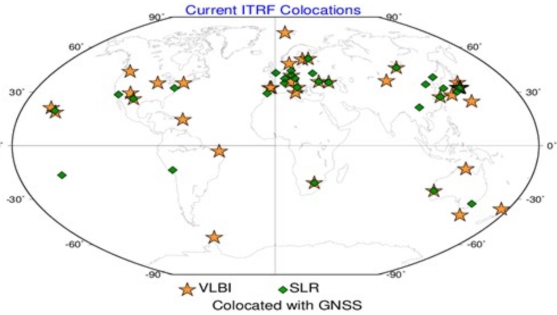

Fig. 1 SLR and VLBI sites co-located with GNSS sites used for ITRF determination (credits: Z. Altamimi).

To connect networks of different geodetic techniques and determine the ITRF, it is fundamental to have co-locations of two or more instruments operating at the same site and having terrestrial ties available. Almost all SLR and VLBI and a large number of DORIS stations are co-located with GNSS, the last therefore linking together the other techniques' networks. However more than 50% of tie vector estimates have an agreement with space geodetic estimates larger than 5 mm, which is caused mainly by technique systematic errors [15]. Co-locating at least three technique instruments (GNSS, SLR, and VLBI) at one fully metrologically calibrated satellite-based platform—a "Core co-location site in space"—is expected to mitigate/cancel technique systematic errors, thus improving the ITRF's accuracy. Furthermore, VLBI satellite observations would give the opportunity to link also the VLBI technique to the Earth's center of mass. After some proposals to achieve co-localization in space that were not approved, a new mission, GENESIS, for co-localization with all four space geodetic techniques was funded in 2023 under the European Space Agency FutureNAV program [16].

3 Basic Mission Concept

The basic idea is to have a very compact and simple in shape (ideally spherical) satellite, equipped with instrumentation to perform tracking and measure the non-gravitational forces (in particular atmospheric drag) and the local residual atmospheric density. A key feature (useful *in primis* for the POD) should be a very precise metrological characterization of the satellite platform: this would turn METRIC into a space-based geodetic node.

3.1 Strategy

The satellite should be placed into a polar or quasi-polar eccentric orbit (450 km × 1200 km), see Figure 2. Once in orbit, it is not foreseen to have any trajectory adjustment, only attitude control (with the satellite slowly spinning around a well-defined axis). The mission duration should last nominally 11 years, in order to cover one solar cycle. The satellite should be tracked at least by SLR and GNSS. At the same time, the availability of acceleration measurements will make up a virtual drag-free spacecraft (close to the ideal concept of a test mass). Both tracking and acceleration measurements should make a POD comparable in accuracy possible with the ones currently achieved for geodynamic satellites and other geodetic missions. From the precise orbit, using standard procedures, the relativistic signals could be extracted and characterized.

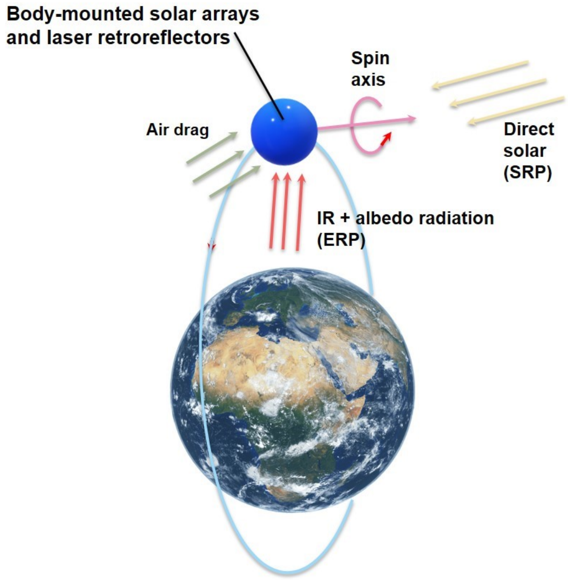

Fig. 2 METRIC basic mission concept.

It has to be noticed that the accelerometer measures the overall acceleration vector, the sum of the various surface forces acting on the satellite. This is fine for the POD, while the atmospheric drag alone has to be extracted in some way. The separation of atmospheric drag and solar radiation pressure is achieved naturally due to orbital geometry.

3.2 Satellite Characteristics at a Conceptual Design Level

In order to simplify the extraction of the drag signal, the satellite should have a shape as simple as possible. A spherical one is ideal, with a constant cross section independent from orbit and attitude; see again Figure 2. A compact body is preferable, with a diameter of 50–60 cm and a mass in the 100–200 kg range. The power consumption (including scientific payload and the other subsystems) is estimated to be 30–40 W and would come from multi-junction, body-mounted solar arrays. The satellite should be spin-stable, with a non-spherical inertia tensor and spin around principal inertia axis. A cold gas system is planned for spin-up; magnetorquers should be used for coning control and sporadic spin trimming.

The compactness of design should ease a pre-launch precise metrological calibration of the system. This very important step should allow characterization of various quantities (relative positions of the instruments, biases of tracking equipment) on which the various scientific objectives (and especially the geodetic one) rely.

4 Main Requirements of VLBI Observations for METRIC

We have to consider at least three topics to be studied and designed for this aim:

- VLBI transmitter characteristics;
- observation feasibility and measurement concept;
- visibility from VLBI and VGOS stations.

The VLBI beacon that could be placed on the METRIC satellite should broadcast a signal that mimics the extragalactic radio source signal currently observed during VLBI geodetic experiments, using legacy and VGOS antennas. Observations of quasars and satellites within the same sessions will provide the opportunity to directly link the dynamic reference frame of the satellite orbit to the quasi-inertial reference frame, i.e. the International Celestial Reference Frame (ICRF). Several studies are underway on the impact of a VLBI transmitter onboard a dedicated satellite or onboard next generation Galileo satellites, as well as on the assessment of the qualitative and quantitative impact to the satellite. Moreover, observations on the derived geodetic parameters have been carried out (see [17, 18, 19]). Simulations of VLBI observations of Earth-orbiting satellites equipped with co-located space-geodetic instruments under different scenarios (see [20]) have been also carried out. All these studies represent a good floor from where to start VLBI METRIC oriented observations. A feasibility study of a VLBI beacon onboard METRIC is needed to enable the observation of the satellite with VLBI radio telescopes. We plan to design a beacon that can broadcast in different sub-bands in the interval from 2 GHz to 14 GHz so that the signal can be received by legacy and VGOS antenna networks in their standard geodetic receiver setups. Discussions of including higher frequencies in Ka-band are ongoing in order to maximize the covered signal bandwidth. Possible investigation of linking the ICRF across frequency bands using METRIC as a well-calibrated multi-frequency target are foreseen. The signal power density has to respect International Telecommunication Union thresholds to ensure compatibility with existent rules. METRIC mission feasibility studies will be oriented towards working in synergy with present efforts carried out by other groups with similar objectives.

5 Conclusions

The METRIC mission concept has the potentiality to address three important scientific objectives, namely atmospheric science, fundamental physics, and geodesy, with a single, integrated satellite platform in a close Earth orbit. Further studies will be required to consolidate the satellite and instrument requirements, as well as the scientific return.

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