ESA's Initiatives on Support to GNSS Navigation for cis-Lunar Missions and GNSS Science

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ESA Activities related to Interoperable GNSS SSV

ID	Activity	Objectives
1	GNSS Space Service Volume Extension – Phase 1	Impact analysis and identification of technology and operational drivers
2	GNSS Space Service Volume Extension – Phase 2	Detailed Req identification and development of new POD concepts for GNSS SSV and cis-Lunar Missions
3	Next Generation of Space Receiver – AGGA5	Identification of new Requirements
4	NAVISP Study – Earth-Moon GNSS-based System study and Receiver development	Activity related to the use of GNSS Signals for Moon missions and identification of potential Augmentation of GNSS Infrastructure on the Moon

ESA Activities related to Interoperable GNSS

- Activity
    - GNSS Space Service Volume Extension
- Main Objectives

1. Analyzing the impact of the GNSS SSV extension on
    - existing GNSS POD concepts for satellite missions in LEO, MEO, GEO, GTO, HEO, Moon and beyond
    - existing GNSS software designs for space users
    - existing operational concepts for space users
    - ground operations

taking full advantage of the extension of the GNSS signal availability for the before mentioned orbit types.

2. Identification of drivers for

- potential new POD concepts for satellite missions in LEO, MEO, GEO, GTO, HEO, Moon and beyond

- potential new operational concepts for space users that will perform OD, POD based on GNSS and/or users that will have GNSS receivers as an integral part of the AOCS,

- communication demands between the ground and the space segment

- potential changes of ground segment operations considering the GNSS SSV extension.

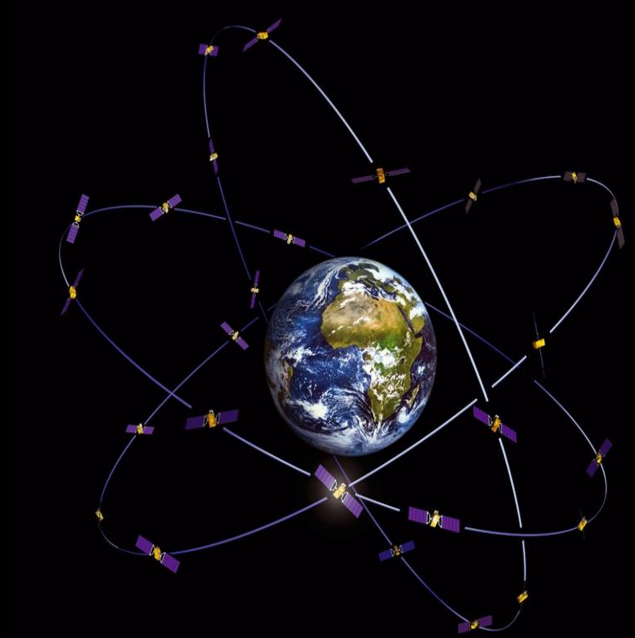
Some Conclusions

- Interoperable GNSS Space Service Volume is considered by ESA as an enabler for many new missions, ranging from science to fully commercial applications
- Interoperable GNSS Space Service Volume will drive developments of technology, new navigations concepts and algorithms for space users for LEO, GEO, HEO, Moon and beyond
- Interoperable GNSS Space Service Volume will have a significant impact on spacecraft design and operations concepts

Earth-Moon GNSS-based system study

Extending GNSS services to Cis-lunar Stduy

1) Earth-Moon and Moon-Earth transfer orbits
2) Lunar Orbit
3) Descent/Landing and Moon Surface Operations



Some of the key challenges

- very low signal levels of GNSS signals;
- kinematics of the receiver (e.g. high Doppler rates and Doppler shifts);
- reduced visibility of satellites;
- no access to navigation data
- need of augmentations

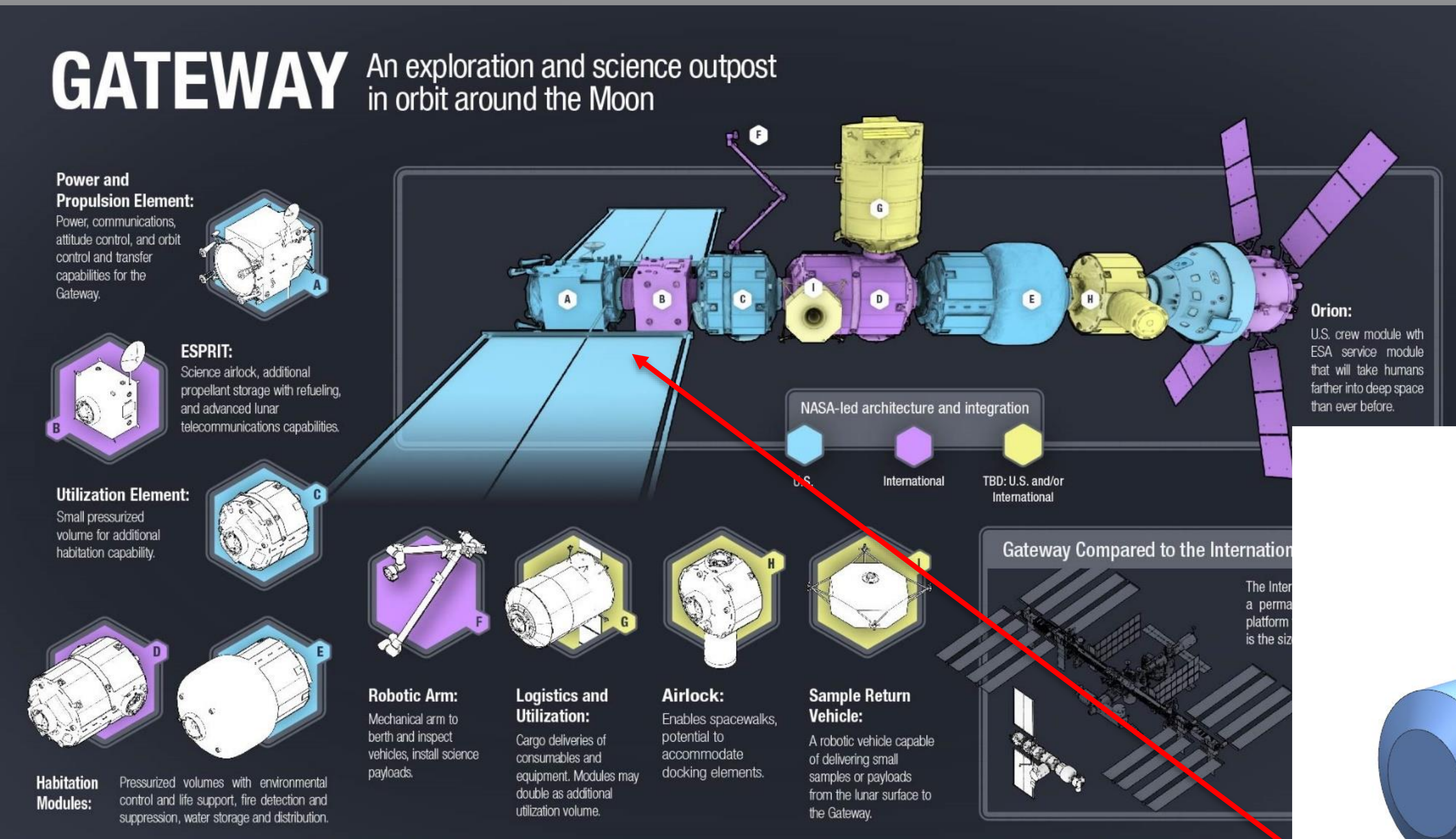
Earth-Moon GNSS-based system study

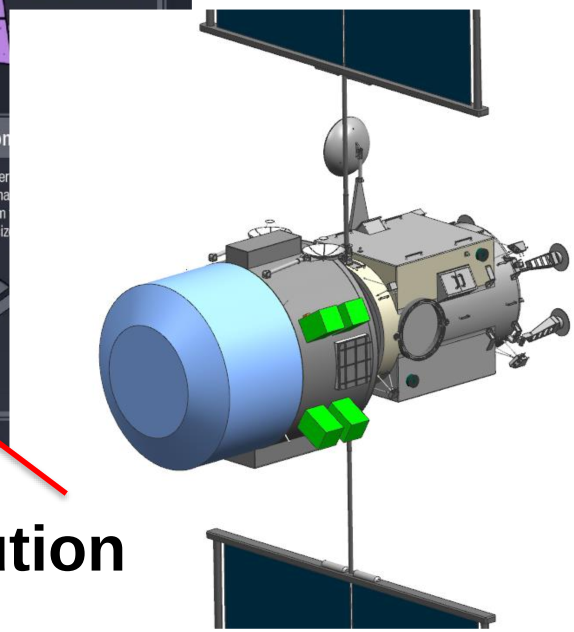
1. to perform a **dedicated System study** on the use of multi-constellation GNSS for Earth-Moon missions: a) consolidating the necessary PNT User Requirements; b) assessing in detail all previous studies; and c) identifying a preliminary architecture with possible enhancements/augmentation to existing GNSS constellations, assessing its feasibility and associated performances (**9 months study**)

2. to **develop and test a high-sensitivity GNSS space-borne receiver** (target TRL5) that might be used in future demonstrations missions to gather data and support further system activities. The unit develop in this activity might be considered for a short In-Orbit Demonstration (IOD) mission (**18 months development**).

Proposals expected end of this year 2018. Activity planned to Be kicked-off in Feb 2019. First results available for ICG-14 in 2019.

ESPRIT Potential European Contribution to Gateway Cis-lunar space station

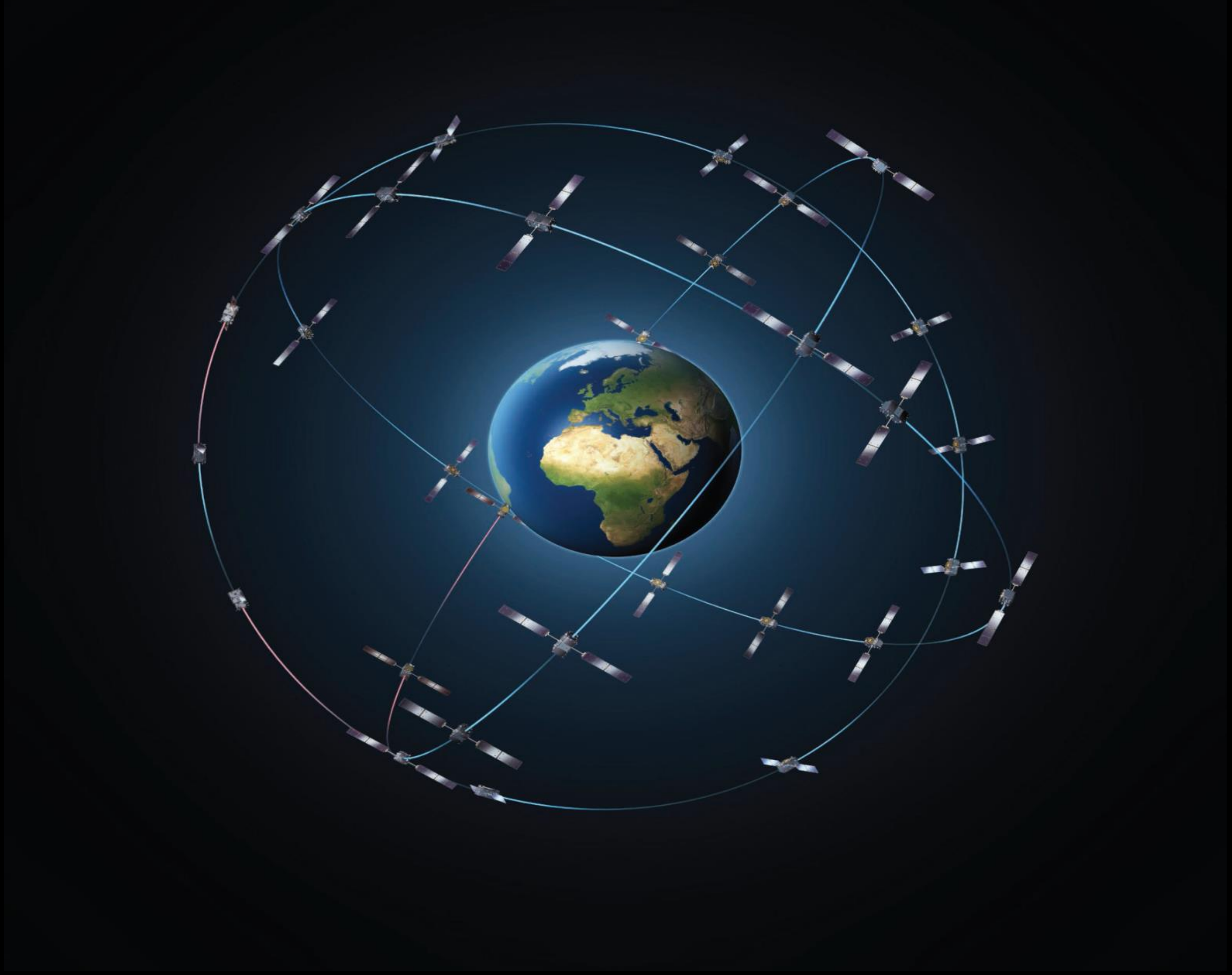




ESA ESPRIT Module contribution

FOSTERING GNSS SCIENTIFIC ACTIVITIES

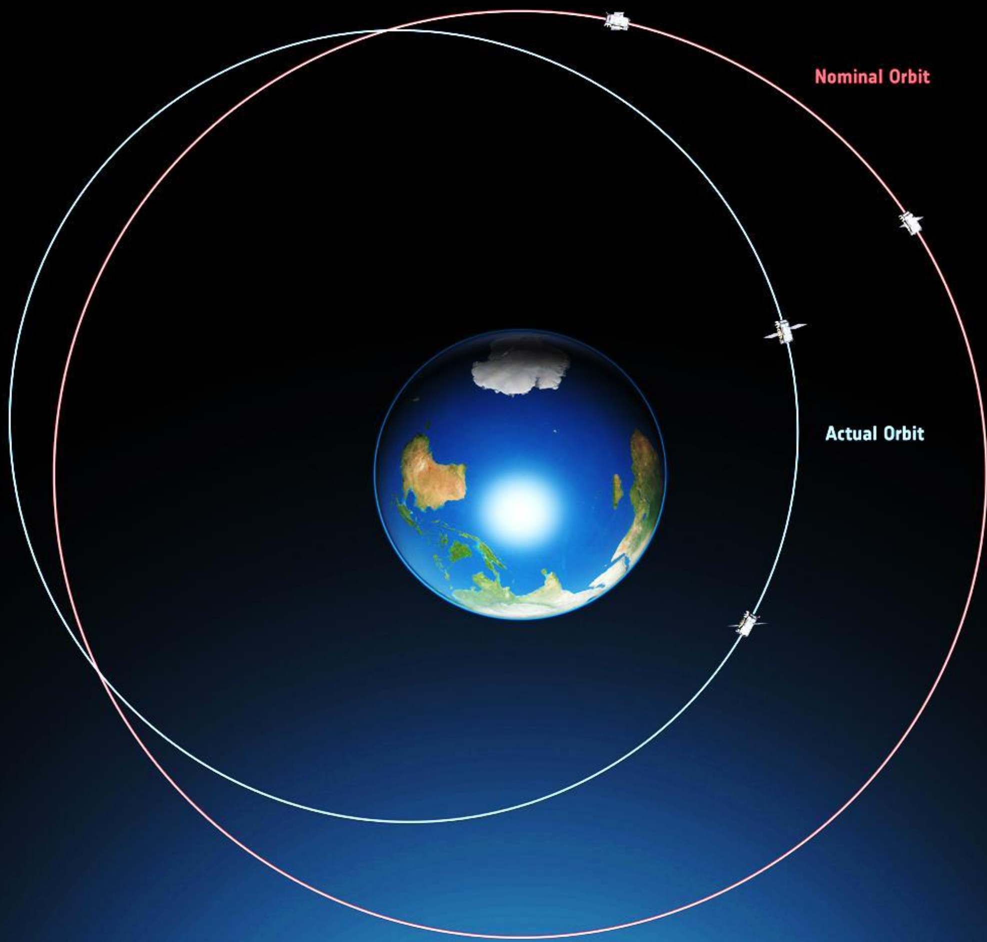
GALILEO SPECIALLY SUITED FOR SCIENCE



GALILEO SPECIALLY SUITED FOR SCIENCE

- Two on-boad two clock technologies, including Highly stable PHM atomic clocks
- New signals, robust modulation schemes with lower noise (e.g. E5-AltBOC);
- Laser Retro Reflectors present on all Galileo satellites;
- Metada public information available for Galileo IOC and FOC satellites
    - Geometry and material/optical properties
    - Satellite Group Delay
    - Mass and Centre-of-Mass provision and Laser Retroreflector Location
    - Absolute calibration of Galileo satellite antennas;
    - Accurate attitude law of Galileo satellites during eclipse.
- Galileo satellites' revolution period avoids Earth rotation resonances: Stable Galileo orbits without manoeuvres;
- Radiation monitors in a number of satellites;
- Galileo disseminates Galileo System Time (GST) and UTC information;
- Compatibility / interoperability with other GNSS systems;
- Two Galileo satellites placed in an eccentric orbit (e.g. Fundamental Physics tests).

GENERAL RELATIVITY TESTS FULLY SUCCESSFULL



GALILEO and GENERAL RELATIVITY

- 2 Galileo eccentric Satellites with 8500 km in height difference per orbit
- Very accurate PHM clock on-board
- Very accurate orbit determination
- Continuous and long-term observation
- Possibility of laser ranging measurements

Most accurate measurement ever of Einstein's predicted Gravitational Redshift. Improving GP-A tests from 1976

Two parallel Physical review Letters accepted – to appear this November 2018

A gravitational redshift test using eccentric Galileo satellites

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(Dated: May 24, 2018)

We report on a new test of the gravitational redshift and thus of local position invariance, an integral part of the Einstein equivalence principle, which is the foundation of general relativity and all metric theories of gravitation. We use data spanning 1008 days from two satellites of Galileo, Europe's global satellite navigation system (GNSS), which were launched in 2014, but accidentally delivered on elliptic rather than circular orbits. The resulting modulation of the gravitational redshift of the onboard atomic clocks allows the redshift determination with high accuracy. Additionally specific laser ranging campaigns to the two satellites have enabled a good estimation of systematic effects related to orbit uncertainties. Together with a careful conservative modelling and control of other systematic effects we measure the fractional deviation of the gravitational redshift from the prediction by general relativity to be $(-0.02 \pm 2.48) \times 10^{-5}$ at 1 sigma, improving the best previous test by a factor 5.6. To our knowledge, this represents the first reported improvement on one of the longest standing results in experimental gravitation, the Gravity Probe A hydrogen maser rocket experiment back in 1976.

The classical theory of general relativity (GR) provides a geometrical description of the gravitational interaction. It is based on two fundamental principles: (i) the Einstein equivalence principle (EEP) and (ii) the Einstein field equations that can be derived from the Einstein-Hilbert action. Although very successful so far, there are reasons to think that sufficiently sensitive measurements could uncover a failure of GR. For example, the unification of gravitation with the other fundamental interactions, and quantum theories of gravitation, generally lead to small deviations from GR (see e.g. [1]). Also dark matter and energy are so far only observed through their gravitational effects, but might be hints towards a modification of GR.

From a phenomenological point of view, three aspects of the EEP can be tested: (i) the universality of free fall (UFF); (ii) local Lorentz invariance (LLI); and (iii) local position invariance (LPI). Constraints on UFF have been recently improved by the Microscope space mission [2], while LLI was recently constrained, for example, by using a ground fibre network of optical clocks [3] (see e.g. [1, 4, 5] for reviews). In this paper we focus on testing LPI.

LPI stipulates that the outcome of any local non-gravitational experiment is independent of the space-time position of the freely-falling reference frame in which it is performed. This principle is mainly tested by two types of experiments: (i) search for variations in the constants of Nature (see e.g. [6], and [7] for a review) and (ii) gravitational redshift tests. The gravitational redshift was observed in a ground experiment for the first time by Pound, Rebka and Snider [8, 9].

In a typical clock redshift experiment, the fractional frequency difference $z = \Delta\nu/\nu$ between two clocks located at different positions in a static gravitational field is measured, by exchange of electromagnetic signals. The EEP predicts $z = \Delta U/c^2$ for stationary clocks, where ΔU is the gravitational potential difference between the locations of both clocks, and c is the velocity of light in vacuum. A simple and convenient formalism to test the gravitational redshift is to introduce a new parameter α defined through (see e.g. [1]):

$$z = \frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2} \qquad (1)$$

with α vanishing when the EEP is valid.

The so far most accurate test of the gravitational redshift has been realized with the Vessot-Levine rocket experiment in 1976, also named the Gravity Probe A (GP-A) experiment [10–12]. The frequency differences between a space-borne hydrogen maser clock and ground hydrogen masers were measured thanks to a continuous two-way microwave link. The total duration of the experiment was limited to 2 hours constrained to the parabolic trajectory of the GP-A rocket, and reached an uncertainty of $|\alpha| \le 1.4 \times 10^{-4}$ [12]. The future Atomic Clock Ensemble in Space (ACES) experiment [13, 14], an ESA/CNES mission, planned to fly on the ISS in 2020, will test the gravitational redshift to around $|\alpha| \le 3 \times 10^{-6}$. Furthermore, other projects like STE-QUEST propose to test the gravitational redshift at the level of

Led by SYRTE/ Obsevatoire de Paris

Test of the gravitational redshift with Galileo satellites in an eccentric orbit

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(Dated: June 3, 2018)

On August 22, 2014, the satellites GSAT-0201 and GSAT-0202 of the European GNSS Galileo were launched into space, but failed to reach their nominal orbit. Instead they were injected into an eccentric orbit and only after several correction maneuvers their continuous operation could be secured. This mishap turns out to be a fortunate opportunity for testing fundamental physics since the onboard atomic clocks – now on an eccentric orbit ($e \approx 0.16$) – allow for a sensitive test of General Relativity. Here we report on an analysis of approximately three years of data from these satellites including three different clocks. From this we determine the test parameter quantifying a potential violation of the combined effects of gravitational redshift and relativistic Doppler effect $\alpha = (-1.0 \pm 1.6) \times 10^{-5}$ representing a 4-fold improvement over the measurement of Gravity Probe A in 1976.

INTRODUCTION

The frequency shift that any clock experiences in a gravitational potential is at the very heart of the theory of General Relativity. The universal validity of this gravitational redshift is one constituent of the Einstein Equivalence Principle, which provides the underlying foundation of the theory [1]. Putting this very foundation to test still remains of fundamental importance, even though in more than 100 years, General Relativity has passed all such experimental tests and seen many of its predictions verified, culminating in the recent detection of gravitational waves by the LIGO consortium [2]. Yet, with the nature of dark matter and dark energy not understood and a unifying theory of quantum gravity still elusive, certainly no full understanding of gravity can be claimed today. Only recently, the MICROSCOPE mission [3] could achieve an improved test of another aspect of the Einstein Equivalence Principle by testing the universality of free fall of two test masses in orbit at a precision of $\eta < 2 \times 10^{-14}$. The gravitational redshift on the other hand has only been tested at a relative precision several orders of magnitude below this [4–7]. Its first experimental verification was provided by Pound and Rebka in 1960 [4], when they detected the effect using a Mössbauer emitter and absorber over a height difference of ≈ 23 m. The most accurate test so far dates back to 1976, when the Gravity Probe A (GPA) mission sent a hydrogen maser on board a Scout rocket on a trajectory reaching 10000 km in altitude. During the flight they performed an accurate frequency comparison to a ground based maser and verified the total relativistic frequency shift including the relativistic Doppler shift to within 7×10^{-5} total uncertainty [6].

Today, 40 years later, a very much unexpected opportunity to improve on this fundamental test presents itself as has been pointed out in [8]: In August 2014 the two Galileo GNSS satellites GSAT-0201 and GSAT-0202 equipped with passive hydrogen maser clocks were accidentally sent to an eccentric orbit. In this letter we report on how we use the clock data from these satellites to obtain an accurate test of the gravitational redshift competitive with and even improving the result from GPA.

GRAVITATIONAL REDSHIFT FOR GALILEO SATELLITES

The elapsed coordinate time t for a clock moving along a path in a weak gravitational potential U at a velocity v can be derived from

$$\int dt = \int d\tau \left(1 - \frac{U}{c^2} + \frac{v^2}{2c^2}\right), \qquad (1)$$

where t is the coordinate time and τ denotes the clock's proper time. The second term in the bracket accounts for the gravitational redshift and the third for the relativistic Doppler effect. The resulting time delay is nowadays routinely taken into account in Global Navigation Satellite Systems (GNSS) [9]. For a clock on a Kepler orbit of semi-major axis a and eccentricity e it can be written as

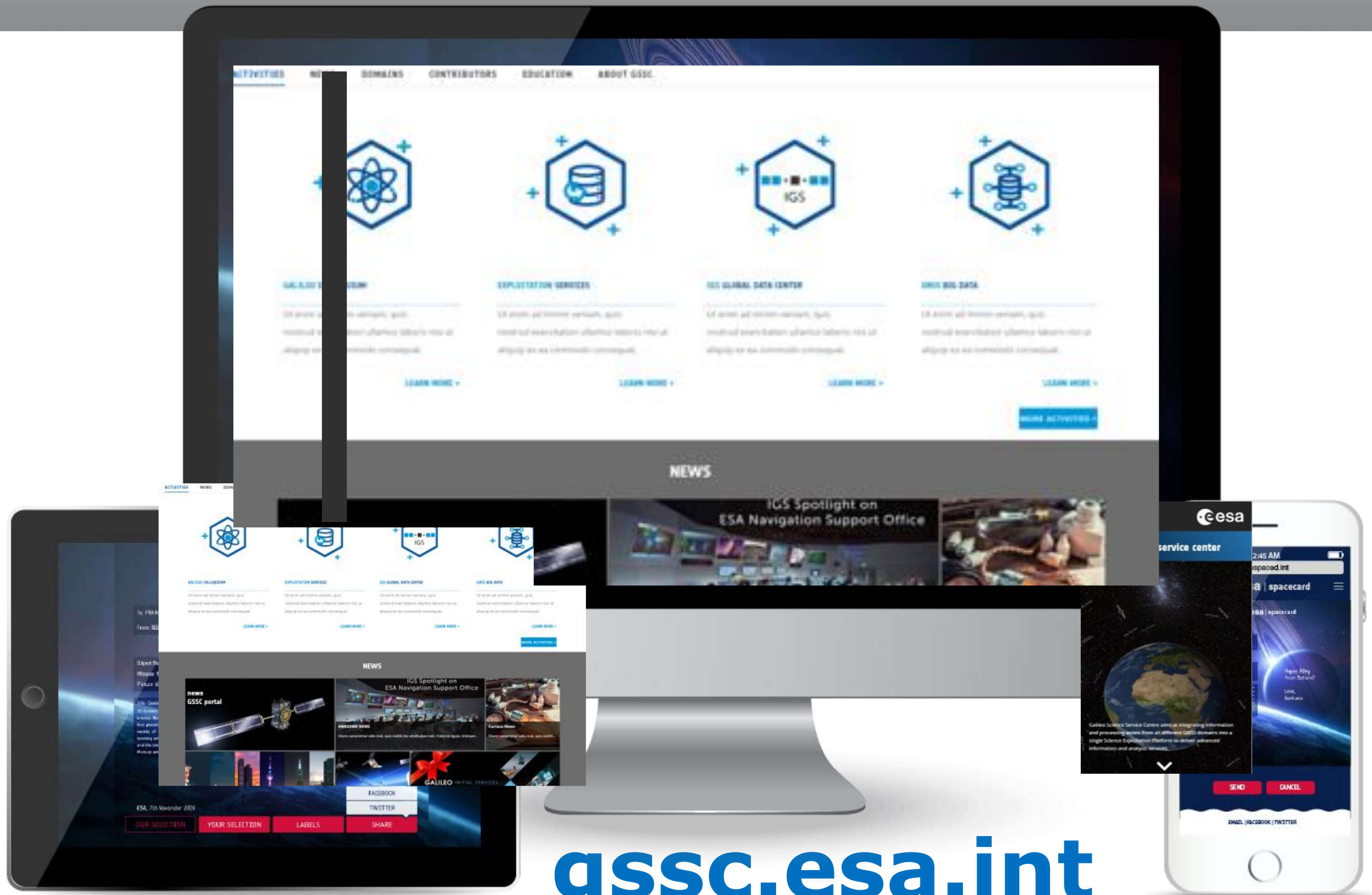
$$\Delta t = \left(\frac{3GM_E}{2ac^2} + \frac{\Phi_0}{c^2}\right)t + \frac{2\sqrt{GM_E a}}{c^2} e \sin E(t). \qquad (2)$$

Here $E(t)$ is the eccentric anomaly of the orbit and Φ_0 accounts for the gravitational potential at the location of the Earth based reference clock. This equation provides a constantly accumulating first term, as well as a second term that is modulated due to the eccentricity of the orbit. The latter is usually very small, nonetheless it is applied as an eccentricity correction in GNSS, rewritten as

$$t_{\mathrm{rel}} = \frac{2\vec{v}\cdot\vec{r}}{c^2}. \qquad (3)$$

Led by ZARM/ Univ. of Bremen

Galileo Science Support Centre (GSSC) portal opens this week



gssc.esa.int

The GNSS Science Support Centre (GSSC) is and initiative of ESA to foster GNSS scientific research and cooperation. It aims at integrating information and processing assets from all different GNSS scientific domains into a single virtual archive.

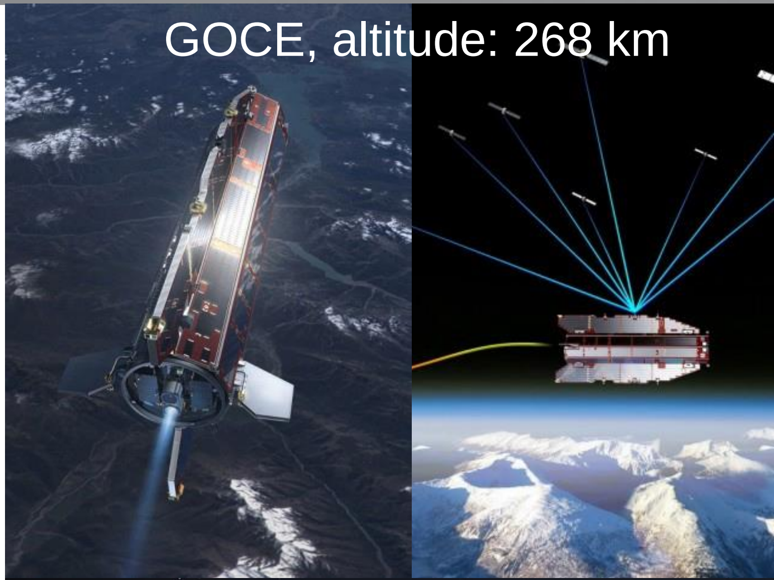
ESA GSSC Facilities at ESAC, Madrid (Spain)

Located at European Space Astronomy Center - ESAC

Towards a worldwide reference GNSS Science Exploitation and Preservation Platform

Towards the provision of a GNSS spaceborne data repository for scientific Research

- ESA intends to provide via ESA's GSSC portal single-entry point availability of **public GNSS data observables from ESA/EU Earth Observation satellite missions**.
- First natural candidates **ESA Earth Explorers** and **EU Copernicus ESA Sentinel satellites** (GOCE and SWARM data already included)
- **Interest for scientific purposes and in support to future GNSS SSV activities.**
- **Interest for international cooperation. Proposed for discussion at WG-B**.



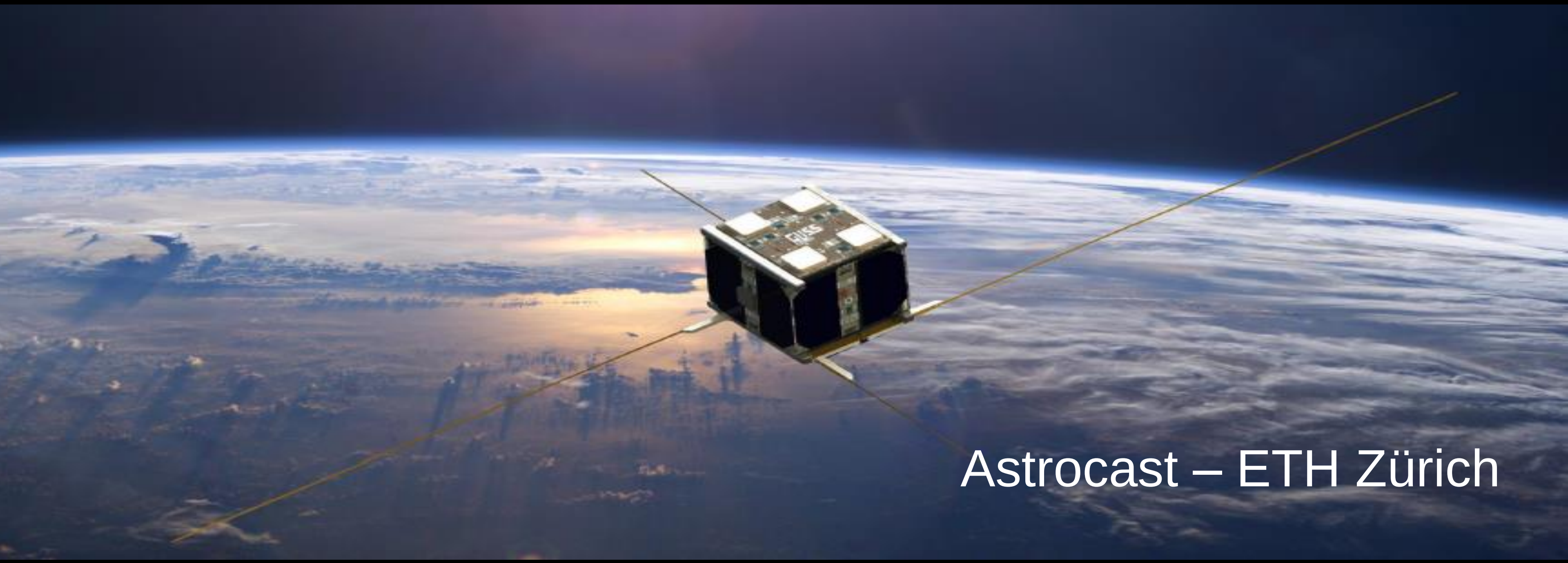
SENTINEL SATELLITES

ESA/EUTMETSAT MetOp – C launch on Nov 7, 2018
with GNSS Radio oculation (GRAS instrument)

STUDIES PLANNED BY ESA IN SUPPORT TO PNT SCIENCE (Part of ESA NAVISP and EU H2020 programs 2018-2019)

1. **Weather Monitoring based on GNSS and Crowdsourcing (IoT and GNSS Science)**
2. **GNSS science exploiting commercial aircrafts**
3. **Space weather and GNSS (nowcasting & forecasting)**
4. **Pulsar time-scale demonstration**
5. **Space-based relativistic PNT system**
6. **PNT using Neutrino Particles**
7. **GNSS and Dark matter**
8. **GNSS Big Data processing in support to science**
9. **Dedicated Cubesat GNSS Science program**
10. **GNSS performance at Polar & Antarctic latitudes**

Supporting GNSS Scientific Cubesats with Universities



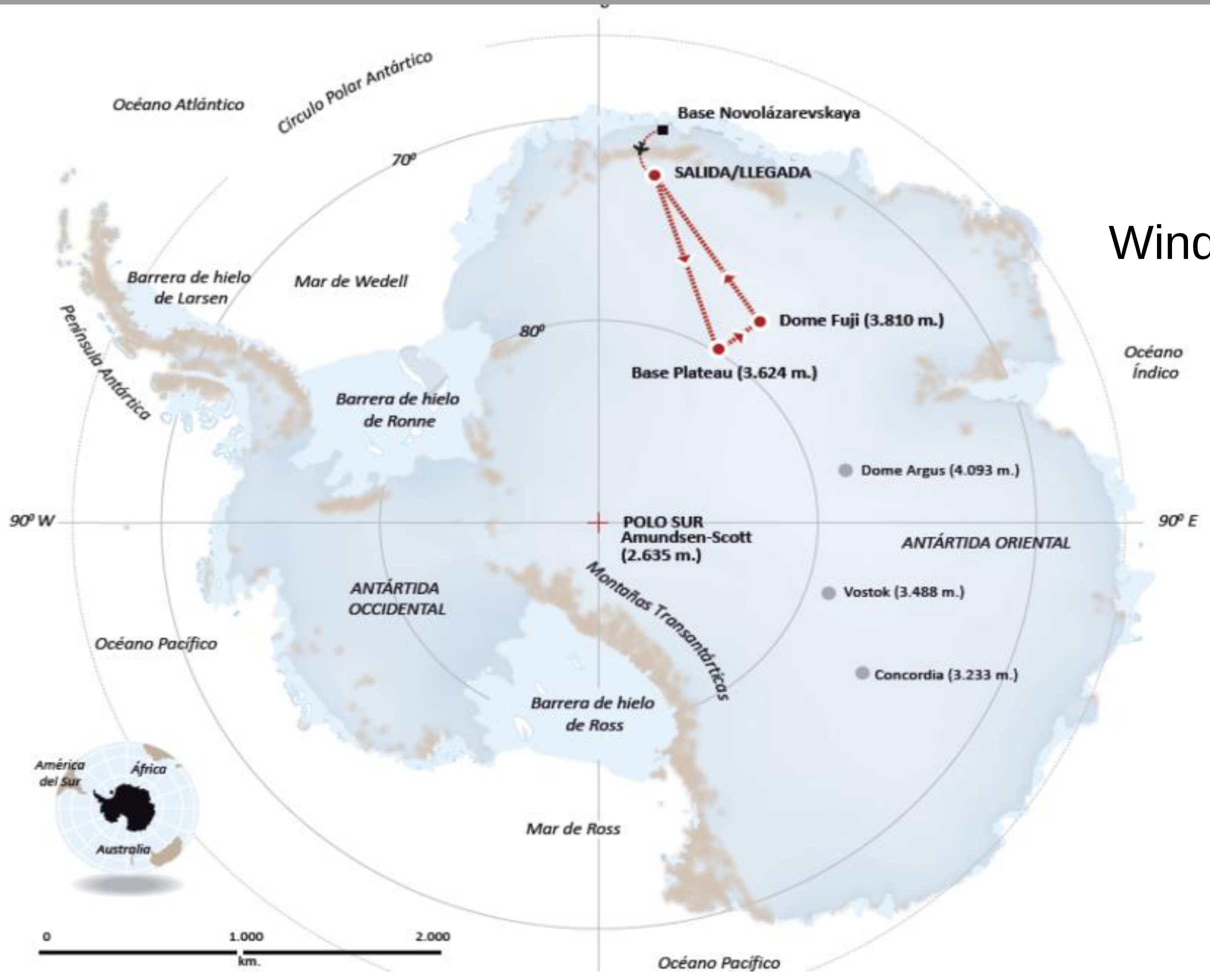
Launch planned 19th Nov 2018.It includes several GNSS scientific tests (e.g. POD, air density estimation, radio occultation, etc). First GNSS receiver in space tracking 5 GNSS Systems (GPS, Galileo, Glonass, Beidou and QZSS)

Measuring Galileo performance in the Antarctica and performing several scientific tests (e.g. ionosphere, scintillation, etc)

Windsled expedition planned from Dec 2018 to Feb 2019

First ever measurement of Galileo perfromances in Antarctica with the nominal Galileo constellation

WindSled expedition



7th GNSS / GALILEO Scientific Colloquium, 2019

Scientific and Fundamental Aspects of GNSS / Galileo

7th International Colloquium

Organised by ESA and ETH University, Zurich in 2019

This bi-annual colloquium brings together members of the International scientific involved in the use of Galileo and other GNSS in their research. The various possibilities to use GNSS satellites for scientific purposes are reviewed in detail during 3 days.


Thank you !