Testing theories of gravitation with the Interstellar Probe Radio Experiment

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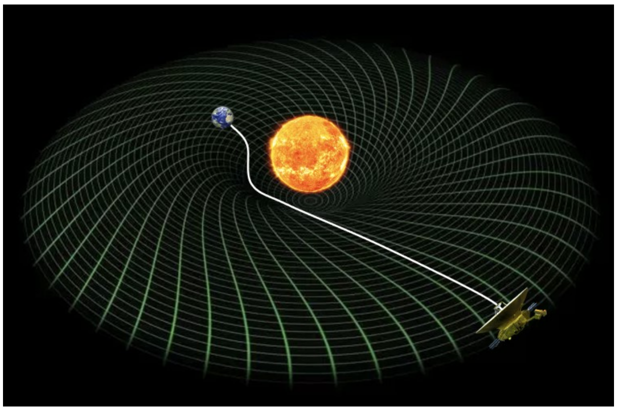
Abstract

General Relativity (GR) will soon celebrate its 110th birthday, holding up against all experimental enquiry. Nonetheless, unification theories attempting to quantize gravity, such as string theory, are gaining footing. These hypothesize additional scalar, vector, and tensor long-range fields that couple to matter [33], introducing violations to GR. Although the latter have never been detected, it is possible that Einstein will not have the last word. What is certain is that gravity tests are still alive, pushing the validity of GR to new scales and accuracies, or -potentially- suggesting alternative routes for new physics.

Building upon the legacy of Voyager and Pioneer, which demonstrated outer Solar System exploration capabilities, the Interstellar Probe mission concept [24] aims to characterise our heliosphere through state-of-the-art instrumentation, opening new frontiers for GR testing. In this work, we investigate the possibility of constraining the Eddington parameters β and γ, the Nordtvedt parameter η and the mass of the graviton via the Compton wavelength λ_C, by processing 10 years of radiometric data from the Interstellar Probe. To achieve this, we propose a radio link strategy for delivering ranging with accuracies at the 1 meter level.

Numerical simulations suggest a lower bound $\lambda_C > 10^{14}$ km, outperforming the most optimistic bounds obtained from planetary ephemerides [7] and gravitational wave detection methods [2]. The attainable accuracy on γ, β and η is $\approx 10^{-5}$, comparable to that of the Mercury Orbiter Radioscience Experiment (MORE) onboard BepiColombo performed during cruise [15]. The proposed experiment interrogates fundamental physics from an unique dynamical setting, investigating possible violations of the Einstein Equivalence Principle (EEP) underlying GR.



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1. Introduction

Although Einstein's Equivalence Principle (EEP) underlies General Relativity (GR), there are no strong theoretical reasons to expect this principle to be valid in nature, suggesting that GR should be replaced by a more inclusive theory of gravity [14]. In fact, many theories support a violation of the EEP at some level, both from the effects of quantum gravity and those deriving from string theory [33]. This motivates conducting tests of GR, the EEP, and the $1/r^2$ law, in an effort to search for new interactions.

Exposure to large gravitational potentials and the accompanying velocity variations have endowed spacecraft with wide signals for testing fundamental theories of gravity, exploited via atomic clocks, interferometers and laser ranging experiments. On astronomical scales, experiments have been conducted, such as gravitational-wave detection [1], which show consistency with GR predictions. Yet, at intermediate scales (10-1000 AU, see Figure 1) gravity has never been accurately tested. Closing this gap is foreseeable with the performances of modern radiometric techniques and instrumentations, capable of unprecedented measurement accuracies, such as the cm-level ranging accuracy demonstrated by BepiColombo [10].

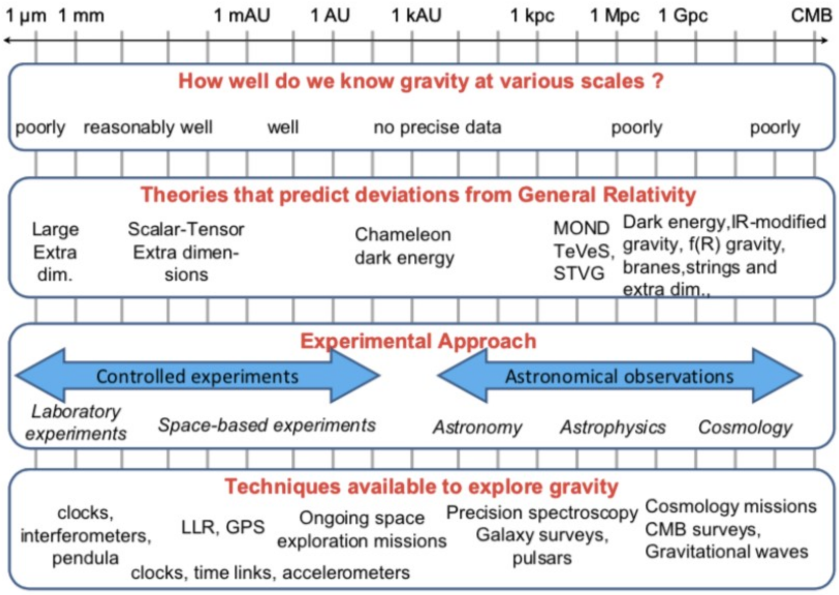

Figure 1: Knowledge of gravity at different scales (adapted from [31])

An Interstellar Probe mission concept [24] is expected to travel faster and further than any preceding spacecraft (7 AU/year) building upon the heritage of Voyager and Pioneer to explore our galactic 'neighbourhood' via a consortium of instruments. Its spin-stabilisation and favourable X-band antenna aperture curtail the need for re-orientation manoeuvres, enabling accurate temporal resolution of non-gravitational signals. In light of these arguments, this represents an unique dynamical framework to conduct the aforementioned gravity tests

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at unprecedented scales. The aim of this work is to simulate this experiment by means of a covariance analysis, processing 10 years of radiometric observables.

The first part of the experiment concerns the comparison and classification of alternative metric theories of gravity, for which we adopt the parametrized post Newtonian (PPN) formalism [35]. This expresses the Einstein field equations in terms of small deviations from Newton's laws, quantified by a set of parameters which take specific values in each theory. We set out to measure the Eddington parameters β and γ, expressing the non-linearity in the superposition law for gravity and the space-time curvature produced by a unit rest mass [32], respectively. We also measure the Nordtvedt parameter η, searching for possible violations of the EEP for massive bodies [33]; in other words, we verify that the probe and the Earth fall towards the Sun at the same rate, irrespective of their gravitational self-energy.

The second part concerns scalar–tensor modifications of GR, many of which suggest a coupling between the scalar field and matter [14]. This coupling can be expressed by the Compton wavelength λ_C of the massive graviton in the Yukawa form. Its effect would be that of a "fifth force" violating the $1/r^2$ law at macroscopic scales.

2. Dynamical Model

Given the high performing tracking system foreseen to be operating on the probe, the dynamical model must accurately describe all non-gravitational accelerations acting on the spacecraft. Partly due to the fact that the subsistem design is not finalized yet, we refrain from a specific implementation of the non gravitational accelerations, but rather opt for an empirical approach based on a stochastic modelling with conservative a-priori values for the associated uncertainties. During the actual mission, onboard sensor measurements will help restricting the a-priori values, for a more refined orbit determination process.

Figure 2 schematizes the forces acting on the probe: gravity (magnitude: $10^{-4} \sim 10^{-5}$m/s^2), anisotropic thermal re-radiation by the Radioisotope Thermoelectric Generators (RTGs) ($\sim 10^{-9}$m/s^2), solar radiation pressure ($\sim 10^{-10}$m/s^2), and interstellar dust drag ($\sim 10^{-15}$m/s^2). In addition, re-orientation manoeuvres are simulated once per month, and estimated with a residual thrust uncertainty in the antenna plane direction. Charged-particle effects are yet to be investigated, since little is known on the spacecraft's potential charge during flight [3].

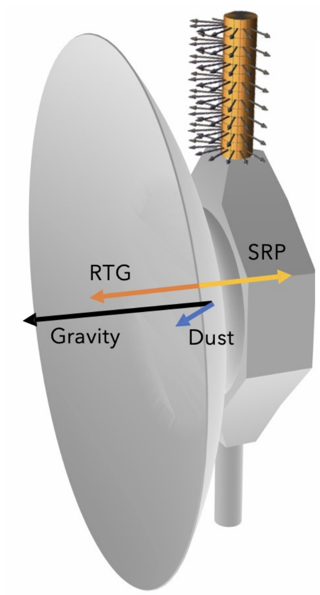

Figure 2: Forces acting on the ISP. Direction is representative for most of the trajectory. The RTG thermal re-radiation is also shown.

The equations of motion are integrated using a variable-step, variable-order numerical integrator [25]. The positions of the planets and moons are obtained from DE438 planetary ephemerides [17]. Light propagation is correct to order c^{-2} [11]. To define a reference trajectory, the boundary conditions from the proposed baseline [30] have been adopted. This starts from a Jupiter gravity assist in 2037, and crosses the IBEX ribbon at (-180E, -22S) after approximately 14.8 years.

2.1. Modified Newtonian Gravitation

In the simplest form of the massive graviton scenario, Newton's gravitational potential is multiplied by a Yukawa exponential [34]:

$$U = -G \sum_{i \neq j} \frac{m_i m_j}{r_{ij}} \mathrm{e}^{-r_{ij}/\lambda_C} \quad (1)$$

where r_{ij} is the distance between the distance between bodies i and j. Thus, the effect of λ_C will become more pronounced as the test body travels further from the attracting body. For present purposes, a fair approximation is to solely consider the contribution of the Sun.

To date, various methods have been used to placed lower bounds on λ_C. Ref. [32] argued that, if the graviton is massive, gravitational waves would travel slower in accordance with their wavelength. Consequently, the LIGO-Virgo detectors would sense this distortion of wavefronts. Cataloguing a series of gravitational wave events, [2] have reached a lower bound of $9.8 \cdot 10^{13}$ km. A similar constraint has been obtained via the observation of galaxy clusters [28]. Ref. [7] have placed a competitive bound of $3.9 \cdot 10^{13}$ km by dynamical fitting of INPOP (19a) ephemerides. Different studies have proposed ways to improve these constraints by a joint analysis of multiple planetary probes [15, 13]

2.2. Anisotropic RTG thermal re-radiation

The spacecraft will generate forces as thermal radiation is emitted from its surfaces in an anisotropic manner. Its build up can be significant over long timescales: had it not been for corrective manoeuvres, New Horizons would have undergone a position error of 185000 km [29]. Moreover, this effect is now widely believed to be the culprit for the mysterious 'Pioneer Anomaly' detected from the Doppler tracking data of the Pioneer 10 and 11 spacecraft [4].

In accordance with energy equilibrium, the power radiated by the RTGs is equal to the heat production (which follows the decay of plutonium) minus the fraction converted to electricity. The re-radiation off the spacecraft body is computed using the pyRTX[1] non-gravitational accelerations computation library. The antenna is the main contributor to this reflection, which induces an deceleration along the boresight direction (towards the Earth). Our analysis agrees with the findings by [29], comparing this acceleration for New Horizons and the Interstellar Probe, which are similar from a thermal control design standpoint. In contrast with New Horizons, here the symmetry of the RTGs does not give rise to any residual torque. Nonetheless, due to the protracted mission duration, material degradation is expected to take place, which will vary the thermo-optical properties of the insulating material. Hence, these are appended as stochastic parameters in the estimation filter.

2.3. Interstellar Dust Drag

The spacecraft will experience a drag force arising from the presence of interstellar dust particles. The dust density models of Ref. [21] have been adopted to simulate these impacts, yielding the resulting acceleration shown in Figure 3. The force direction is influenced primarily by the motion of the Solar System in the interstellar medium, which is roughly 26km/s. The main limitation lies in the fact that the flux of

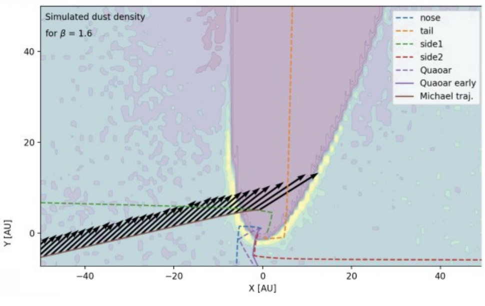

Figure 3: Dust drag magnitude and direction for the reference trajectory. The β ratio reflects the dust optical properties, morphology, and size, constraining the gravitational focusing effect. Courtesy of [21]

[1] https://github.com/gaelccc/pyRTX

the largest particles dominates the drag calculation, yet these are also loosely constrained. Nonetheless, this will be partly overcome by in-situ measurements via the dust impact analyser.

3. Observation Model

The observation model outlines the type and accuracy of radiometric data that is simulated in the experiment. The onboard communication system consists of a 5m X-Band High Gain Antenna (HGA) using 52W of transmitting power [5]. During the first 10 years of flight, as the spacecraft travels trough inner heliosphere (70 AU), it will be tracked by the Deep Space Network (DSN) with three 8h passes a week.

In contrast to most interplanetary missions, whereby Doppler is the primary observable, here the majority of the information is cast in the ranging measurements, as these are more sensitive to the slowly-varying dynamics [16] experienced in interstellar space. In this case, Pseudo Noise (PN) regenerative ranging is simulated in two-way or three-way mode. This offers the distinct advantage of creating a relatively noise-free copy of the uplink signal for modulation onto the downlink carrier [6]. To evaluate the foreseeable noise contributions in the PN regenerative ranging signal, a link budget was developed and summarised below.

The science downlink at 1000AU necessitates an upgrade of DSN capabilities in terms of electronic synchronised collectors, as to enable a larger effective aperture via the combination of multiple antennas [5]. Consequently, the signal-to-noise ratio in the downlink receiving chain is maximised, meaning the thermal contribution to the range jitter is relatively low.

The assessment of range systematics is more complex, primarily due to the difficulty in separating media effects from station biases [22], requiring their inclusion in the estimation filter. These arise primarily from ionospheric and -wet- tropospheric effects. Note that plasma delays are absent due to the southern ecliptic latitude of the baseline trajectory. At the same time, this latitude suggests the use the DSN complex at Canberra (Australia) to maximise the antenna elevation therefore limiting atmospheric effects. Based on Figure 4 one may suggest a measurement campaign as follows:

- 2-Way Range and Doppler with Canberra until 2040;
- 3-Way Range and Doppler with Canberra (Up) & Madrid (Down) until 2044;
- 3-Way Range and Doppler with Canberra (Up) & Goldstone (Down) until 2047;
- Delta Differential One-Way Ranging (DDOR) continuously.

Ranging measurements at interstellar scale have never been achieved, adding to the innovativeness and logistical complexity of the experiment. Aside from physical considerations, one must consider delays associated with the (relativistic) Round Trip Light Time (RTLT) of the signal, which is solved as part of the orbital solution.

Note that in regenerative ranging, the coherent transposition of the signal does not rely on an onboard frequency reference. Nonetheless, the precise transmission and reception times are needed to correlate the signal. For present purposes the Station Time (ST) is especially significant. This is an atomic time showing slight deviations from the reference time (UTC). For the case of 2-Way ranging (i.e. same uplink and downlink station), the relevant quantity

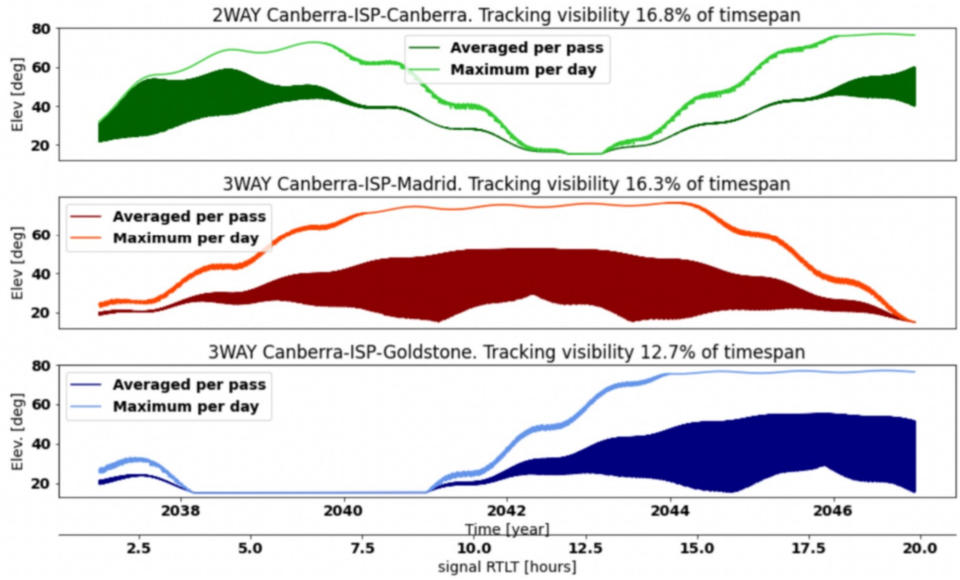

Figure 4: Interstellar Probe elevation and visibility windows per DSN complex. Canberra selected for uplink to curtail atmospheric delays. Elevation cutoff is set at 15 deg.

is the ST stability: H-masers can guarantee a stability of 10^{-15} over 1000s [6], yielding a negligible contribution to the noise. For 3-Way ranging, however, one must correct for ST offsets between participating stations. This is nowadays achievable to the ns-level by means of GPS and two-way satellite time and frequency transfer [26, 18].

Finally, there is always some delay between the onboard receipt of a signal at the front end of the HGA and the retransmission at the HGA aperture, due to bus traffic and rerouting and processing in the onboard electronics [9]. The residual uncalibrated delay is assumed to be at the ns-level, in line with modern transponders such KaT on BepiColombo [10].

In light of the above discussion, ranging data is simulated as having a random noise contribution of 1m at 300s integration time, which is in agreement with 2-Way PN regenerative ranging residuals for New Horizons [23]. To cover a representative spectrum of cases, station biases are estimated every 2 weeks (best case) as well as every day (worst case).

4. Discussion & Conclusion

We have adopted a covariance analysis to simulate the estimation accuracy for a series of parameters associated with GR, by processing 10 years of radiometric data from the Interstellar Probe. The methodology rests on the assumption that DSN stations will perform clock synchronization to the ns-level to enable accurate 3-Way PN ranging observables, as well as an augmentation the antenna aperture capabilities to maximise the downlink signal.

The formal uncertainties from the covariance analysis are reported in Table 1. The estimation bounds are a result of the variable range bias stability, that will be tightened when additional ground station specifications become available. Evidently, the most significant breakthrough is projected in λ_C, which can be estimated effectively at large distances. This would test the validity of the $1/r^2$ law at unprecedented accuracies, or suggest a coupling of matter by demonstrating that the graviton does indeed hold a mass. The estimate of η is also promising, which would serve to (dis)prove the validity of the EEP for all self-gravitating bodies in an external gravitational field. The parameters β and γ only show a marginal improvement; the present estimates outperform the BepiColombo MORE experiment at cruise, but not during the extended orbit phase [12]. Still, these could serve as auxiliary proof of GR validity at Solar System scales.

To reflect on the influence of GR deviations on our setup as compared to the 'classic' case of planetary orbiters, Figure 5 displays the partial derivatives of the Interstellar Probe (left) and the Earth (right) states with respect to the sought parameters. In the Earth -equivalently, planetary orbiter- case, the partials are of secular and/or periodic nature, with planar components almost indistinguishable. On the other hand, the left partials inflict a more distinct signature, manifested as an initial 'kick' which deviates the trajectory over time. These steady-state dynamics stress the importance of accurate and continuous ranging measurements in the prospect of future GR tests.

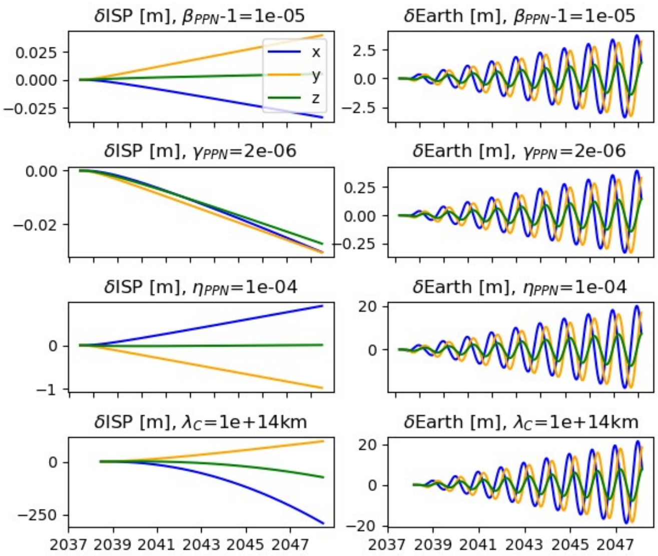

Figure 5: Amplitude of deviation in the ISP (left) & Earth (right) states with respect to parameters of interest, multiplied by their respective a-priori knowledge.

The numerical models presented in this work will need to be refined, and some logistical challenges associated PN ranging measurements at interstellar scales remain to be investigated. Yet, these preliminary results are very promising. The Interstellar Probe mission concept offers an unique dynamical setup to test the validity of GR at new scales without any dedicated payload. Moreover, we strongly recommend augmenting the tracking campaign to beyond 10 years as to further tighten the uncertainties on the sought parameters, especially λ_C which displays an exponential signature.

Table 1: Preliminary results for covariance analysis

Parameter	**Formal Error**	**Theoretical Value**	**Current knowledge**
(X,Y,Z) ISP [m]	(35,85$\sim$ 90, 89 $\sim$ 90)	N.A.	100m
acc_{RTG} [m s^{-2}]	$<10^{-12}$ $>10^{-15}$	$2.98\cdot10^{-9}$ boresight	$0.5\cdot10^{-10}$ from New Horizons thermal analysis [19]
γ-1 [-]	$1.5\cdot10^{-5} \sim 9.1\cdot10^{-6}$	0	$2.3\cdot10^{-5}$ from Cassini [8]
β-1 [-]	$3.8\cdot10^{-5}$	0	$3.9\cdot10^{-5}$ from MESSENGER [27]
η [-]	$4.7\cdot10^{-5} \sim 2.1\cdot10^{-5}$	0	$1.1\cdot10^{-4}$ from LLR [20]
λ_C lower bound [km]	$8.61\cdot10^{13} \sim 1.07\cdot10^{14}$	∞	$7.1\cdot10^{13}$ from grav. waves [2] $3.9\cdot10^{13}$ from INPOP [7]

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