Fundamental Physics in Space and Required Technologies

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Abstract

Space combined with a range of advanced technologies enables vitally important Fundamental Physics experiments that are impossible to perform on the ground. These *in situ* controlled experiments expand our understanding of nature in ways that are critically different from space based observational missions. In the following we describe recent work focusing on three related areas encompassing the scientific rationale for improved Equivalence Principle tests, the investigation of advanced precision drag free and attitude control space systems, and the modeling of forces and torques on gravitational proof masses.

1) The Scientific Rationale For Improved Equivalence Principle Tests

(with Francis Everitt, Suwen Wang, and Paul Worden, Stanford, and James Overduin, the Johns Hopkins University)

Central to Einstein's interweaving of space, time, and gravity into his general theory of relativity is a peculiar fact, first seen by Newton, which marks off gravity from all other forces of nature. Consider the two formulae $F = ma$ and $F = GMm/r^2$. Mass enters both, but in different roles; first as the receptacle of inertia and second, the source of gravitation. Taking this unexplained 'equivalence' of these two 'm's as fundamental, Einstein made it one of the two founding assumptions of GR. A consequence of the observed equivalence is the so called Universality of Free Fall – objects of different composition should fall with the same acceleration in a uniform gravitational field. Since the time of Newton this consequence has been used to test the EP to higher and higher precision. The laboratory of space will enable advances over the present limits by a factor of 10^5.

Abstract of STEP

STEP (the Satellite Test of the Equivalence Principle) will advance experimental limits on violations of Einstein's equivalence principle (EP) from their present sensitivity of 2 parts in 10^{13} to 1 part in 10^{18} through multiple comparison of the motions of four pairs of test masses of different composition in an earth-orbiting drag-free satellite. Dimensional arguments suggest that violations, if they exist, should be found in this range, and EP violations are also predicted by many of the leading attempts at unified theories of fundamental interactions (e.g. string theory), as well as cosmological theories involving dynamical dark energy. Discovery of a violation would constitute the discovery of a new force of nature and provide us with a critical signpost toward unification. A null result would be just as profound, because it would close off any possibility of a natural-strength coupling between standard-model fields and the new light degrees of freedom that nearly all such theories predict (e.g., dilatons, moduli, quintessence). STEP should thus be seen as the intermediate-scale component of an integrated strategy for fundamental physics experiments that already includes particle accelerators (at the smallest scales) and supernova probes (at the largest). The former may find indirect evidence for new fields via their missing-energy signatures, and the latter may produce direct evidence through changes in cosmological equation of state, but only a gravitational experiment like STEP can go further and reveal how or whether such a field couples to the rest of the standard model. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

STEP Science Goals

The Satellite Test of the Equivalence Principle (STEP) will probe the underlying foundation of Einstein's General Theory of Relativity, the (local) equivalence of gravitational and inertial mass, often called the weak equivalence principle. The equivalence principle (EP) originated in Newton's clear recognition (1687) of the strange experimental fact that mass fulfills two conceptually independent functions in physics, as both the source of gravitation and the seat of inertia. Einstein's "happiest thought" (1907) was the realization that the local equivalence of gravitational and inertial mass tells us something very deep about gravity: it tells us that the phenomenon of gravitation does not depend on the properties of matter (for it can be transformed away by moving to the same accelerated frame, regardless of the mass or composition of the falling object). Rather, the phenomenon of gravity must spring from the properties of spacetime itself. Einstein eventually identified the property of spacetime that is responsible for gravitation as its curvature. General relativity, our currently accepted ”geometrical" theory of gravity, thus rests on the validity of the EP. But it is now widely expected that general relativity must break down at some level, in order to be united with the other fields making up the standard model of particle physics. It therefore becomes crucial to test the EP as carefully as possible. Historically, there have been four distinct ways of testing equivalence: (1) Galileo's free-fall method, (2) Newton's pendulum experiments, (3) Newton's celestial method (his dazzling insight that moons and planets could be used as test masses in the field of the sun) and (4) Eotvos' torsion balance. Of these, (3) and (4) are at present the most exact: the celestial method now makes use of lunar laser ranging to place limits on the relative difference in acceleration of the earth and moon toward the sun of $3*10^{-13}$ [1], and constraints of $0.3 +- 1.8*10^{-13}$ come from modern state-of-the-art torsion balance experiments[2]. But both these methods have reached an advanced level of maturity and it is unlikely that they will advance significantly beyond the 10^{-13} level in the near term. STEP is conceptually a return to Galileo's free-fall method, but one that uses a 7000 km high ”tower" that constantly reverses its direction to give a continuous periodic signal, rather than a single shot 3 s drop. A free-fall experiment in space has two principal advantages over terrestrial torsion-balance tests: a larger driving acceleration (sourced by the entire mass of the earth) and a quieter environment, particularly if drag-free technology is used. These and other factors will enable STEP to improve existing constraints on EP violation by five to six orders of magnitude, from $2x10^{-13}$ to $1x10^{-18}$[3-5]

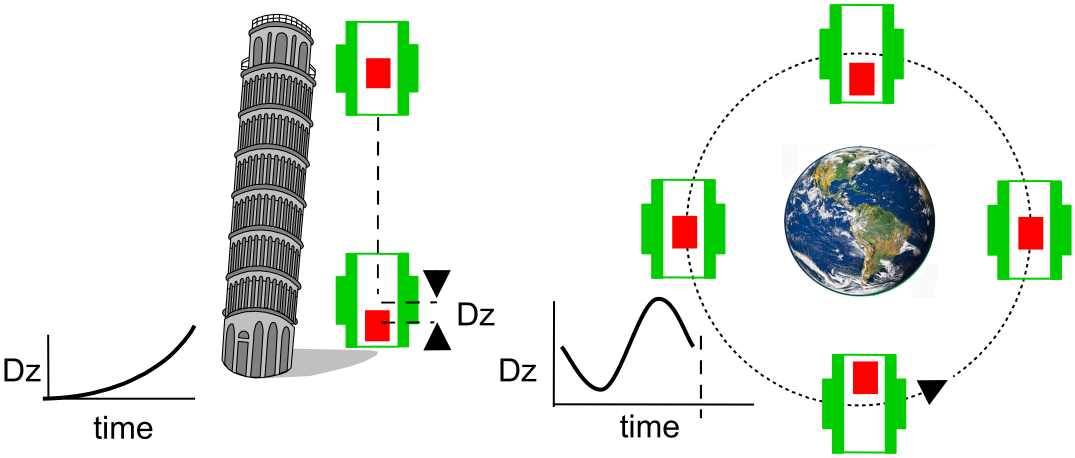

Figure 1 STEP experimental concept: masses of different composition (depicted by red and green) fall in the gravity field of the earth. An EP violation gives rise to a periodic signal in an orbiting experiment with radially constrained test masses.

Theoretical Motivation

Theoretically, the range $10^{-13} < \partial a/a < 10^{-18}$ is extremely interesting. This can be seen in at least three ways. The simplest argument is a dimensional one. New effects in any theory of quantum gravity must be describable at low energies by an effective field theory with new terms like $\beta(m/m_{QG}) + O(m/m_{QG})^2$ where β is a dimensionless coupling parameter not too far from unity and m_{QG} is the quantum-gravity energy scale, which could be anywhere between the grand unified theory (GUT) scale m_{GUT} $\sim 10^{16}$ GeV and the Planck scale m_{Pl} $\sim 10^{19}$ GeV. In a theory combining gravity with the Standard Model, m could plausibly lie anywhere between the mass of an ordinary nucleon (m_{nuc} ~1 GeV) and that of the Higgs boson (m_H ~100 GeV). With these numbers one finds that EP-violating effects should appear between $(m_{nuc}/m_{Pl}) \sim 10^{19}$ and (m_H/m_{GUT}) $\sim 10^{14}$, the range of interest. This makes STEP a potential probe of quantum gravity [6].

The dimensional argument, of course, is not decisive. A second approach is then to look at the broad range of specific theories that are sufficiently mature to make quantitative predictions for EP violation. There are two main categories. On the high-energy physics side, EP violations occur in many of the leading unified theories of fundamental interactions, notably string theories based on extra spatial dimensions. In the low-energy limit, these give back classical general relativity with a key difference: they generically predict the existence of a four-dimensional scalar dilaton partner to Einstein's tensor graviton, and several other gravitational-strength scalar fields known as moduli. In the early universe, these fields are naturally of the same order as the gravitational field, and some method has to be found to get rid of them in the universe we observe. If they survive, they will couple to Standard Model fields with the same strength as gravity, producing drastic violations of the EP. One conjecture is that they acquire large masses and thus correspond to very short-range interactions, but this solution, though widely accepted, entails grave difficulties (the Polonyi or "moduli problem") because the scalars are so copiously produced in the early universe that their masses should long ago have overclosed the universe, causing it to collapse. Another possibility involves a mechanism whereby a massless "runaway dilaton" (or moduli) field is cosmologically attracted toward values where it almost, but not quite, decouples from matter; this results in EP violations that lie in the same range as that identified above and can reach $\sim 10^{14}$[7]. Similar comments apply to another influential model, the TeV "little string" theory [8].

The second category of specific EP-violating theories occurs at the opposite extremes of mass and length, in the field of cosmology. The reason is the same, however: a new field is introduced whose properties are such that it should naturally couple with gravitational strength to Standard Model fields, thus influencing their motion in violation of the EP. The culprit in this case is usually dark energy, a catch-all name for the surprising but observationally unavoidable fact that the expansion of the universe appears to be undergoing late-time acceleration. Three main explanations have been advanced for this phenomenon: either general relativity is incorrect on the largest scales, or there is a cosmological constant (whose value is extremely difficult to understand) – or dark energy is dynamical. Most theories of dynamical dark energy (also known as quintessence) involve one or more species of new, light scalar fields that could violate the EP [9]. The same thing is true of new fields that may be responsible for producing cosmological variations in the electromagnetic fine-structure constant α[10].

In all or most of these specific theories, EP violations are suggested to appear in the STEP range, $10^{-18} < \partial a/a < 10^{-13}$. To understand the reasons for this, it is helpful to look at the third of the arguments alluded to above for regarding this range as a particularly rich and interesting one from a theoretical point of view. This line of reasoning shares some of the robustness of the dimensional argument, in that it makes the fewest possible assumptions beyond the Standard Model, while at the same time being based upon a convincing body of detailed calculations. Many authors have done work along these lines, with perhaps the best known being that of Carroll in 1998 [11], which we follow in outline here. Consider the simplest possible new field: a scalar ϕ (as motivated by observations of dark energy, or alternatively by the dilaton or supersymmetric moduli fields of high-energy unified theories such as string theory). Absent some protective symmetry (whose existence would itself require explanation), this new field ϕ couples to Standard Model fields via dimensionless coupling constants β_k (one for each SM field) with values not too far from unity. Detailed but standard calculations within the Standard Model (modified only to incorporate ϕ) show that these couplings are tightly constrained by existing limits on violations of the EP. The current bound of order $\partial a/a < 10^{-12}$ translates directly into a requirement that the dominant coupling factor (the one associated with the gauge field of quantum chromodynamics or QCD) cannot be larger than $\beta_{QCD} < 10^{-6}$. This is very small for a dimensionless coupling constant, though one can plausibly "manufacture" dimensionless quantities of this size (e.g. $\alpha^2/16\pi$), and many theorists would judge that anything smaller is almost certainly zero. Now STEP will be sensitive to violations as small as 10^{-18}. If none are detected at this level, then the corresponding upper bounds on β_{QCD} go down like the square root of $\partial a/a$; i.e., to $\beta_{QCD} < 10^{-9}$, which is no longer a natural coupling constant by any current stretch of the imagination. For perspective, recall the analogous "strong CP" problem in QCD, where a dimensionless quantity of order 10^{-8} is deemed so unnatural that a new particle, the axion, must be 4 invoked to drive it toward zero. This argument does not say that EP violations inside the STEP range are inevitable; rather it suggests that violations outside that range would be so unnaturally fine-tuned as to not be worth looking for. As Ed Witten has stated, "It would be surprising if ϕ exists and would not be detected in an experiment that improves bounds on EP violations by 6 orders of magnitude" [12]. Only a space test of the EP has the power to force us to this conclusion.

The fundamental nature of the EP makes such a test a "win-win" proposition, regardless of whether violations are actually detected. A positive detection would be equivalent to the discovery of a new force of nature, and our first signpost toward unification. A null result would imply either that no such field exists, or that there is some deep new symmetry that prevents its being coupled to Standard Model fields. A historical parallel to a null result might be the Michelson-Morley experiment, which reshaped physics because it found nothing. The "nothing" finally forced physicists to accept the fundamentally different nature of light, at the cost of a radical revision of their concepts of space and time. A non-detection of EP violations at the 10^{-18} level would strongly suggest that gravity is so fundamentally different from the other forces that a similarly radical rethinking will be necessary to accommodate it within the same theoretical framework as the Standard Model based on quantum field theory. STEP should be seen as the integral "intermediate-scale" element of a concerted strategy for fundamental physics experiments that also includes high-energy particle accelerators (at the smallest scales) and cosmological probes (at the largest scales). Accelerators such as the Large Hadron Collider (LHC) may provide indirect evidence for the existence of new fields via their missing-energy signatures. Astronomical observatories such as the SuperNova Acceleration Probe (SNAP) may produce direct evidence of a quintessence-type cosmological field through its bulk equation of state. But only a gravitational experiment such as STEP can go further and reveal how or whether that field couples to the rest of the standard model. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

2) Advanced Precision Drag Free and Attitude Control Space Systems

(with Matthias Matt and Ivanka Pelivan, ZARM University of Bremen, and Stephan Theil, DLR)

Introduction

Future fundamental physics and astrophysics missions will require spacecraft attitude and translation control of unprecedented precision. Missions requiring Drag Free Control, such as LISA Pathfinder, LISA, and STEP rely on inertial sensors of such high sensitivity that their full performance can only be realized after launch. LISA and the Interferometric Synthetic Aperture Radar missions require multiple spacecraft formation flying, presenting new challenges for attitude and translation control design. The global space astrometry mission, GAIA, requires attitude control that confronts the state of the art.

These challenges levee two prerequisites for mission implementation, 1) development of high fidelity attitude and translation control simulations and 2) development of procedures for in-space optimization of satellite control and on-board instruments. What sets these challenges apart from conventional spacecraft is the complex interaction dynamics of vehicle control with on-board payload systems

The Stanford University Precision Attitude and Translation (PAT) Control Program leverages Stanford University's unique experience in having successfully flown the world's only three-axis drag free satellites, Discos/Triad launched 1972 and Gravity Probe B launched 2004. GP-B employed high precision attitude and roll control - active control of six degrees of freedom.

The PAT Control Program focuses on high accuracy attitude control, drag free control, and payload-spacecraft interaction dynamics. Efforts include the implementation of advanced spacecraft environment and dynamics models, development of spacecraft and payload sensor and actuator models, error modeling, parameter identification, state estimation, control algorithm design, and command template formation for post-launch tuning and optimization.

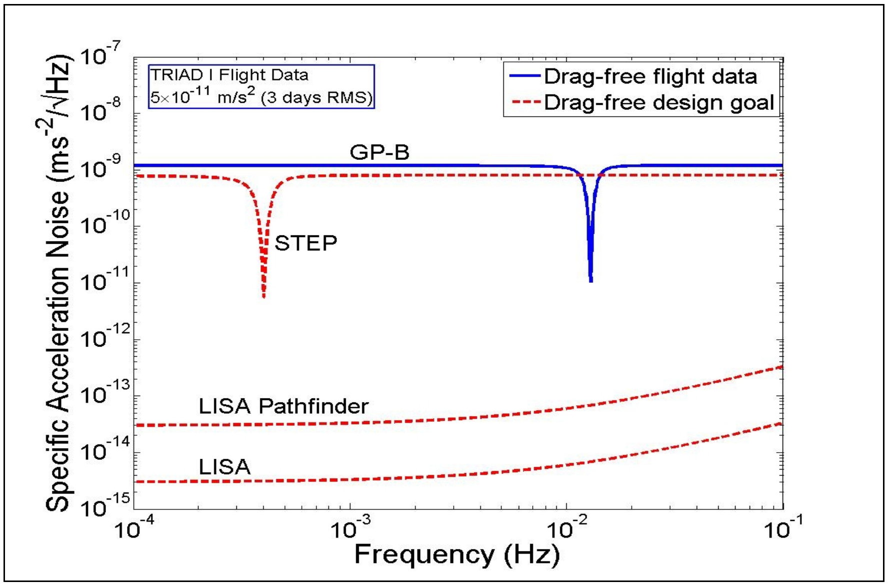

Figure 2 – Comparison of drag-free control requirements

Work is continuing in collaboration with the "First Look" project located at the Zentrum Angewandte Raumfahrt-technologie und Mikrogravitation (ZARM), University of Bremen, Germany. This collaboration is developing a generic drag-free simulator to assist future science missions including GAIA and STEP. As visiting researchers at Stanford, Matthias Matt and Ivanka Pelivan of ZARM have completed the refinement of Attitude and Translation Control simulator core dynamics to include the GP-B spacecraft dynamics and to validate the models by comparing the simulator results with the flight data.

Modeling Of Forces And Torques On Gravitational Proof Masses.

(with Alex Silbergleit, Stanford and Valerio Ferroni, University of Rome “la Sapienza”)

The heart of a drag free control system is the gravitational reference sensor comprised of a proof mass ideally shielded from all but gravitational forces. Parasitic disturbances induce system biases that will perturb the path of the proof mass from a pure geodesic. These disturbances can also impact the overall experiment error and must be properly accounted for in the error budget [13, 14]. The leading disturbances to the gyro-rotor proof masses for Gravity Probe B were caused by electrostatic patch fields. We have therefore initiated a program to develop an analytic model of electrostatic interaction of STEP test masses.

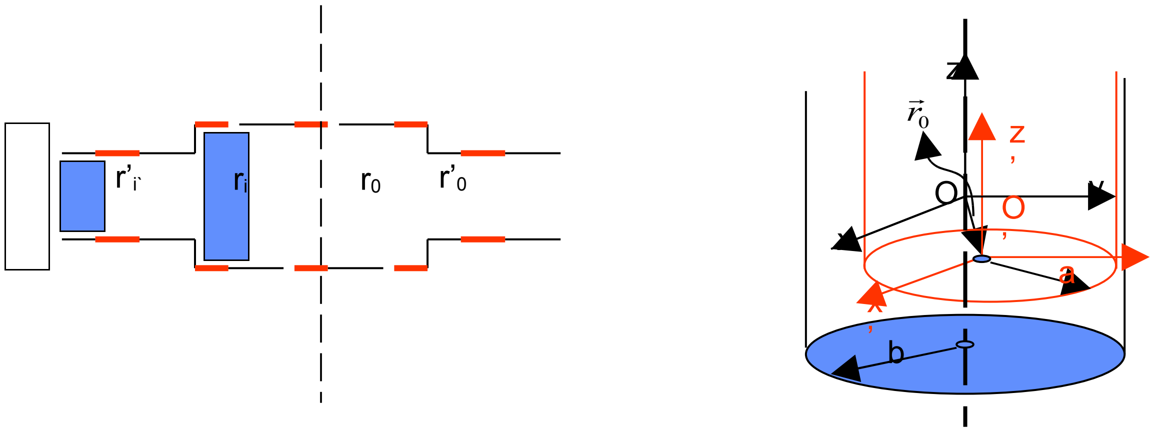

Figure 3 – STEP proof mass configuration and shifted cylinder idealization.

Publications are in preparation detailing forces and torques evaluated for two Infinite Shifted Cylinders.

Forces

Given two slightly shifted cylindrical conductors with parallel axes and carrying an arbitrary distribution of voltage, we determine the relative patch effect force to linear order in the small shift by employing the energy conservation principle: energy, computed to quadratic order in the shift, derived from the solution of a boundary value problem written for the potential in the vacuum gap between the two cylinders. Non-standard separation of variables method is used to solve this problem.
In addition to the small shift it was assumed that the gap between the surfaces was much smaller than the radii. Force formulas expressed by means of the Fourier coefficients of arbitrary boundary functions; a specific case where we considered a single patch on each of the cylinders was also investigated.

Torque

We considered the domain formed by two coaxial cylindrical conductors: we imagined these surfaces so close together and patches far from the edge that the infinite cylinders approximation is justified. Patch effect torques for the inner cylinder along the longitudinal axis and two orthogonal directions have been calculated.

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