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Space Project SEE for Measuring G and its Possible Spatial and Time Variations

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Proyecto espacial SEE para la medición de G y sus posibles variaciones espaciales y temporales

Resumen. *La misión llamada SEE (Satellite Energy Exchange) fue designada para realizar mediciones extremadamente precisas sobre gravitación fundamental mediante la observación de la perturbación orbital a las órbitas contraidas de cuerpos orbitantes de pruebas en un medio gravitacional de femto-g hasta atto-g. La misión SEE usará la dinámica novedosa y original de cuerpos en prueba. La gravitación no está presente en las teorías de unificación. El objeto amplio de la misión SEE consiste en fortalecer el desarrollo de la teoría gravitatoria y la teoría de unificación llevando a cabo pruebas gravitacionales sensitivas capaces de discernir sobre la viabilidad de las diferentes teorías alternativas. La misión SEE introducirá y realizará nueva tegnología para la creación de un medio cercano-zero, de control criogénico pasivo de temperatura, de capacidad pasiva de resguardo de estación, de medición de distancias sin contacto y de resolución sub-micrónica, todo lo cual promete tener aplicaciones en amplia variedad de naves espaciales.*
Palabras clave: *campos unificados, gravitación, misión SEE*.

Abstract. *A SEE (Satellite Energy Exchange) mission is designed to make extremely accurate measurements on fundamental gravitation by observing the orbital perturbation of unconstrained orbiting test bodies in a femto-g to atto-g environment. A SEE mission will use novel and original test body dynamics. Gravitation is the missing link in unification theory. The broad objective of a SEE mission is to support development of gravity theory and unification theory by carrying out sensitive gravitational tests capable of discriminating among alternative theories. A SEE mission will introduce and utilize new technology for near-zero-g environment creation, passive cryogenic temperature control, passive station-keeping capability, and non-contact sub-micron-accuracy distance measurement, all of which promise to have applications in a wide variety of spacecraft.*
Keywords: *unified fields, gravitation, SEE mission.*

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Introduction

Project SEE (Satellite Energy Exchange) is an international effort to plan and conduct a next-generation space mission in gravitation. A SEE mission would test for time variation of the gravitational constant G, test for equivalence-principle (EP) violation by searching for both composition-dependent (EP/CD) and inverse-square-law (EP/ISL) violations –at ranges both on the order of meters and on the order of the radius of the Earth– and determine the gravitational constant G (Sanders and Deeds, 1992). We note that four of our tests/measurements are

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expected to be the best of any existing or proposed experiment, while two (the two EP/CD tests, which will be obtained automatically from the data analysis) are expected to chiefly confirm prior or already planned experiments.

A SEE mission would entail launching a dedicated satellite, the heart of which would be an experimental chamber in which two or three test bodies –one large "Shepherd" and one or two small "Particles"– would float freely, experiencing only each other's gravity and that of the Earth and other bodies in the solar system. Observation of the mutual perturbations of the test bodies will provide the required data for the tests and measurements of a SEE mission.

The problems and opportunities entailed in the control of a satellite and acquisition of data have been carefully re-thought from first principles by the SEE team, with the result that several very novel techniques have been developed. These techniques have been gradually integrated, over a period of 10 years, into a truly holistic design concept for the SEE satellite. Among these techniques are (1) means of non-contact absolute measurement of distance with sub-micron precision at stand-off distances exceeding 1 meter, (2) means of achieving and maintaining cryogenic temperatures in the satellite for extended periods (many years) with no expenditure of energy, (3) means of obtaining nearly all the station-keeping thrust for drag-free operation with virtually no expenditure of energy, and (4) means to make the satellite itself essentially "gravitationally invisible" to the test bodies. The SEE team is now in the process of developing these technologies for application to a wide variety of satellites and missions.

SEE differs from other proposed gravity missions in four important respects:

1. The focus of SEE is post-Einsteinian; it is not limited only to test general relativity. SEE is truly a next-generation gravity mission which will measure or test a number of links of gravitation and unified theories.

TABLE 1
EXPECTED ACCURACY OF SEE TESTS AND MEASUREMENTS

TEST/MEASUREMENT	EXPECTED ACCURACY
EP/ISL AT ~FEW METERS	2×10^{-7}
EP/CD AT ~FEW METERS	$<10^{-7}$ ($\therefore \alpha < 10^{-4}$)
EP/ISL AT ~R_E	1×10^{-10}
EP/CD AT ~R_E	$<10^{-16}$ ($\therefore \alpha < 10^{-13}$)
G	0.33 PPM (330 PPB)
(G-DOT)/G	$<10^{-13}$/YR IN ONE YEAR
GR VIOLATIONS	UNDETERMINED

2. SEE is multi-purpose and observational in approach; it is not designed to test one or two hypotheses using a single-purpose instrument.

3. The SEE satellite uses new and unique test-body dynamics, based on the limited three-body problem of celestial mechanics.

4. SEE uses extremely advanced passive technology for most aspects of satellite control and data acquisition; it is not hampered by undue reliance on methods which have been in use for two or three decades.

5. The SEE Satellite design is holistic; it is not a combination of modules having separate and possibly competing requirements.

6. Because of reliance on passive technology, the life of a SEE mission can be extended indefinitely if needed. Since there is no reliance on liquefied gas or consumable fuel, the SEE satellite can continue to take vast amounts of data as long as the data continue to be of high scientific value.

Objectives

A SEE mission has six measurement goals:

1. Test for violation of the Equivalence-Principle (EP) by Inverse-Square-Law (ISL) violations (EP/ISL) at distances on the order of meters.

2. Test for EP/ISL violation at distances on the order of the radius of the Earth.

3. Test for violation of the Equivalence-Principle (EP) by Composition Dependent (CD violations (EP/CD) at distances on the order of meters.

4. Test for (EP/CD) violations at distances on the radius of the Earth.

5. Measure the absolute value of the Gravitational constant G.

6. Test for non-zero value of G-dot, the time derivative of G.

Expected accuracies (Alexeev *et al.*, 1999, 2000) are shown in Table 1. SEE will be better by far than any existing and/or planned experiments in the measurement of G, the test for G-dot, the test for EP/ISL violation at both distances. Our long-range test for EP/CD will be 2-3 orders better than the existing tests, albeit at somewhat lower accuracies than those of existing and/or proposed experiments, and will thus be at sufficient accuracies to bolster confidence in the results of other experiments, assuming that their accuracies goals are realized and that their results are correct.

In addition, Damour and colleagues have pointed out that various post-Einsteinian resonances might be observable in orbits in which precession rates associated with the orbits add to integer multiples of 2π radians/*yr*. We have suggested ways that a SEE mission might observe such resonances, and we will evaluate this possibility thoroughly.

The actual accuracies for the various EP tests will depend on the ratio of the characteristic interaction length Λ to the separation of the interacting bodies. To achieve the expected accuracies listed above, the requirement for the EP/ISL tests is that these two lengths must be similar, and the requirement for the EP/CD tests is that Λ must not be significantly smaller. Of course, there exist a possibility of standard tests of unified models via their prediction of PNN parameters (Ivashchuk *et al.*, 2000).

I. Value of the Research

Gravitation is the missing link in efforts to achieve a satisfactory unification theory of physics. Most of the current promising approaches, including string theories, p-brane theories, and supergravity, contain gravity at a fundamental level. Although a number of different theoretical schemes have been proposed, a lack of precise experimental evidence presently makes it almost impossible to assess the validity of alternative schemes. The very precise experimental data to be provided by a SEE mission augurs for major advances in gravitation theory.

The mission results will either (1) give extremely accurate confirmation of presently-accepted theories or (2) indicate violations of them, while suggesting the direction of necessary changes. The substantial volume of precise new data to be provided by a SEE mission will expose conflicts with some existing theories, thus revealing which theories are consistent with both the new evidence and previous evidence. This process is vital for indicating the most promising directions for further developments in unified theories.

A striking feature of recent theories of quantum gravity and string theory is that they cannot retain a constant G, but rather require various secular rates of change (Melnikov, 1994, 2000). It is evident that gravity is central to the behavior of fields and coupling "constants" (Schmidhuber, 1997). It is apparent that gravity need not be synonymous with general relativity if new gravitational fields, besides the metric, are introduced, such as the dilaton field. The assumption that the "coupling constant" G is actually constant is not consistent with these unification theories. Their predictions of (G-dot)/G are typically a few parts in $10^{11}/yr$ or somewhat less –two or three orders of magnitude above our accuracy.

A test of G-dot is one of the very few ways of discriminating among these theories (see, for example, Marciano, 1984; Bronnikov, Ivashchuk & Melnikov, 1988; Melnikov, 1994; Drinkwater *et al.*, 1999; and Ivashchuk & Melnikov, 2000). The current experimental –rather, observational– evidence regarding G-dot is confused, as discussed below in the next section (Review of Relevant Research). SEE, on the other hand, will provide a *controlled* experiment and very fine accuracy, which can discriminate among various possible unified theories.

Tests of the equivalence principle, both by inverse-square-law (ISL) tests and composition-dependent (CD) tests, are extremely important because of the far-reaching and profound consequences of any violation (Sabbata *et al.*, 1992). Any apparent violation could be interpreted most readily as evidence of the existence of a new super-weak force, presumably of short range and therefore mediated by a massive particle –*i.e.*, a Yukawa-type force. However, if the experimental data indicate apparent EP violations but do not fit the Yukawa hypothesis, then other alternatives must be entertained.

The motivation for an improved determination of the gravitational constant G is two-fold: first, simply that it is very poorly known in relation to all other fundamental constants; second, that various theoretical methods for calculating the value of G are now becoming available, thus supplying tests of these theories –but only if the experimental value of G is sufficiently accurate (Gillies, 1997). Most importantly, various multi-dimensional theories produce relations between fundamental constants, and it is hoped that the set of constants of some multi-dimensional theory will be prove to correspond to the known fundamental constants, and will yield extremely accurate values of some constants via the most precisely known ones (Schwarz, 1989; Sanders & Deeds, 1992; Melnikov, 1994).

A SEE mission also has the possibility of testing for possible spatial variation of G according also to the direction in which the force is applied. This experimental possibility arises because the interactions used in the SEE experiments are all essentially in the plane of the Earth orbit of the SEE satellite. Since the orbital plane precesses once per year about the Earth's axis, its orientation also goes through an annual cycle in solar-system coordinates. A directional dependence of G might be observed in a SEE mission as an annual cycle in the period of the Shepherd (with sensitivity better than 1 part in 10^{12} during a three-month period). Clearly, it will be essential to find ways to eliminate from the analysis both systematic errors of seasonal origin and any modulation of G due to the solar gravitational potential. There has never been a credible laboratory measurement of G-dot (using test masses in a controlled situation) at cosmologically interesting levels of precision. Attempts have been made to do so, but all have fallen far short of the presently foreseen requirements.

The finding of any violations of EP or of a non-zero G-dot would require fundamental changes in the theory of physics and would guide the selection of the correct form of Unification Theory (UT). G is a fundamental constant, which soon must be explained theoretically in terms of UT and the values of other fundamental constants, so a good measurement of G will also guide UT selection (Ivashchuk and Melnikov, 2000).

II. Review of Relevant Research

1. Terrestrial Tests of EP

The Equivalence Principle (EP) may be tested by searching for either violations of the inverse-square law (ISL) or composition-dependent (CD) effects in gravitational free fall.

In the watershed year of 1986, Fischbach startled the physics community by showing that Eotvos' famous turn-of-the-century experiment is much less decisive as a null result than was generally believed (Fischbach *et al.*, 1986). Prior to this time, experiments by Dicke (Roll *et al.*, 1964) and Braginsky (1971) had demonstrated the universality of free fall (UFF) to very high accuracy with respect to several metals falling in the gravitational field of the sun. The interpretation of these results at the time was that they validated UFF. It was implicit that any violation would have infinite range, like gravity (Adelberger, 1994). During the 1970s and early 1980s there had also been a flurry of activity concerning possible ISL violations, which eventually led to null results at the levels of precision then available (Fujii, 1971 and 1972; Long, 1976 and 1984).

Since 1986 it has become customary to parameterize possible apparent EP violations as if due to a Yukawa particle. This approach unites both ISL and CD effects very naturally, while the parameter values in the Yukawa potential suggest what experimental conditions will permit sensitive tests of the EP, by either inverse-square law test or composition-dependent tests, or both.

Following Fischbach's 1986 conjecture, many investigators undertook tests of the EP by searches for either CD or ISL violations. Although a number of anomalies were initially reported, nearly all of these were eventually explained in terms of overlooked systematic errors or extreme sensitivity to models, while most investigators obtained null results (Fischbach & Talmadge, 1999).

Only two experiments –an EP/CD experiment by Thieberger (1981) and an EP/ISL experiment by Achilli *et al.* (1997)– have not succumbed. However, these two experiments are also widely assumed to be wrong, on the basis of a rather literal faith in current fifth-force models, because a number of other experiments found no non-Newtonian effect with bounds that are tighter (in the context of these models) than those of Thieberger and Achilli. By far the tightest bounds are those obtained by Adelberger and his "Eot-Wash" group at the University of Washington (Adelberger *et al.* 1987 and 1990, Adelberger 1994, and Su *et al.*, 1994). This group expects a further improvement of at least an order of magnitude (Adelberger, 1997). Their bound on the interaction strength α is approaching 1 part in 10^-9 for the long-range ($\Lambda > R_E$) composition-dependent test (Adelberger, 1997). This result, like all EP tests, is to some extent model-dependent. For example, the limits on α which are most commonly shown in Gibbons-Whiting diagrams assume that the mediator is a *vector* boson and that the mixing angle θ_5 is zero (i.e., the fifth force "charge" is simply the boson number: θ_5 = B).

Nevertheless, a rather paradoxical situation has developed, in that the faith of gravitational physicists in the EP has weakened since 1986, despite not only the dearth of contrary experimental evidence, but also the actual tightening of the bounds of possible EP violations. This conceptual shift can reasonably be attributed to the influence of theory development during this period. There is a growing belief, now approaching a consensus, that unification theories (supergravity, superstrings, M-theory, etc.) are likely to require some form of violation of the equivalence principle. Thus, the search for EP violations continues.

We must stress that it is especially important to do ISL tests –even in ranges of Λ where CD tests have already set tight limits on α– because the model-dependence of ISL tests is different and, more importantly, *less* than that of CD tests (Sanders & Deeds, 1992). More broadly, although it is very difficult to imagine how an EP violation could result from anything other than a Yukawa-type exchange, any departure from the Yukawa paradigm would open up other possible interpretations with potentially far-reaching consequences, as indicated above.

For reviews of terrestrial searches for non-Newtonian gravity, see Fischbach, Gillies *et al.* (1992), Franklin (1993), Adelberger (1994), & Fischbach and Talmadge (1999).

2. Terrestrial Determinations of G

The Luther & Towler determination of 1982 was used for the 1986 official CODATA value of the gravitational constant G*, viz.* 6.6725910^-11 N•m^2/kg^2, with an error of 128 ppm. Several other experiments which also claimed high-precision were ignored by CODATA because of inadequate documentation of systematic errors.

In 1995 and 1996 the publication of four new very careful G determinations (Fitzgerald & Armstrong at the New Zealand Bureau of Standards; Michaelis, Haars, & Augustin at the Physikalish-Technische-Bundesanstalt (PTB); Wallesh, Meyer, Peil & Schurr at Bergische Universitat in Wupperthal; and Bagley & Luther at Los Alamos National Laboratory) abruptly undermined the until-then relative complacency about our knowledge of G: Although all four experiments claimed accuracies of ~100 ppm, the scatter of the results was much larger, and the results from the two bureaus of standards were conspicuous outliers in terms of the official CODATA value. The result by the PTB was 0.6% (6000 ppm!) above the CODATA value.

These events touched off an unprecedented burst of activity in G determination. At a conference in London in November, 1998, on the occasion of the 200th anniversary of Cavendish's experiment, which was attended by virtually all the active researchers, no fewer than nine new determinations of G were presented. Results are presented in a special issue of Measurement Science and Technology, 1999, N10.

The principal groups now engaged in terrestrial experiments to redetermine G are those led by Gundlach (U. Wash), Newman (UC, Irvine), Karagioz (Moscow), Faller (U. Colo/JILA), Holzschuh (U. Zurich), Speake (Birmingham), Quinn (BIPM), Paik (U. Maryland), and Luo Jun (China) in addition to the teams in Wupperthal, Los Alamos, and New Zealand. For reviews of terrestrial determinations of G and experiments in progress, see Gillies (1987, 1988, 1990, and 1997).

J. Gundlach has published the result (gr-qc/0006043) with accuracy estimated to be about 14 ppm, and several of these groups hope for accuracies as low as 10 ppm or better. However, history casts some skepticism on such accuracy goals: Most experiments in recent decades which began with a goal of 100 ppm have hit various snags, and they ended with estimated errors at least an order of magnitude worse (Luther, 1992).

It is useful to consider three possible scenarios concerning the outcome of the present activity in G determination:

1. Several other groups will claim accuracy of ~10 ppm, and the scatter among the results will also be about 10 ppm.

2. Several other groups will claim accuracy of ~10 ppm, but the scatter will remain about 100 ppm.

3. No other group will claim accuracy below about 100 ppm.

Unless the first scenario, or something like it, is attained, it will be likely that terrestrial methods for G determination have already reached their limit, and only by going to space can G be improved.

The central fact of G-determination efforts in our times is that the current burst of activity is a once-in-a-lifetime phenomenon (similar situations arose historically in roughly 1880 and 1930). Within the context of any technological developments now being either studied or contemplated, we will very likely know the limits of G determination by terrestrial methods within a very few years.

3. Tests and Measurements of G-dot

A SEE mission will provide the first controlled laboratory test of G-dot at a cosmological level of interest. All previous high-accuracy experimental G-dot research is based on inferences from various natural phenomena (including nucleosynthesis, orbital dynamics, tidal friction, etc.) rather than *controlled* experiments. The experimental results are a rather puzzling collection of (1) stringent upper limits on |(G-dot)/G| (as small as 10^{-12}/yr) and (2) various non-zero estimates of (G-dot)/G (typically ~10^{-11}/yr) (Gillies, 1987 and 1997).

To illustrate the confusion, in the mid-1980s three groups used similar data sets (chiefly based on archived LLR data of the Earth-Moon distance) to estimate |(G-dot)/G|. Although two groups obtained similar upper limits of ~10^{-11} or less (Nordtvedt, 1996), a third obtained ~10^{-12} (Muller *et al.*, 1993). Moreover, two previous controversies in G-dot work during the past 20 years remained unresolved for a number of years: (1) Uncertainty about the size of the lunar tidal acceleration of the Earth's rotation rate, which in turn clouded the use of ancient eclipse records to infer secular changes in the Moon's period (Newton, 1968, and Van Flandern, 1981), and (2) uncertainty about the extent of perturbation of the orbits of Mars and Mercury by uncharted asteroids, which in turn clouded the use of radar-ranging data to infer possible secular changes in the periods of the planets (Hellings *et al.*, 1983; Reasenberg, 1983, and Hellings, 1988). The high complexity associated with interpreting data from various naturally-occurring phenomena argues strongly for a controlled experiment to test G-dot at a cosmologically-significant level.

4. Space-Based Proposals

A number of investigators have proposed space-based approaches for making the very high-accuracy measurements needed for experiments in fundamental gravitation. Such proposals generally cite the gravitational noise in the terrestrial environment, and the relative quiet of the space environment as motivations for going to space. However, most proposals for space-based gravity measurements have unfortunately concentrated only on the idealized physics of the test-body interactions and have ignored many of the physical realities and difficulties of space (Sanders & Gillies, 1993). Thus, these proposals have not produced realistic experimental designs.

Only three realistic proposals have been made for determining the gravitational constant G, namely : NEWTON (University of Pisa group), SEE, and STEP (G/ISL).

The Pisa group is not presently seeking funding for NEWTON, and the G/ISL experiment is no longer on STEP. For reviews of proposals for determining G in space, see Smalley (1975), Spallicci (1988), and Sanders & Gillies (1996).

Likewise, only a handful of realistic proposals exist for space-based tests of the EP. In addition to SEE, these include the original STEP (Blaser *et al.*, 1993 and 1994) and several variants, especially MiniSTEP (Everitt *et al.*, 1996), which is now known simply as "STEP"; Pisa's non-drag free GG-FEEP (Nobili *et al.*, 1995); and H-J Paik's proposal for a SQUID-based EP test (Paik, 1996). All these proposed experiments promise results substantially better than previous Earth-based experiments.

The SEE experiments, like most fundamental gravity research, can be done only in space because of their requirement for high-quality microgravity and long test-body interaction times (days to years) in a microgravity environment. Neither drop tests nor low-gravity parabolic flights can provide either the necessary low gravities or the long durations. Only space can provide an environment which is virtually free of gravitational noise. Further, by careful experimental design, a number of other potential systematic errors can be made smaller or more controllable than on the surface of the Earth. Gravitational experiments in space thus hold promise for better accuracy than terrestrial experiments, which appear to be approaching their limits of accuracy.

5. The Space Environment

Although space does indeed offer escape from unavoidable noise in the terrestrial environment, some caution may be advisable in assessing predictions that errors will be reduced by multiple orders of magnitude. Such predictions are made by SEE and other space-based experiments. However, these predictions will be fulfilled only if the investigators can discover and account for any yet-unknown or poorly understood phenomena which may exist, having magnitudes between the expected new low error levels and the levels of present experimental errors. Achieving an understanding of such phenomena must be a prime objective of early-phase study of any proposed gravity mission in space.

6. Test-Body Charging and the South-Atlantic Anomaly (SAA)

Charging of the SEE test bodies by protons in the Van Allen belts is an important issue which must be addressed. Van Allen electrons are not an issue because they will not penetrate the SEE experimental containment. We have previously shown that charging of the test bodies by very-high-energy cosmic rays was not a problem because these events are comparatively rare (Sanders & Deeds, 1992). It also turns out that the South Atlantic Anomaly (SAA) –a region of intense Van Allen activity which results from the low altitude of the Earth's magnetic field lines over the South Atlantic Ocean– is not an issue for SEE because the SAA is overwhelmingly a low-energy phenomenon (Sanders *et al.*, 1997). Rather, peak charging rates for the SEE test bodies occur at the crossings of the magnetic equator.

Since it has become virtual folk wisdom in recent years that the South Atlantic Anomaly (SAA) is the problem for satellites with regard to charge accumulation, we must reiterate that the Van Allen peaks for the SEE satellite are at the magnetic equators, not at the SAA. Thus, the SAA is no problem for SEE: the SAA is a low-energy phenomenon, and the SEE satellite is naturally shielded against low-energy protons because we have elected to use radiation barriers rather than liquefied gas to achieve and control cryogenic temperatures. These radiation barriers are several centimeters thick *in toto*, so they stop all but the high-energy protons and also the secondaries. In test-body charging calculations for SEE, using models of the Nuclear Physics Institute (NPI) of Moscow State University, it was shown that the SAA does not even show up as a bump or even a shoulder at proton energies above 13 MEV, which is the energy necessary to penetrate 1 mm. In short, the SAA has nothing to do with SEE (Alexeev *et al.*, 1999).

III. Need for Low Gravity

It is very clear that investigations into the nature of gravitation need more than merely a significant reduction below terrestrial gravity; such experiments need to virtually eliminate background forces and to approach the ideal of zero gravity as nearly as possible.

Low gravity is needed on the SEE mission because SEE is based on orbital-perturbation principles. The essence of an orbital-perturbation experiment is that the effects of very tiny forces are amplified by long observation intervals (often decades or more in astronomical work). Thus, the SEE test bodies must "float" freely for long periods of time (one day to several years) in order to reveal the perturbing forces acting upon them. In all Earth-based facilities, available microgravity durations are less than one minute. The gravitational force due to the Earth is much larger than the field which can be produced by any test body.

Space is especially crucial for the SEE G-dot experiment. Space offers the almost legendary ability of orbital perturbations to render minute effects detectable. There is no terrestrial analog for the tests of G-dot which can be done by means of orbital perturbation inside a drag-free satellite with extreme microgravity in its interior.

We may surmise that the disappointing accuracies of various terrestrial determinations of G, including those of some of the recent experiments –which claim accuracies of 100 ppm, but differ by much more– very likely reflect the difficulties in making gravitational measurements on the surface of the Earth.

It might seem that the problems of terrestrial apparatus must inexorably yield to new technologies –that the promise of ever increasing *sensitivities* would also lead to ever improving *accuracy*. However, this may not be true, since it is various systematic errors– chiefly due to the background gravitational forces from surrounding objects and to inherent limitations of the torsion balances –which seem to have placed an effective ceiling on the attainable accuracy in terrestrial experiments (Gillies & Ritter, 1993). Thus, the progress in the accuracy seen in the past in various gravitation experiments may not be replicated in the future.

In summary, background gravitational noise in the terrestrial environment and instrumental noise are far too large to be compatible with the extreme microgravity environment required to carry out most fundamental-gravitation experiments –including those of a SEE mission. The required conditions can be found only in space.

IV. Measurements and Measurement Techniques Planned for Use in Space

1. Basic Concept

The SEE (Satellite Energy Exchange) concept is rooted in the tradition of orbital-perturbation analysis. Thus, we seek to make very precise measurements of small effects, by allowing time to magnify them naturally. As with all such analyses –from the discovery of Uranus to the explanation of the perihelion precession of Mercury– our analysis methods will disentangle the sought-after effects from each other and from various background effects (such as the influence of the Moon and of the Earth's harmonics). Although in some cases the background effects may be large, they will generally be calculable and –since SEE provides for *controlled* experiments– we will often have the added luxury of being able to choose the phases of the effects under investigation, relative to each other and relative to the unwanted background effects. Finally, although we begin with specific hypotheses, if neither these nor other existing hypotheses provide satisfactory fits to the data, and if exhaustive searches for further systematic errors prove fruitless, then this circumstance will invite theorists to posit new hypotheses.

2. Dynamics of the SEE Method

Here we briefly describe the rather paradoxical relative motion of the two test bodies –the large "Shepherd" and the small "Particle"– during a SEE encounter: Two co-orbiting satellites –one trailing the other– may exchange substantial gravitational energy if their orbits are nearly identical, so that they remain very close together for several orbits around the Earth. If the body in the lower (and therefore faster) orbit approaches the other from behind, the trailing body is picking up energy from the leading body and, after the passage of some time, may acquire sufficient energy to rise above the leading body (stated more precisely, the semi-major axis of the orbit of the trailing body may grow to exceed that of the leading body). At this point the trailing body will begin to *fall back*, while still continuing to pick up energy from the leading body. The relative trajectory of the two bodies can be very smooth if their pre-encounter orbits are both circular (or otherwise very similar); otherwise the trajectory has a cycloidal character.

We note that, although the gravitational force is of course always attractive, a SEE encounter gives the paradoxical appearance of mutual *repulsion* by the two bodies. This can be understood in terms of the virial theorem.

It is convenient to scale the experimental masses and distances so that the duration of a SEE encounter is typically about one day, the encounter length is typically 5-10 meters, the change in the altitude of the small test body (the Particle) during an encounter is typically a small multiple of 10 cm, and the instantaneous relative speeds are typically 100 to 300 microns/sec. This requires the Shepherd mass to be ~100 to 250 kg. The change of the altitude of the small body during an encounter is proportional to the mass of the Shepherd and approximately inversely proportional to the distance of closest approach.

Note that a SEE-encounter trajectory is rather long and narrow –in fact, it is virtually one-dimensional. The extremely narrow shape of a SEE trajectory has an important consequence: Nearly all the information is contained in the *separation* of the test bodies as a function of time. This fact greatly simplifies data analysis, in that it results in very relaxed pointing requirements for the SEE satellite. This fortuitous circumstance is rather unusual among high-precision space experiments.

3. SEE Measurements I: SEE Encounters (for G, EP/ISL, and EP/CD)

The bulk of the scientific investigation on a SEE mission would entail precise analyses of the relative motion of the two test bodies –the large "Shepherd" and the small "Particle"– during a number of SEE encounters, as described above in the previous section. Here we present the basic principle for measuring each individual effect, although of course no effect can be isolated and measured in the absence of the other effects.

The value of G is obtained from the accelerations of the Particle during a SEE encounter. Thus, account is taken of the peculiar and counter-intuitive dynamics which results from the fact that both bodies are in orbit around the *Earth* and are chiefly under the influence of its gravity rather than each other's (and which may be understood in terms of the virial theorem). More particularly, the measured value for G is inversely proportional to the square root of the time required to complete any prescribed portion of a SEE encounter.

The intermediate-range (~meters) EP test based on an inverse-square-law (ISL) test will straightforwardly compare the measured values of MG (M is the Shepherd mass) obtained at various locations along the trajectory of each SEE encounter, and then search for apparent variation of MG as a function of the separation of the test bodies. We note that uncertainties in the Shepherd mass M drop out.

The long-range (~radius of the Earth) EP test based on an ISL test takes advantage of the fact that a relative precession of the perigees of the test bodies would be caused by the perturbing force of a putative Yukawa-type particle. This precession is due mainly to the cubic term in the force, in exact analogy to the anomalous precession of Mercury predicted by general relativity.

We know of two distinct ways of detecting such a precession: The original method (Sanders and Deeds, 1992) involves detailed analysis of the SEE-encounter trajectory, based on intra-capsule measurements of the relative positions of the test bodies. The "signal" in this case is a slight difference between the apsidal and siderial periods of the Particle. More recently Nordtvedt (1998) has suggested an improved method based on ground tracking, which is described in the next section.

The intermediate-range (~meters) EP test based on composition dependence (CD) is done essentially by comparing the values of G obtained with Particles of different composition. Complete SEE encounters may be used. We note here that the value of the Shepherd mass is again unable to contribute any error. Moreover, by accurately replicating the trajectories within the capsule, we virtually eliminate any contribution of the mass-distribution errors in the capsule walls to the CD-test error. This is because whatever Newtonian perturbations may exist along a given trajectory should be the same, *ceteris paribus*, for any Particle on the same trajectory.

The long-range (~radius of the Earth) EP test based on composition dependence (CD) may be obtained by searching for an apparent violation of Kepler's third law for simultaneously-orbiting test bodies within the capsule. That is, the relationship between orbital radii and orbital periods will differ very slightly between two test bodies if their composition difference causes them to fall at different rates in the Earth's field. This test is closely analogous to laser radar ranging (LLR) measurements of lunar parallactic inequality. Even the techniques for obtaining extreme accuracy are similar in principle: In the LLR case, the *relative* distance of the Earth and the Moon from the Sun is inferred essentially by comparing the Earth-Moon distances at new moon and full moon, and this can now be measured to within about 1 cm –many orders of magnitude more accurately than the various astronomical distances involved can be known (see, for example, Nordtvedt, 1996a and 1996b). Likewise, SEE will measure the *differential values* of the orbital radii and periods of the test bodies, using on-board precision-measurement systems, and the result will be many orders of magnitude more accurate than the absolute values of these quantities based on ground tracking.

A strength of SEE is that it can do the composition-dependent EP tests with a large number of different materials. This is because the SEE Particles are small enough that several dozen different Particles can easily be stowed. Moreover, if two Particles are used in simultaneous SEE encounters with the Shepherd, then myriad pairs of materials are available.

4. SEE Measurements II: Tests for G-dot, ISL Violations by Nordtvedt Method, and Post-Einsteinian Effects

Searches for time variation of G and for various post-Einsteinian effects would be carried out on a SEE mission by precise measurements of the perturbations of the Earth orbit of the Shepherd, as determined by ground tracking, rather than by analysis of on-board trajectories of the test bodies during SEE encounters.

A second method of long-range (~radius of the Earth) EP/ISL test has been suggested by Nordtvedt (1998). It utilizes *ground tracking* of the Shepherd rather than intra-capsule comparison of the Shepherd and Particle orbits to infer precession of the Shepherd's perigee. This requires a slightly eccentric (e~0.01) orbit. Nordtvedt's method provides substantial improvements in accuracy.

For G-dot, what is to be measured is the Shepherd's orbital period. An anomalous secular increase would indicate that the product $M_E G$ is decreasing (Note that we cannot separate G-dot from M_E-dot). A finding that $M_E G$ is either time-varying or constant would be of enormous interest [importance]. With centimeter-level tracking, a relative change in $M_E G$ of a few parts in $10^{14}/yr$ can be detected within a year. This exceeds the sensitivity needed to distinguish among the predictions of a number of different theories, which typically predict that G is changing at a few parts in $10^{11}/yr$ or less.

Moreover, it may also be possible to detect a small anisotropy of space by slight fluctuations in the period of the Shepherd's Earth orbit, since the orientation of the Shepherd's orbital plane in solar-system coordinates is subject to an annual cycle. However, it will be of utmost importance to distinguish any such observed effect from a possible seasonally-varying systematic error.

Our plans for a G-dot test presume that the GRACE mission will be successful in providing high-accuracy data on the seasonal variation of the Earth's gravitational field and, further, that the generally increasing demand for precision geodesy will result in follow-on missions of similar capability. In contrast, the current state-of-the-art for time-varying geodesy is about two orders of magnitude short of our needs (Chen & Tapley, 1999).

Perturbations in various orbital parameters may indicate violations of general relativity, as outlined in recent papers by Damour and colleagues (1994a and 1994b). Choosing specific initial values of the orbital elements would result in resonance conditions, which may be necessary to observe such post-Einsteinian effects in LEO. Further, Sanders and Gillies (1996) have pointed out that a sun-synchronous orbit can combine two or more resonances, thus enhancing the observability of these effects.

We note that all prior G-dot research is based on *inferences* from various natural phenomena (including nucleosynthesis as well as orbital perturbations) rather than controlled experiments. Thus, they are based on only indirect knowledge of the relevant data. (The various orbital perturbations used to infer G-dot have ranged from slowing of the Earth's axial rotation, to planetary movement, to the slowing of binary pulsars). A SEE mission will provide the first controlled laboratory test of G-dot at a cosmological level of interest.

V. Estimate of Time Profile of Reduced-Gravity Levels Needed

The microgravity-quality requirements for an orbital-perturbation experiment are inherently extremely stringent. SEE experiments require accelerations in the femto-g to atto-g range for matters or days or years. This is obviously many orders of magnitude beyond that what can be provided on the shuttle, the Space Station, or any terrestrial lab (even if a proxy for orbital motion could somehow be simulated on Earth). Only a dedicated free-flyer, which is carefully designed to provide ultra-high-quality microgravity, can meet these requirements. The SEE experimental design incorporates self-calibration capability –the ability to measure and account for departures from zero internal field. This is because *a priori* mass distributions at the time of satellite construction cannot be sufficiently accurate. In addition, we will use four different flight configurations to achieve automatic near-complete cancellation of accelerations on a time-averaged basis over very long periods of time.

For the SEE encounters *per se* –which determine G and test for the intermediate-range EP/ISL and EP/CD violations– accelerations must be known within the experimental chamber to about $10^{\wedge -14}$ g (or $10^{\wedge -8}$ micro-g) for the duration of an experimental run, which is typically a few hours up to about one days. Our calibrations will determine the accelerations on the test bodies due to the chamber to $10^{\wedge -15}$ g. The actual instantaneous accelerations will typically be $10^{\wedge -11}$ g or somewhat more, which will not be deleterious.

For the G-dot test, we need and can achieve about $10^{\wedge -18}$ g throughout the mission life on a *time-averaged* basis. We will use time blocks about 3 months long for the time averaging. During each block, four flight configurations are used for equal amounts of time, which effects automatic cancellation of accelerations at a level approximately three orders of magnitude below the smallest accelerations detectable in calibrations. This provides the effective atto-g environment needed for the G-dot experiment.

1. The Gravity Gradient of the Earth's Field

We note that the gravitational gradient of the Earth's field –a major concern in many proposed precise space-based experiments– has no adverse impact whatsoever on the various SEE experiments. This is because SEE is based on *orbital-perturbation analysis*, and therefore actually requires the natural field of the Earth, including gradients. The SEE data analysis will therefore not need the exhaustive corrections which other proposed space-gravity experiments must use to counteract the undesired but natural gravity gradients.

Rather, the SEE capsule is intended solely to be "gravitationally invisible" to anything inside it –we do not want it to create a modified or artificial gravitational field.

VI. Technical Implementation Details

1. Design Concept of SEE Satellite

The purpose of the SEE satellite is to shield the test bodies (Shepherd and Particle) from everything except gravitational forces –so that the test bodies floating within ideally see only each other's gravity and that of the bodies of the solar system– and to provide an observation platform with coordinate system.

The basic form of the SEE satellite is an experimental chamber, consisting of a closed cylinder, which is surrounded by 6 to 10 open cylinders. The open cylinders act as reflective radiation shields for the purpose of passive cryongenic cooling and temperature control. Simulations have demonstrated the capability of this arrangement to provide very fine temperture control.

Materials: The experimental chamber is expected to be aluminum. Various materials will be considered for the other cylinders, especially composites.

The size of the SEE satellite is determined chiefly by the requirement to fit within the extended shroud of the Atlas V 500 (or whatever larger shroud may be available by the time of launch). This fixes the dimensions of the SEE satellite's outermost cylinder (length = 10.65 m, diameter = 140 cm), unless a subsequent larger version of the shroud becomes available before the SEE launch date. We note that anything which fits within an Atlas shroud could also be launched by a Russian Proton or Progress.

The mass of the SEE satellite will be about 2 tons. This mass is chosen so that the radiation pressure of solar photons will "blow" the satellite sideways by only 5 or 6 cm (more or less, depending on the average reflectivity of the outer surface. The satellite could easily be constructed to be much lighter. However, if it were lighter than 1 ton, it could be "blown" sideways as much as 15 cm, thus limiting the usable experimental volume and possibly causing the walls of the experimental chamber to actually collide with the test bodies, since they do not feel the solar radiation pressure.

Mass balancing: The mass of the SEE satellite will be distributed so that there is no net gravitational force in the experimental chamber. The fact that this can be done is readily seen by analogy to electrostatics –the charge on a closed conductor distributes itself in such a way that it produces no internal field. In our case, the mass in the walls of the experimental chamber will neutralize only the field of the rest of the satellite, not that of the Earth. In principle the required mass balance may be effected via the mass distribution of the experimental chamber alone, but our experience suggests that it will be more efficient to employ a combination of the chamber and the other cylinders to bring about the required zero internal force.

Instrument Bus(es): The satellite will need one or two 1-axis reaction wheels. These must be quiet enough for use in telescopes and surveillance satellites, and they must be able to spin comfortably at a rate such that their total angular momentum is equal to that of the rest of satellite when it is rotating about it cylindrical axis at the rate of one turn in two minutes (L ~50 kg m^2/sec).

The purpose of the reaction wheel(s) is to exactly cancel the angular momentum along the cylindrical axis. This allows the satellite to tumble about a perpendicular axis without the application of any torques except small trimming torques. Such a tumbling motion, at the mean rate of one turn per orbital revolution, means that the capsule can fly with the cylinder axis approximately horizontal at all times, as required.

The SEE satellite will have two antennae in the shape of circular hoops, one at each end of the satellite, mounted on the the outermost cylinder coaxially with it and of the same diameter. Electrically, each antennae will be configured as a double dipole (like on GRACE satellites).

The power supply will be an array of solar cells covering most of outer surface. Need ~1 kw total. Traditional solar panels are unacceptable because of the stringent requirement to maintain constant distribution of all mass in the satellite.

The downlink/uplink and data rate requirements of the SEE satellite are very modest compared to those of most satellites. Once-per-day communication each way is sufficient. These requirements will be quantified on the basis of further data simulations to determine what quantity of data collection is needed and the extent to which on-board data reduction is desirable.

The key scientific instrumentation of the SEE satellite is its diffractive distance-measuring system, MAARS (micron-accuracy absolute ranging system). This determines the positions of the test bodies in the coordinate frame of the experimental chamber. Other interferometric monitoring may be used to continuously monitor satellite dimensions, since the measurement paths will be essentially fixed, thus obviating most problems of allignment and ambiguity resolution.

A system must be designed and built to neutralize charge on the test bodies (Alexeev *et al.*, 1999, 2000). A system must also be designed and built for caging and uncaging of the test bodies. A number of options are under consideration.

Conclusions

We have described here a novel method of gravitational interaction parameters measurements: G, G-dot, alpha and lambda, using the three body system in space dynamics. Once more we stress that it is the next generation of gravitational experiments, devoted more to problems comimg from modern inified theories of four known physical interactions. Our extensive studies already done show that using this approach we may improve our knowledge of the least known fundamental constant G by 3 orders and measure or place limits to Yukawa-type parameters of possible new interactions alpha and lambda and G-dot about 2 orders better, than we know now. We think that further studies within optimization of trajectories, experimental set up and data processing will only improve these conclusions. The large international team of US and Russian scientists with possible participation of other groups hope to realize this space project in several years.

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