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Control Technology Challenges for Gravitational Physics Experiments in Space

Daniel B. DeBra*
Stanford University, Stanford, Calif.

Proposed relativity experiments have a broad variety of control requirements which are unique or challenging extensions of existing technology. Examples of experiments include the predicted rotation of spacecraft perihelion, drift of a gyroscope in a rotating gravity field or moving through the field, the relative orbital drift of counterrotating satellites, an equivalence principle experiment in orbit employing concentric proof masses and gravity wave detectors employing spacecraft. These experiments are translated into typical performance requirements for orbit adjust, drag-free control, attitude control, and instrument suspension systems. The control requirements range from state-of-the-art to new, very challenging needs. That will be extremely difficult even in the benign environment of space.

I. Introduction

A NUMBER of experiments have been proposed to test the theories of relativity and gravitation. Some of these experiments can and have been performed on the Earth. Others must seek the unique environment of space to free themselves of gravity, seismic noise, or take advantage of astronomical distances. Once in the space environment, many things must be done automatically which could be done manually in the laboratory. Other kinds of control requirements arise in the process of getting into space. Some are demanding extensions of existing technology, whereas others are unique to relativity experiments.

General relativity is a theory involving gravitation. The effects are of the order of the ratio of gravity potential to kinetic energy at the speed of light. This ratio is very small: about 10^{-9} at the surface of the Earth, and only 10^{-6} even at the surface of the sun. Thus the effects predicted are very small and require extreme precision in measurement and freedom from disturbances. Newtonian theory is changed by these small effects, which include modification of orbit mechanics, changes in the orientation of a gyro without a torque, and questions of the equivalence of inertial and gravitational mass. Relativists have found it difficult to perform tests of their theories. The space environment has opened up new possibilities, and this discussion is limited to experiments that can be performed in spacecraft.

The relativity experiments that have been chosen for discussion are ones that require one of four types of control: orbit adjust during the initial setting-up of the experiment, drag-free control to rid the satellite or spacecraft of the effects of external disturbances, attitude control, and special control requirements associated with the instrumentation such as suspension systems. For background information on the theory and experiments for evaluating the parameterized post-Newtonian theories of relativistic gravity, see Refs. 1 and 2.

II. Description of Some Space Relativity Experiments

Perihelion Rotation

To date, the only accurate verification of the general theory of relativity is the observed rotation of the perihelion on Mercury with respect to the sun. After all of the Newtonian perturbations have been accounted for in the tracking data, the residual 43 arc-s/century is explained by Einstein's theory to about 1%. The European Space Research Organization (ESRO) has sponsored studies of a similar experiment to be performed by an artificial satellite. Israel et al.[3] have described the mission, named SOREL, which was designed to determine the principal parameters of the relativity theory and the oblateness of the sun. Planets have a much smaller area-to-mass ratio and therefore experience about seven orders of magnitude less perturbing acceleration from radiation pressure. To compensate for this nongravitational disturbance, a drag-free control system can be used. In this control, which is discussed later, an unsupported, shielded, internal proof mass serves as a reference, and the spacecraft is controlled to follow it. Orbit parameters to improve the accuracy of determining the constants are discussed, and a drag-free performance level of 10^{-13} *g* is established.

Schiff Gyro Test

By Newtonian physics, an ideal gyroscope remains fixed with respect to inertial space, that is, with respect to the "fixed" stars. Schiff[4] calculated the change in orientation of the gyro which would be predicted by the general theory of relativity and proposed testing the theory by the observation of a gyroscope. The support forces make the drift and uncertainties in the gyro performance excessive compared to the predicted relativistic effects when performed in the 1-*g* environment of Earth. In orbit, these disturbances are reduced by six to eight orders of magnitude, and, in addition, the relativistic effects are increased. There are two effects predicted (see Fig. 1).

The first results from the gyro moving through a gravitational field. The net effect is small, being about a 7 arc-s/yr change in the orientation of the spin axis. This effect depends on the theory in the same way as the precession of the perihelion of Mercury. The second predicted effect, the Lense-Thirring precession, depends upon a gravitational field being produced by a rotating body: the Earth. It is approximately two orders of magnitude smaller than the main effect, but there never has been an experiment performed to test it. The development of a gyro that would have adequate performance to make these measurements was begun in the early 1960's at Stanford University by W. Fairbank, R.H. Cannon, and B.O. Lange. The ambitious development of the experiment is described by Everitt.[5] In it the gyroscopes are supported electrostatically in a cryogenic environment. Their orientation is read out with a superconducting magnetometer, which detects the orientation of a magnetic moment produced by the spinning rotor, which is itself coated with a super-

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*Professor, Dept. of Aeronautics and Astronautics and Dept. Mechanical Engineering; also Director, Guidance and Control Laboratory. Fellow AIAA.

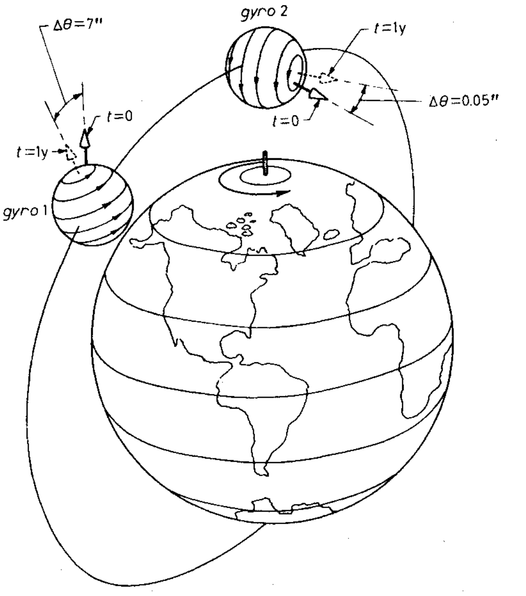

Fig. 1 Relativistic motions of gyroscopes.[5]

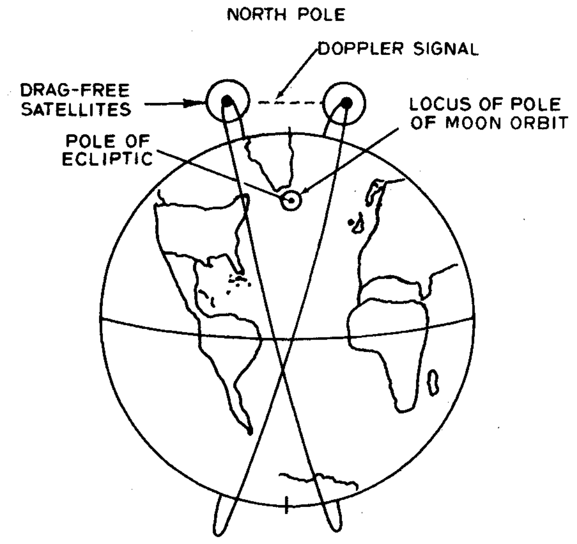

Fig. 2 Orbit configuration for experiment proposed. Orbits shown noncoplanar only for illustration.[17]

conductor. The orientation of the gyros is compared with an integrally mounted telescope. The telescope and gyros assembly is constructed of a monolithic piece of quartz, all of which is located in the cryogenic environment to provide good temperature stability, freedom from creep, and superconduction to provide shielding and the method of readout. The Dewar that supplies this low-temperature environment and isolates the experiment from the rest of the satellite introduces a compliance between the experiment and the satellite, which complicates the attitude control. The boiled-off helium from the Dewar is used for attitude control thrusters.

Counter-Rotating Satellites

Two experiments have been proposed to measure the Lense-Thirring effect involving two counter-rotating satellites. Davis[6] proposes two satellites in the same type of orbit but in opposite directions in order to have a differencing type of experiment. Davis calculates the difference in the rotation of the line of apsides and discusses ground tracking, laser ranging, and multiple-frequency ranging. Van Patten and Everitt[7] proposed two satellites in polar orbits counter-rotating and using only the Doppler signal from relative tracking between the two satellites (see Fig. 2). The measurements involve the rotation of the two orbit planes. Although both proposals calculate the Lense-Thirring effect, Davis[6] calculates the effect on the line of apsides, whereas Van Pattern and Everitt[7] calculate the rotation of the line of nodes. The latter experiment has the advantage of being able to distinguish between small inclination angles that would cause differential rotation of the two orbit planes from the relativistic effect, which has the same sense for both orbits. The experiments require state-of-the-art drag-free satellite performance to cancel perturbations that would disturb the orbits because the net effect of the relativistic effect is extremely small, amounting to a few tens of meters per year along the equator.

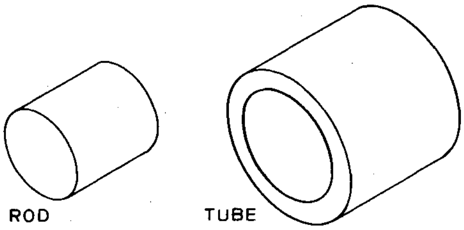

Fig. 3 Test masses.[10]

Equivalence Principle

Experimentally, the equivalence of gravitational and inertial mass has been established to a level of approximately 10^{-11} through experiments performed on the Earth by Roll et al.[8] and Braginsky and Panov.[9] The studies and preliminary laboratory experiments by Worden and Everitt[10] predict establishing the principle in the orbital environment to a level of 10^{-17}. There are two concentric proof masses, one a solid superconductor and the other a hollow cylinder of different material coated with superconductor levitated on superconducting coils that are shaped like a trough. The masses are free to slide along the length of the trough. Any differences in the gravitational and inertial mass should appear as relative motion of the two proof masses (see Fig. 3).

With the satellite inertially oriented, the centripetal acceleration and gravity rotate with respect to the masses at orbital frequency. By using one of the proof masses as the reference for a drag-free satellite, the other proof mass is forced to keep a fixed relative position with respect to it, and that force should be a direct measure of the Eötvös acceleration, that is, the acceleration that would arise, if any, due to the difference in the gravitation and inertial mass. Extremely small effects become important in this experiment, particularly if they have any component that might vary at orbital frequency. The mass attraction of the satellite on the proof masses is not important because it is a constant and will not vary at orbital frequency. Mass attraction gradients are important even for very small deflections. Worden and Everitt cite several sources of relative position uncertainty. Density inhomogeniety of 10^{-6} produces a mass center shift so that the masses move 100 nm at twice the orbital frequency due to the gravity field gradient. The calculated amplitude for free thermal vibration of an oscillator tuned to orbital frequency is 25 nm. By contrast, the mass centers of the two proof masses must be within 3 pm in order for the twice-per-orbit differential acceleration due to the local gravitational and inertial mass of 10^{-18}. Even though the designed Eötvös acceleration is at orbital frequency, measurements must be made with great care in the presence of disturbances 10^5 larger.

Gravity Waves

Thorne and Braginsky[11] have proposed an experiment using the Doppler measurement of the relative position of a spacecraft with respect to the Earth as a means of detecting gravity waves. A gravity wave that passes the spacecraft and the Earth leaves a characteristic signature three times on the Doppler history. Furthermore, the relative amplitude and relative time of these signals depend only on the angle between the propagation direction of the wave and the line of sight between the Earth and the spacecraft. This not only helps detection but should make possible the calculation of the direction of the wave if more than one spacecraft is involved. Two areas of technology need to be improved to make this experiment feasible. First, the Doppler tracking needs several orders of magnitude improvement, but the existing state-of-the-art has not been pushed by requirements. The improvements in Doppler appear feasible with available techniques. The second area involves drag-free performance. The motion of the spacecraft with respect to the proof mass must be limited. Either a proportional control system must be used, or the deadband for operation of an on-off propulsion system needs to be reduced to 100 nm.

Spinning Rings

Chapman[12] has proposed measuring the effect displayed by a spinning body that is displaced normal to its orbit if it has spin angular momentum normal to the plane of the orbit. Chapman calculates that a fused silica fiber ring 5 m in diameter and spun approaching its burst speed would be displaced 2 nm. By using two coaxial hoops spun in opposite directions, the displacement could be doubled and a differential measurement made. As in the equivalence experiment, the suspension and the necessity to keep the disturbing interactions between the satellite and the spinning bodies small are of utmost importance.

Other Experiments

Other experiments have been proposed for experimentally investigating relativistic gravity. For example, Braginsky has proposed a principle-of-equivalence experiment employing a dumbbell[13]; Weber[14] has proposed a gravity wave antenna in space; and there are the clock experiments,[15] but they do not depend upon aspects of automatic control. Furthermore, all of the experiments use information filtering, for example, the work by Anderson,[16] in which he discusses the tracking of spacecraft: information processing, filtering, and, specifically, the efficient way in which a Kalman filter simplifies the data handling for sequential estimation problems.

III. Control Technologies

Orbit Adjust

In the gyro experiment, the net effect on the gyros depends upon the orientation of the orbit plane. If an inclination angle exists, the oribit plane will regress, and this regression needs to be small during a period of at least a year for the amplitude of the relativistic effects to continue to increase linearly with time. This requires a small fraction of a degree, which is modest compared with the requirement of the two counter-rotating satellites experiment[7,17] Here, the *difference* in inclination must produce less than a 1-km variation between the orbit planes, and the coinclination of the sum angle must be an order of magnitude smaller. In addition, in order to avoid secular and long-period terms from the moon's orbit, the planes must be within 100 arc-s of the pole of the ecliptic. The orbital period and phasing are quite critical also. The orbital period must be noncommensurate with the Earth's rotational speed, and the two satellites must have encounters that occur within 3 km of the North and South Poles. It is clear that these requirements cannot now or in the immediate future be met by direct launch. It requires considerable tracking to determine the orbit before corrections can be made at an altitude of 800 km. Van Patten and Everitt[7] estimate about 15 weeks before the final adjusts and trimming. Since the satellites must be drag-free, this can be done impulsively before the drag-free control system is turned on, or by commanding perturbations to the proof masses of the individual drag-free satellites. Some combination of the two may turn out to be optimum. While the orbit planes are being matched, the orbit periods must be matched to 120 μs.

Drag-Free Control

Since the drag-free control was suggested by Lange in 1961,[18] there have been a number of studies,[19-22] and one successful flight.[23] Many papers have contained calculations for ambitious drag-free satellite design. On Sept. 2, 1972, the first drag-free satellite was launched and flew successfully, operating for 19 months before exhausting its propellant in the spring of 1975.[23] In this flight, performance at 5×10^{-12} g was established based on a three-day tracking average. In the gyro experiment, drag-free performance significantly helps relax some of the requirements for reducing torques from the support forces but is not as demanding. Drag-free suspension is absolutely essential for the principle of equivalence. The satellite will not be rotating, and, since the information desired will change its orientation with respect to the satellite, bias forces that are stable will be acceptable. It is the variations in disturbances at orbital frequencies which become important for this experiment. Thermal effects are systematic, and others have been discussed in the papers cited. In the counter-rotating satellites and in the project SOREL, the performace required goes well beyond what was established in the 1972 flight. In order to acheive this improved per-

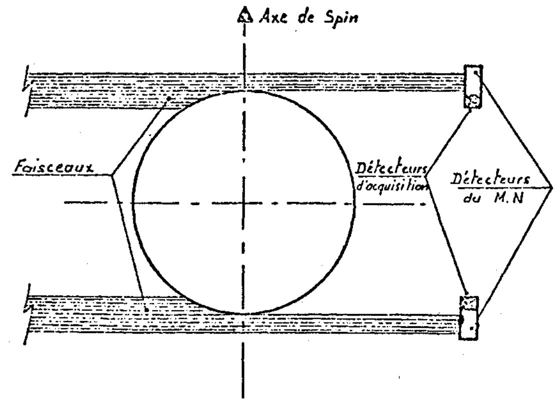

Fig. 4a Optical pickoff proposed for SOREL.[20]

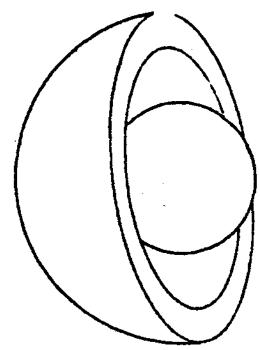

Fig. 4b Transit satellite proof mass and housing sectioned.[23]

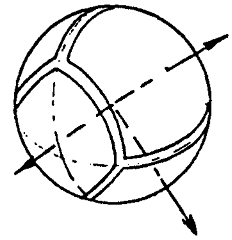

Fig. 4c Plate configuration in the transit satellite housing for capacitive sensing.

formance, it would be necessary to spin the satellites so that any residual disturbance will get averaged out in the plane of spin. Calculations indicate that performance at the level of 10^{-13} g should be achievable, and a variety of designs have been suggested. One approach is to design a very large cavity with a small reference proof mass. The disturbances are all position-dependent, and so the disturbance to the proof mass is reduced by keeping all parts of the satellite as far away as possible. With the larger cavity, however, the accuracy of locating the proof mass with a sensor degrades, and, since the disturbing forces have gradients, the variation in the null point can result in variable forces that are significant at the level required by these experiments. The contrary philosophy suggests using a close-fitting proof mass and housing; then the sensing is more accurate, and, through use of tight control, the relative motion of the satellite with respect to the proof mass will be minimal. This requires smaller impulse bit size for efficient use of propellant and more frequent firing, which is another tradeoff with reliability (see Fig. 4).

In the gyro experiment, the propellant used for both attitude and translation control will be the boiloff helium from the Dewar. Since this gas must escape in any event, there is no need to use tight-sealing on-off control valves. Rather, the gas must continue to flow, and it is modulated to come out of opposed thrusters proportional to the input signal that is applied to the valve.[24] In this way, a proportional system is obtained without a compromise in the cost of the propellant, since the dominant requirement is for maintaining low temperature. The Thorne-Braginsky gravity wave experiment[11] could take excellent advantage of this approach if there were reason to justify going to low temperatures in the satellite. If a limit cycle of 100 nm is the largest permitted, then the firing interval for the gas valves will be on the order of 1/s. This would result in tens of millions of operations per year, which would press the state-of-the-art of cold gas, hot gas, or electric engines.

There seems to have been adequate sensor work done to insure this kind of precision with a capacitive pickoff employing acceptably small gaps. The bias forces that might appear in the Thorne-Braginsky gravity wave experiment would be unimportant as long as they did not change in the time for light to travel to about 10 A.U., which is the separation distance proposed in order to obtain adequate sensitivity.

Attitude Control

In satellites that have drag-free performance that uses the satellite spin for averaging, the direction of the spin axis is important because the averaging takes place only in the plane perpendicular to that axis. If the spin axis is misaligned with respect to the orbit plane and orbit frequency disturbances are troublesome, special attention must be paid to avoid the in-track coupling that occurs in that case. Attitude control also may be required in order to operate the experiment adequately. In the counter-rotating satellites, the Doppler information requires 2-deg attitude control for the antenna correction, which is needed because the antenna is not, in general, located at the mass center. Whenever the satellite rotates, the effective center of radiation of the antenna moves about the satellite mass center, and hence it contributes to the Doppler signature. Two-degree attitude information is adequate to compensate for this.

The most demanding attitude control is for the gyro experiment.[24] Here, the experiment package must be controlled to 0.1 arc-s in order to provide the telescope with a sufficiently narrow operating range that it can be designed for 0.001-arc-s accuracy without introducing significant nonlinearities. The outer part of the spacecraft need not be pointed so precisely. In order to provide precise pointing of the experiment package without requiring high bandwidth control of the large inertias of the rest of the vehicle, an internal actuator was designed into the satellite. This allows one to push against the Dewar with tight control for the inner experiment package while the orientation of the satellite is aligned more leisurely using the gas jets. Because of the compliant structure joining the satellite and the Dewar through the insulation, stability problems exist unless great care is taken. A classical design, in which the inner actuator effort was used as an indication of the relative orientation of the outer satellite and Dewar, provided adequate control with some lead and integral compensation. However, that design was extremely sensitive to model errors in the satellite, e.g., gas pressure. The quadratic synthesis designs that were developed by Bull[24] are much less sensitive. Subsequent work by Hadaas and Powell[25] has made it possible to use a cost function that simultaneously minimizes sensitivity with very small loss in performance.

Suspension Systems

The electric suspension of the gyroscopes uses much of the technology developed for Earth-based electrically suspended gyros and the low-level accelerometers developed for space use. The need for operation in the laboratory leads to special problems, however. Levitation currents at 1 g are three or four order of magnitude larger than required in orbit, and their presence increases the difficulty of achieving the sub-arc-second pickoff accuracy required. Nikirk[26] describes the laboratory model development, and very recent studies by Sonnabend[27] may provide additional help in the final orbital design.

Chapman[12] has not worked on the suspension for his proposed spinning rings beyond some preliminary thoughts. There, the orientation of the satellite, as well as its position, must be maintained with extraordinary accuracy.

Table 1 Summary of control requirements

Experiment	Orbit adjust	Drag-free, m/s^2	Attitude control, rad	Suspension
Perihelion	. . .	10^{-12}	$\sim 10^{-3}$	. . .
Gyro	$\delta i \sim 0.1$ deg	10^{-8}	10^{-6} control, 10^{-8} measure	10^{-16} rad/s
Counter-rotating satellites	$\delta i \sim$ and Δi 2-100 arc-s $\Delta T \sim 120\ \mu$s	10^{-12} av	0.03	. . .
Equivalence	$e \sim$ possibly $< 10^{-5}$	10^{-16} at ω_0	Will depend on suspension	10^{-16} m/s^2 at ω_0
Gravity waves	. . .	$\sim 10^{-12}$ for 10^3 s	10^{-6} for 10^3 s	. . .
Spinning rings	. . .	$\sim 10^{-15}$	?	$\sim 10^{-15}$ m/s^2

The development work on a suspension for the Worden and Everitt[10] equivalence-principle experiment will combine some interesting technology. One of the masses will be a drag-free reference, and the other will be suspended with respect to the satellite or with respect to the first proof mass. The cryogenic methods used in the laboratory version of the experiment must be re-examined for use when trying to achieve the equivalence to 10^{-17} g on orbit. Active feedback may be introduced in interesting ways.

IV. Conclusions

There have been some very challenging and significant experiments proposed in recent years which exploit space to confirm theories of gravitation and relativity. Control technology will play an important part in achieving these. A summary of some of the requirements is given in Table 1.

Acknowledgments

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