THE CONTROL OF LIQUID HELIUM IN SPACE BY ELECTROSTATICS FOR THE SATELLITE TEST OF EQUIVALENCE PRINCIPLE EXPERIMENT

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ABSTRACT

The equivalence of gravitational and inertial mass has been advanced to a basic postulate of the Einstein view of gravity. As such it deserves the most rigorous testing possible. Recent advances in technology (SQUIDS, superconducting bearings, space-operable liquid helium cryogenics) have made it possible to test this equivalence to one part in 10^{17}, an advance of a factor of a million. The Satellite Test of the Equivalence Principle has been proposed to NASA and ESA for flight in about 2000. It will incorporate an extremely sensitive accelerometer in a liquid helium cryostat in Earth orbit at 550 km.

All sources of noise must be rigorously controlled to achieve this sensitivity. One such source is the motion of the liquid helium cryogen in the gravity-gradient field existing in an orbiting satellite, The use of electrostatic forces to confine the helium has been proposed. A system of electrodes charged to several thousand volts would limit the motions to 0.1% of the free motion, well below that needed.

Such a system has been designed and analyzed. A demonstration model of the system has been demonstrated in a NASA zero gravity aircraft. The analysis, test and test results are described in this paper. The system has been shown to meet the requirements of the mission.

SCIENTIFIC BACKGROUND

Einstein took the bold step of making the equivalence of gravitational and inertial mass a postulate. Making the equally bold postulate that the speed of light is a constant independent of the motion of the observer, he was able to derive the entire general theory of relativity, in which gravity is the result of a curvature in space-time, If the equivalence principle fails, then this simple and elegant description of gravity, which is fundamental to our current view of the universe, also fails. A second and equally fundamental reason for our interest is that the Einstein description of gravity conflicts with quantum mechanics. Both cannot be correct in their present form, and a demonstration that the equivalence principle fails would be a clue to the direction one must take to resolve the problem.

Improvement in techniques for the measurement of force has been the a major factor in our increasingly precise understanding of the nature of mass, Galileo's measurements of rate of fall of masses of different densities first showed that the common-sense conclusion that heavier masses fall faster than light ones was incorrect. (He probably timed rolling balls on an inclined planes; his supposed observations of balls dropped from the leaning tower of Piss was almost certainly not the source of his quantitative conclusions.) He achieved an accuracy of perhaps 1%. His results were of great importance, because they were the first to show that the proportionality between the attractive force of gravity and the retarding force of inertia was independent of density.

Newton took the next technological step; by using masses of different densities as the bobs of pendulums he achieved accuracies of O. 1%. He also incorporated his observations into one of the grandest generalizations of all of science; his laws of motion, The invention of the torsion balance led to the next great leap. Eötvös measured gravitational force in 1896 by balancing the Earth's gravity against the centripetal force of its rotation, demonstrating the equivalence principle to one part in 10^7. Using the same basic technique, with the sun replacing the Earth, Dicke and co-workers[1] achieved an accuracy of 5 x 10^{-11}, the best to date. This appears to be a practical limit set by the Earth's micro-seismicity.

Four recent advances in technology, all related to cryogenics, have increased our capability to measure force greatly. These are; 1) the superconducting quantum interference device (SQUID) which can now measure motions with a sensitivity of 10^{-15} m; the use of the Meissner effect (the exclusion of magnetic fields from the interior of a superconductor) to form an extremely low-force bearing; 3) the reduction of thermal noise by experiment operation at liquid helium temperatures, say 2 K; and 4) the ability to conduct low temperature experiments in space, where gravitational disturbances are smaller, where we can eliminate the supports necessary to support a mass in one g, and equally importantly, where the source can be modulated by placing the experiment in Earth orbit.

STEP MISSION

Using the modem techniques detailed above, the Satellite Test of the Equivalence" Principle (STEP) experiment will be able to detect differences in gravitational and inertial masses to about one part in 10^{17}, about a factor of 10^6 better than Dicke's results.

The heart of the experiment is a set of differential accelerometers composed of two concentric masses of different composition and density, each supported by a magnetic bearing[2] (Figure 1). The relative positions of the masses of each accelerometer is determined by a SQUID inductive position sensor to an sensitivity of about 10^{-15} m. The masses are maintained in a freed position by an electrostatic

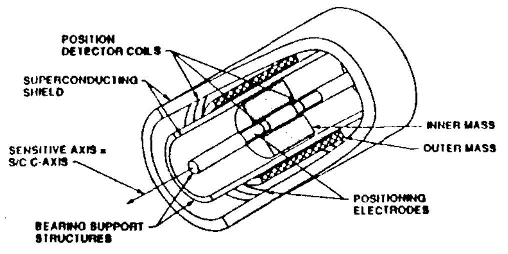


Figure 1. STEP Differential Accelerometer

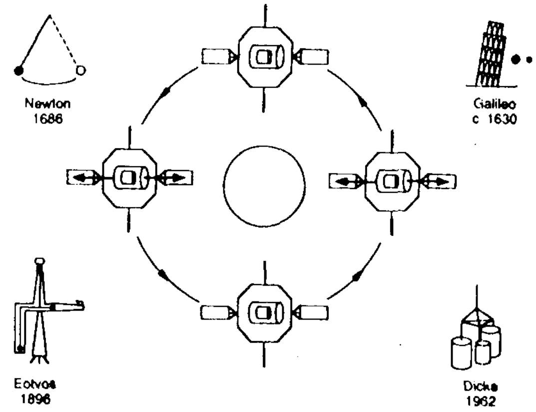


Figure 2. STEP Orbit

feedback system whose output is a direct measure of the forces on each proof mass.

The accelerometers are placed in a drag-free satellite in an orbit of about 550 km (Figure 2). If the equivalence principle is violated, the masses will be subject to a differential force which reverses sinusoidally once per orbit. Thus most sources of noise can be made negligible by filtering at the 95 minute orbital period. (To eliminate certain sources of error, the spacecraft will be rotated in orbit at certain times, but the principle is the same; filtering will be applied at the net rotation rate with respect to the earth.)

The STEP accelerometers must be operated at a temperature of about 2 K. At the present time the only practical method for obtaining this temperature in space is to operate the experiment in a liquid-helium-cooled cryostat.

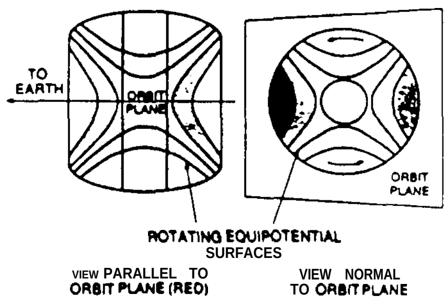


Figure 3. Helium Distribution in Orbit

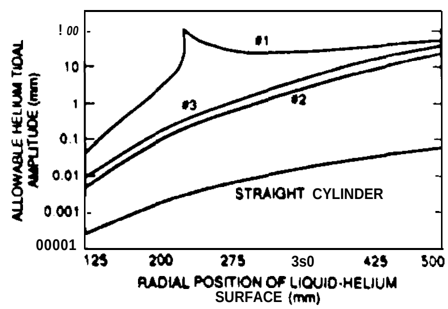


Figure 4. Allowed Motion of Helium

The fluctuating gravitational forces resulting from the motions of the liquid helium are one of the few effects which can introduce significant disturbances at the orbital frequency into the equivalence-principle accelerometers. The gravity-gradient forces tend to move the helium away from the center of the satellite along the Earth-radial direction and toward the center at right angles to that direction (Figure 3). Since the attitude of the satellite is fixed in inertial space, the gravity gradient and the helium distribution rotate at the modulation frequency with respect to the spacecraft. These gravity-gradient accelerations are on the order of 10^{-7} g for the dimensions of the STEP cryostat.

As shown in Figure 4, the allowed motion of the helium free surface is dependent on the product of the helium mass involved in the disturbance and the distance of the disturbance from the center of mass of the accelerometers. For a reasonable helium mass, motions at a distance of 12,5 cm must be as small as 0.01 to 0.1 mm.

ELECTROSTATIC CONFINEMENT

It is proposed to control the gravity-gradient-induced motions of the liquid helium by use of electrostatic forces. It is well known that electric fields generate a pressure which acts to force move dielectrics into a region of high field. The equivalent pressure gradient of the electrostatic fields is given by[3]:

$$\nabla p = -\frac{\epsilon_0 E^2}{2} \times \nabla \epsilon_r + \frac{\epsilon_0}{6} \times \nabla \left[E^2 \times (\epsilon_r - 1) \times (\epsilon_r + 2) \right]$$

Here ϵ_0 is the vacuum dielectric constant and ϵ_r is the relative dielectric constant of helium, about 1.05, The first term is proportional to the gradient in the dielectric constant. Because the liquid helium is relatively incompressible, it is very small in the bulk fluid, but finite at the free surface between the gas and the liquid, where it acts like surface tension.

The second term is a bulk term proportional to the gradient of E^2. The direction of the force is such that a liquid with a relative dielectric constant greater than 1 will be driven into a region of converging fields.

For comparison, the equivalent gravitational potential is given by:

$$\nabla p = \rho a$$

Thus we may compute an equivalent acceleration due to the electrostatic field as:

$$a = -\frac{1}{\rho}\left[-\frac{\epsilon_0 E^2}{2} \times \nabla \epsilon_r + \frac{\epsilon_0}{6} \times \nabla \left[E^2 \times (\epsilon_r - 1) \times (\epsilon_r + 2) \right] \right]$$

Inserting the constants for liquid helium and a field of 10^6 v/m, we find that the equivalent acceleration for the STEP dewar is of the order of 0.1 mg. For the KC-135 cryostat, where spacings are smaller by a factor of 10, we find an acceleration equivalent to 1 mg.

Electrostatic forces have been used for the control of liquids for some time. In particular, Israelsson et. al[4]. investigated the use of electrostatic forces to accomplish the separation of ^{3}He and ^{4}He in a ^{3}He-^{4}He dilution refrigerator. They were able to demonstrate as much as 0.2 g in ^{4}He in a parallel plate geometry at the STEP operating temperature.

The proposed electrostatic system (Figure 5) will use the forces generated by the electrostatic fields to reduce the motion of the helium to an acceptable value. Forces equivalent to accelerations of the order of 0.1 to 1 mg can be generated by the application of electric fields in the range of 0.5 Mv/m. Gravity gradient forces are equivalent to 10^{-7} g; thus we may expect a reduction in helium motions of a factor or 10^3, well below that necessary.

The electrostatic system has been verified by a combination of analysis and experiment. Analytic and computer-based models have shown that the necessary forces can be developed. Studies of miniature versions of several proposed electrode configurations in the NASA KC-135 zero-g aircraft have demonstrated that control can be achieved. The studies also demonstrated that the necessary electric fields could be achieved without electrical arcing in the helium gas. A demonstration video tape showing the dynamic and static behavior of the helium was made from tapes taken during the zero-g experiments.

Analysis and Modeling

The electrostatic forces for simple cases may be calculated analytically. However, for complex geometries finite-element computer modeling is necessary. We use the commercial program "MagNet[5]" to model the fields. This program is capable of producing maps of constant values of any desired function of E. The value of the function along any desired contour may be plotted as well. In particular, maps and contour plots of E^2 have been produced in an effort to evaluate candidate systems. A plot of the E^2 fields is shown on Figure 5 and a typical contour plot of the

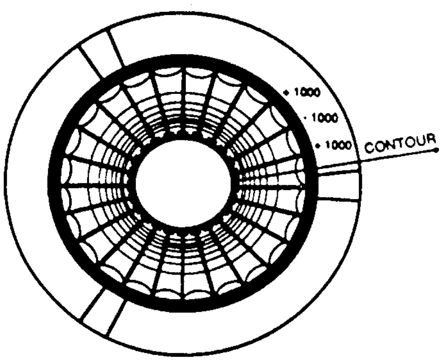


Figure 5. Electrode Configuration and Lines of Constant E^2

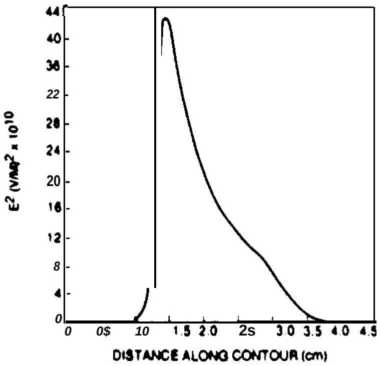


Figure 6. E^2 Along a Contour

configuration used in the KC-135 zero-g tests is shown in Figure 6. Since the electrostatic forces on the liquid helium are proportional to the gradient of E^2, the surface of the liquid will lie on a contour of constant E^2 (in the absence of surface tension.)

In order to do a complete analysis, one must include the effects of gravity gradients, surface tension, and electrostatics. The program "Surface Evolver[6]" is capable of such calculations. It computes the minimum energy for any set of forces which can be described by an analytical function. A Surface Evolver model of the zero-g aircraft experiment including electrostatic and surface tension forces for liquid helium at 2.05 K and with 2 Kv potential applied between electrodes is shown in Figure 7. AS compared to Figure 5, note the rounding of the surface, leading to a star-shaped pattern,

Efforts to analyze the surface of liquid helium solely under the influence of surface tension indicate that a stable equilibrium is not possible, presumably due to the zero wetting angle of liquid helium[7,8]. Our current interpretation of this result is that the liquid helium will coat all internal surfaces to a finite thickness. Thus the different surface energies of wetted and un-wetted surfaces will not affect the distribution, In the absence of electrostatic forces, only the very weak forces of surface tension and gravity gradients will affect the distribution

The Surface Evolver program appears to manifest this instability by a dependence on initial conditions. If they are close to the final expected condition, they evolve to a starlike configuration, but if they are not, the iterative process does not converge.

EXPERIMENT

Objective

The objective of the flight experiments is to provide a convincing visual demonstration of electrostatic confinement, to test the effectiveness of several proposed configurations and to provide data for comparison with analytical and computer modeling.

Apparatus

The experiments were flown in a NASA KC-135 aircraft dedicated to zero gravity experiments. The aircraft is flown on a free-fall parabola of about 30 seconds duration. During this period, experiments anchored to the aircraft experience about 10 mg acceleration, while experiments flown in a free-floating package experience a static and dynamic acceleration of the order of 0.1 mg. Since the electrostatic confinement forces are of the order of 1 mg, it was necessary to use this free-float capability to explore electrostatic confinement.

The basic experiment is contained in a double LN_2/LHe cryostat with viewing windows to provide a means of recording data on a video camera (Figure 8). This cryostat is mounted in a float package containing a vacuum pump to keep the helium at superfluid temperatures (i.e. below 2.17 K and at a pressure below 51 Kpa or .05 atm.) The cryostat is fitted with a pressure transducer and several temperature sensors to allow recording of the helium state.

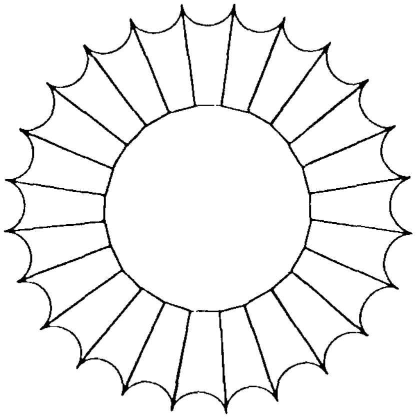


Figure 7. Calculated Distribution of Liquid Helium under Electrostatic Containment

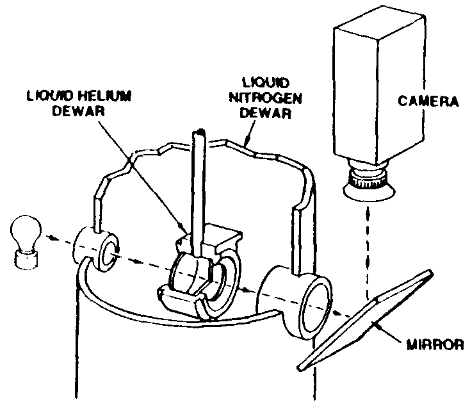


Figure 8. Test Cryostats and Camera

Gauges, valves and a three-axis accelerometer package are ‘also mounted on the float package, The structure is a stainless steel tubular framework with handles to allow manipulation in zero gravity. The float package is connected to a control rack which supplies power to the pump, and has a video monitor and a chart recorder for recording and real-time data monitoring.

In operation, the package is released as the aircraft approaches zero g and is allowed to float freely. Typically it will drift into a wall at least once during the zero-g time. As a result, undisturbed times are seldom longer than seven or eight seconds.

The helium under test is contained in a cylindrical ceil 90 mm in diameter and 32 mm deep. The cell is illuminated from the rear through a diffuser marked with a 1/4" (6.3 mm) grid to allow measurement of the free surface. The data are recorded on video tape. Because of the geometry, only helium motions perpendicular to the line of sight can be observed.

For some parabolas, a small acceleration was applied by a means of a hand-pulled spring scale. As far as possible, the acceleration was applied perpendicular to the line of sight, forcing the liquid to one side of the cell. Typically the force could be applied for three or four seconds.

Experimental Results

Two configurations were investigated. The first consisted of nearly concentric elliptical plates, arranged to converge and diverge in the azimuthal direction. A second set, which was studied more extensively, consisted of a set of 24 radial vanes mounted in insulating rings whose diameters were 1/10 of the those of the helium tank and the instrument well (Figure 5). The plates were 18 mm in the radial direction, 32 mm in the axial (line of sight) direction by 0.5 mm thick. Twelve vanes were connected to one power supply and the alternating twelve to a’ second supply. In most tests, one set was connected to positive voltage and the second set grounded. In some tests, the two sets were at equal positive and negative voltages.

Figure 10 shows a comparison of the behavior of the helium with O voltage and $\pm$ 1000 volts applied. (The picture shown is a hard copy from the video tape, taken after transients have died away.) With 1000 volts applied, the static configuration takes up the star-like configuration shown in Figure 7. The figure with no voltage applied was also tending toward the a star-like configuration, but much more slowly, reflecting the weaker surface tension forces (equivalent to about 0.1 or 0.2 mg as compared to 1 reg.)

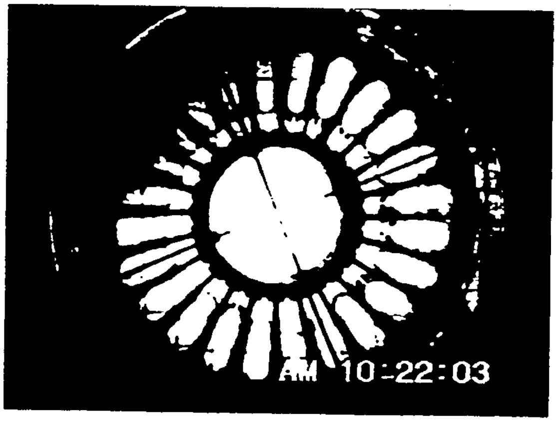
Figure 11 shows the effect of voltage with 8 mg acceleration applied to the right. With 1000 v applied, the helium is largely retained in a star-like configuration, with a small amount of helium on the left side. With no voltage applied. the bulk of the helium is drawn to the left, with only a small amount retained in the center of the star where the surface tension forces are largest.

CONCLUSIONS

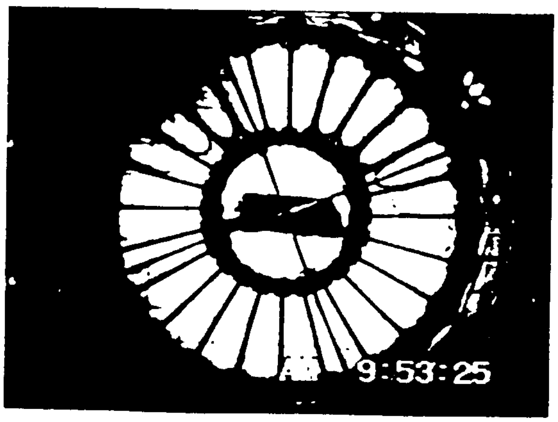
From analysis and examination of the static and dynamic behavior of the liquid helium in near-zero g, we conclude that the electrostatic forces will cause the free surface to assume the desired configuration, and that surface motions caused by the gravity gradient will be reduced by a factor of about 1000.

We now have the experimental and analytical tools to perform and verify proposed designs for liquid helium control.

Voltages up to 2000 volts and gradients up to 1 Mv/m can be sustained in helium at 2.1 K in the flight configuration, sufficient to provide a retaining force equivalent to about 0.1 mg.

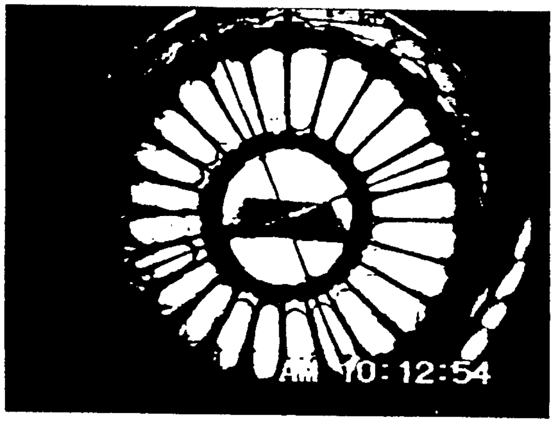


SUPERFLUID HELIUM ±1000 VOLTS No ACCELERATION

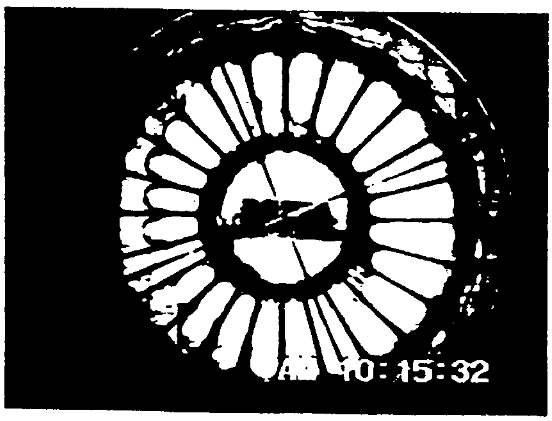


Superfluid HELIUM NO VOLTAGE NO ACCELERATION

Figure 9. No Applied Acceleration



SUPERFLUID HELIUM 1500/0 VOLTS 8 MILLI-G'S TO RIGHT



SUPERFLUID HELIUM NO VOLTAGE 8 MILLI-G'S TO RIGHT

Figure 10.8 mini-g Applied Acceleration

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