Tunnel Detection Utilizing Field-Stationary Gravity Gradiometers

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At the Joint Institute for Laboratory Astrophysics, we have developed a new type of torsion pendulum apparatus. The initial motivation was to improve the accuracy of the Eötvös (equivalence of gravitational and inertial mass) experiment. In this torsion pendulum apparatus, the traditional fiber is replaced with a surrogate in which the fiber's suspension role is provided entirely by a fluid while its restoring and centering functions are achieved by an appropriate electrode array subject to adjustable voltages. Slight modifications of this design result in a low cost gravity gradiometer of potentially very high sensitivity. We are now constructing -- for purposes of testing the concept -- two fluid gradiometers of a size such that, theoretically, their sensitivities will permit one to see the change in gravity gradient resulting from a tunnel at a distance of one kilometer. The status of this development will be discussed.

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In this paper work aimed at a new type of gravity gradiometer will be described. In the past gravity gradiometers of the Eötvös-type have been constructed using a traditional torsion balance; but, despite a significant amount of effort, none of these instruments have achieved the sensitivity that would be expected if they were limited by the Brownian motion of the torsion balance. In practice, other sources of noise have dominated the Brownian motion. The torsion fiber itself is a source of noise, and the torsion balance is extremely sensitive to seismic noise. Also, the sensitivity of the torsion balance is limited because the torsion fiber not only supports the test masses but also provides the torsion constant. An attempt to increase the sensitivity of the torsion balance by increasing the size of the test masses would also require an increase in the radius of the torsion fiber. Increasing the radius of the torsion fiber, however, places even more severe requirements on the position detector.

In an effort to circumvent the limitations of the traditional torsion balance gradiometer, we have developed a new instrumental approach to this problem which separates the two functions of the fiber: we support the gradiometer masses by floating them on a fluid and use electrostatic forces to provide the torsion constant. A schematic of the apparatus is shown in Figure 1. The two gold plated OFHC copper masses are enclosed in a hollow, cylindrical, aluminum container which is 10 in. (25.4 cm) in diameter and 7.6 in. (17.5 cm) high. The cylindrical copper test masses (each of which has a mass of 2.9 kg) are located one on each side. The float is supported by the buoyancy of water which is held at its maximum density. Electrostatic forces are used to keep the float centered and to provide the "fiber's" torsion constant. In practice this is accomplished by using three 1 in. diameter aluminum balls on the top of the float and also three 1 in. balls on the
container lid. Note that the balls on the container are electrically insulated from the top of the container. An ac voltage, typically 1 kV rms, applied to the center electrode keeps the float centered. The ac voltage on the outer electrodes may be varied to change the torsion constant. With a 0.125 in. gap between the electrodes the float is critically damped (torsion constant \( \approx 1 \text{ dyne-cm} \)) at a torque electrode voltage of approximate 40 V rms.

In addition, on the container lid, there are two optical sensing systems (see Figure 2). Locating the detection systems on opposite sides and using their outputs properly summed makes them insensitive to sideways motion of the float without sacrificing the detection system's sensitivity to rotation. The sensing system consists of an infrared light emitting diode–IR LED (whose output light is focused into a line image by a cylindrical glass "lens" attached to the top of the float) and a split photodiode detector. As the float turns, the cylindrical lens moves with respect to the LED-photodiode pair causing the line image to move its position on the split photodiode. This results in a change in the output of the two halves of this device, giving rise (when amplified) to a rotation-dependent voltage as shown on the right half of Figure 2.

One of the difficult problems associated with using a fluid to support the test masses is that convection currents within the fluid tend to rotate the float and thereby introduce noise into the system. We can avoid this problem by choosing water as the fluid because it has the unusual, and here very useful property, that at 3.98°C it has a maximum in its density. If the temperature of the entire apparatus is stabilized to this point, then small variations in the temperature of the water do not change the density of the fluid. Thus there are no buoyant forces to drive convection currents when operating at 3.98°C.

Tests of this surrogate fiber concept using water at its maximum density point have been very encouraging. As the temperature approaches 4°C, there is a
significant decrease in the rotational noise of the float. By circulating cooled water around the instrument, we have been able to keep changes in its temperature to less than ten millidegrees centigrade over periods of 24 hours, and its temperature within 0.1°C of the maximum density point for weeks at a time.

During the surrogate fiber development, the following noise sources have been identified:

Variations in the magnetic field strength at the float are a potential source of noise. In one of the early (test) versions of this fluid fiber concept, the float contained a large piece of brass which had magnetic impurities such that a change of 0.04 G in the external dc magnetic field produced torque many times the magnitude of the gravity gradient torques that one would be looking for. Subsequently, the only materials we have used in the float construction are OFHC copper, aluminum, RTV, epoxy, glass, and Buna-N O-rings. In addition, all parts are machined with cemented carbide tools in an attempt to insure that no magnetic chips are introduced into the material. With these precautions, a change in the magnetic field of 1 G will not produce a significant torque on the float.

Eddy currents produced in the float by rotating magnetic fields give rise to a magnetic dipole moment that leads the rotating magnetic field by 90°. The interaction of this magnetic dipole moment with the rotating magnetic field produces a constant torque on the float in a direction opposite to that of the rotating magnetic field. Shielding the apparatus with a Conetic magnetic shield, however, permits one to reduce the magnitude of the rotating magnetic fields until they will make no significant contribution to the torques on the float.

The most serious limitation of traditional torsion balances is their sensitivity to seismic noise. By comparison, tests with our surrogate (fluid)
fiber show that it is remarkably insensitive to seismic noise because of two aspects that are very different than with a traditional torsion balance. The other oscillation modes of the float (the bobbing mode and the rocking mode) are highly damped, and the position of the float with respect to its container is independent of the acceleration of the container.

Finally, tests to determine whether the day-to-day tilt of the floor (~1-3 arc sec) affected the position of the float have also shown no significant effect.

In the Eötvös-experiment-related version of this development, the position of the float was sensed using an external autocollimator. However, in addition to requiring a window thru the container, this approach introduces the stability of the autocollimator, the stand it rests on, as well as the mechanical integrity of the intermediate linkages between the autocollimator stand and the container lid whose electrode array determines the zero of the "fiber." The sensing system which we have devised for this application promises to have a much higher mechanical integrity in that the sensing optics are a part of the container lid on which the zero-determining electrode array is located.

The fundamental limit to the torque that can be measured is due to the Brownian motion of the float. The mean square torque in a bandwidth of Δf having a given phase is

\[ \langle \tau^2 \rangle = 2k_B T b \Delta f , \]

where \( k_B \) is Boltzmann's constant, \( T \) is the absolute temperature, and \( b \) is the damping coefficient in the equation of motion

\[ I \frac{d^2 \theta}{dt^2} + b \frac{d\theta}{dt} + k\theta = \tau , \]
where \( I \) is the moment of inertia, \( k \) is the torsion constant, and \( \tau \) is some external torque acting on the system. The damping is primarily due to the water.

To get some feeling for the potential sensitivity of our proposed gradiometer float, let us calculate the external mass sensitivity of our present gradiometer for two cases: 1) that of a distant point mass, and 2) that of a distant line (cylinder) mass of infinite length.

The expression for the torque experienced by the quadrupole moment of our float (the two masses, \( M \), separated by a distance \( l \) inside of the float) as the result of a point mass, \( m \), at a distance \( D \) is given by:

\[
\tau = \frac{GMl^2m}{2D^3} \sin 2\phi
\]

We expect to be able to see a torque of \( 10^{-6} \) dyne-cm (~5 times worse than the one day \( k_B T \) limit of our present float). Thus the distance at which one could see an 80 kg man (assuming he stayed there for approximately one day) is given by

\[
D^3 = \frac{6.7 \times 10^{-8} \times 10^4 \times (20)^2 \times 80 \times 10^3}{2 \times 10^{-6}} = \frac{10^{10}}{2 \times 10^{-6}} \text{ cm}
\]

or

\[
D = 21.5 \text{ meters (70.5 feet)}
\]

The expression for the torque resulting from a line mass (an "anti-tunnel") at a closest approach distance \( D \) is given by

\[
\tau_c = \frac{Gm\ell^2 \sigma}{2D^2} \sin 2\phi
\]

where, now, \( \sigma \) is the mass/unit length of an infinitely long mass cylinder. If we assume a mass/unit length of \( 10^5 \) g/cm (a square cylinder of cross section...
2 meters × 2 meters of density 2.5 g/cm³) and again use 10⁻⁶ dyne-cm as our one-day torque sensing capability, and again putting sin 2θ = 1 (gradiometer's axis at 45° to the mass cylinder's direction)

\[ p^2 = \frac{6.7 \times 10^{-8} \times 10^4 \times (20)^2 \times 10^5}{2 \times 10^{-6}} = 1.3 \times 10^{10} \]

or

\[ D = 1.16 \text{ km (0.72 mile)} \]

In addition, for a cylindrical float of this type, the fundamental noise torque due to Brownian motion scales as \( R^{3/2} \), \( R \) being the radius (size) of the float. Because the gradiometer signal torque goes as \( MR^2 \), \( R \) being the radius and \( M \) the mass of the float, the resultant gradiometer's signal-to-noise ratio (noting that \( M \approx R^3 \)) is given by:

\[ \frac{\tau_{\text{gradiometer signal}}}{\tau_{kB \text{ noise}}} = \frac{R^5}{R^{3/2}} = R^{7/2} \]

which represents an extremely favorable situation with respect to sensitivity increase as one scales up the size of this type of apparatus -- a factor of over 10 in sensitivity for every doubling in size!

The suggested application of this development for tunnel detection (see Note 1) is as follows: In a region through which tunneling could be expected, a gravity gradient baseline would be established using an array of these simple and relatively inexpensive gradiometers. The spacing of these units might be of the order of 500 meters. The digging (evolution) of a tunnel would then show up with a characteristic spacial and time dependency as sensed by such a gradiometer array. Given that during the next year of development the requisite long-term stability of the individual gradiometers is achieved,
This field-stationary gravity gradiometer approach should provide a viable new method to detect tunnels.

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Note 1

Our awareness of this problem came about through reading a news story "U.S. Probing Near North Korean Secret Tunnel" in the September 3, 1979, issue of the Denver Post. Phrases in this article such as "hasn't been confirmed but is being investigated," "the United Nations Command continues to search for suspected tunnels under the demilitarized zone," "there are a number of suspected areas being investigated," etc. suggested to us that tunnel detection might not yet be an exact science.