Rotating Tilt Sensor for LISA Torsion Pendulum

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1 Abstract

This paper addresses the construction and performance of a rotating tilt sensor for the Eöt-Wash LISA noise measurement torsion pendulum. The effect of tilt in the torsion pendulum is discussed to demonstrate the necessity for an accurate measurement of absolute tilt. The rotating tilt sensor significantly reduces the effect of zero-point drift at low frequencies, which makes the apparatus roughly four times more sensitive than a stationary tilt sensor. At 0.1 mHz, the rotating tilt sensor resolves tilt on the nanoradian level.

2 Background

Einstein's Theory of General Relativity describes gravity as a reflection of the way a large mass (for example, the sun or the earth) warps the space-time continuum (Figure 1). The acceleration of a large mass causes "ripples" in space-time, which are described as gravitational waves (Figure 2).

Figure 1: Warping of the space-time continuum by a large mass.

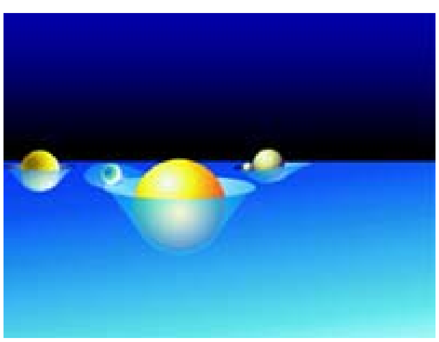
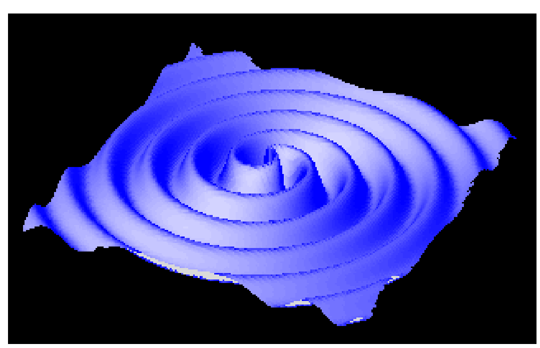


Photo from http://lisa.jpl.nasa.gov

Figure 2: The distortion of space-time, called a gravitational wave.



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The acceleration of any large mass will cause a gravitational wave, but the wave will get weaker as it travels over a long distance. Gravitational waves from binary systems can remain strong enough to measure as they reach the earth. When two stars orbit each other before they collide, they produce a gravitational wave (Figure 3). When a compact star is caught and swallowed by a black hole, a gravitational wave is produced (Figure 4). In addition, two black holes can collide to produce a strong gravitational wave (Figure 5).

Figure 3: Binary system of two galaxies

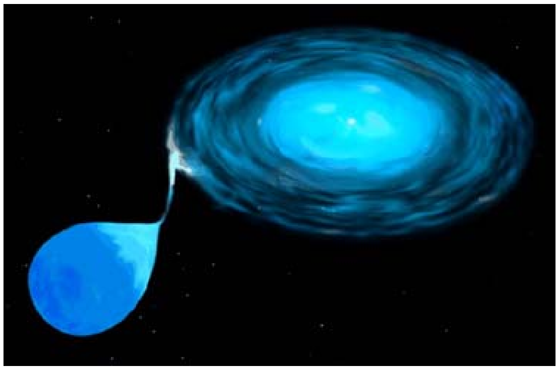


Photo from http://lisa.jpl.nasa.gov

Figure 4: A star caught by a black hole.

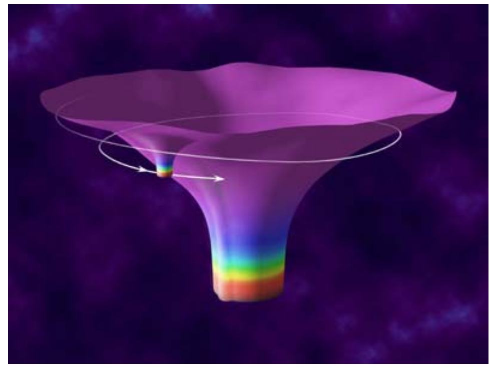
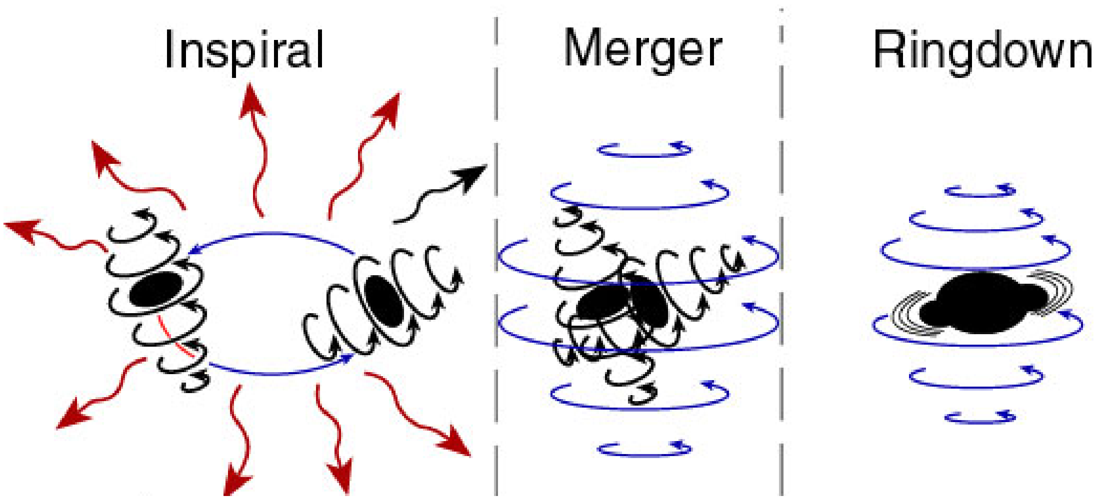


Photo from http://lisa.jpl.nasa.gov

Figure 5: The collision of two black holes.



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Detection and analysis of gravitational waves will provide information about strong-gravity regions of space like supernovae and quasars. As gravitational waves are measured over time, differences in their amplitude and frequency will grant insight into the mass, motion, and direction of the events which cause them.

The detection of gravitational waves at a range of frequencies would help provide insight into the very early universe. The Stochastic Background, which is gravitational radiation from before a trillionth of a second after the Big Bang, may be detectable as the waves finally reach the earth. In comparison, the Cosmic Microwave Background is radiation generated about 380,000 years after the Big Bang. Gravitational waves are largely unaffected as they pass by matter like planets, stars, gasses, and dust, so detection of early waves would help probe much further back into the history of the universe.

2.1 LISA Gravitational Wave Detection

Gravitational waves should be directly detectable from the way they affect the bodies they encounter. If a distortion in space-time passes by an object, it should vibrate. If the distortion hits two separate bodies, they should move with respect to each other. Laser interferometry is a technique which would be able to measure these small changes in the distance between two bodies. The Laser Interferometer Space Antenna (LISA) funded by NASA and ESA is designed to detect gravitational waves from the relative movement of three test masses.

LISA consists of three identical spacecraft which will fly 5 Mkm apart in an equilateral triangle (Figure 6). It will fly 50 million kilometers away from the earth, the center of its equilateral triangle flying in orbit 20 degrees behind the earth (Figure 7). Each spacecraft will contain a sensor with two test masses which float freely (Figure 8). The test masses are highly polished cubicles, reflecting laser light (Figure 9). This allows extremely precise measurements of small movements of the test masses with laser interferometry. The relative motion of the test masses on different spacecraft signals the passing of a gravity wave. LISA should be able to measure movements as small as 20 picometers.

Figure 6: LISA spacecraft orientation.

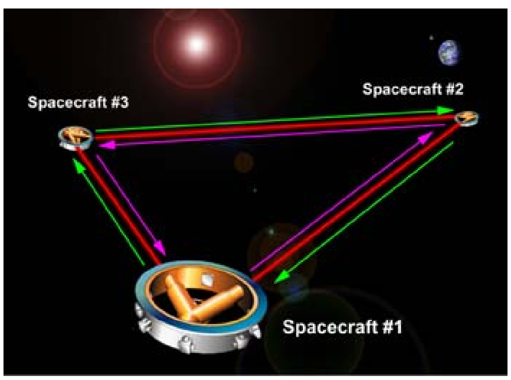


Photo from http://lisa.jpl.nasa.gov

Figure 7: LISA's orbit.

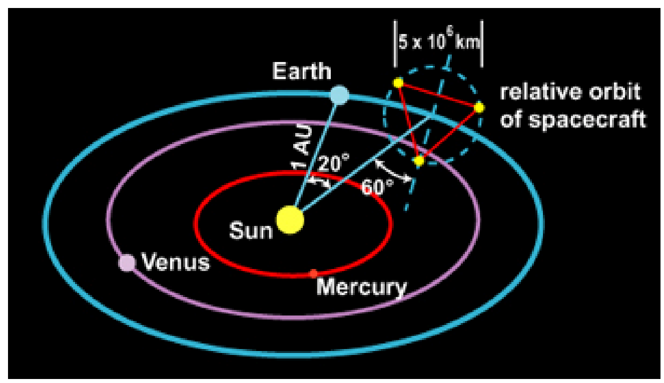


Photo from http://lisa.jpl.nasa.gov

Figure 8: Cross-section of spacecraft, showing two test masses inside.

Photo from http://lisa.jpl.nasa.gov

Figure 9: Highly polished test mass.

Photo from http://lisa.jpl.nasa.gov

In order for the test masses to float freely, they must be shielded so that only gravity affects them. All other forces which could cause the test mass to move must be minimized. LISA's greatest challenge is to eliminate movement of the test masses due to forces other than gravity. Even small movements will causes noise and may mask the signal. The test masses are enclosed in a housing which is 2-4 mm from each surface. Careful analysis of small forces between the test masses and their housing is necessary.

2.2 Small Forces Between Two Surfaces

The LISA test masses and their housing are separated by only 2-4 mm. There are a number of small forces between these two closely spaced surfaces which must be understood. The patch effect is an example. Joining two different metals, or even two different pieces of the same metal, cause electrostatic effects which are much stronger than gravity. Different metals, and different crystal orientations of the same metal, have different work functions. That is, it is preferable for electrons to be in one metal than in another. When the two metals are joined, electrons from the metal with lower work function move to the metal with a higher work function. This electron flow occurs until the two potentials are equal. The movement creates a difference of charge, which results in an electric field over the metal piece (Figure 10). Patches of charged areas on the two surfaces cause electrostatic effects between the test mass and its housing (Figure 11).

Outgassing is a thermal effect which causes small movements of the test masses. Temperature fluctuations assist the escape of gas molecules trapped either inside the metal or on one of its surfaces. As the molecules escape from one surface of the test mass, conservation of momentum requires that the entire test mass move in the opposite direction (Figure 13).

Another thermal effect of concern is the radiometer effect. If one side of the housing is warmer than the other side, the gas molecules between the housing and the test mass will collide with greater frequency and higher energy than the gas molecules on the cooler side. This will cause the test mass to move away from the warmer side of the housing (Figure 14). Self-gravity is also an issue. The mass of the spacecraft can couple to the mass of the test bodies, producing a gravitation force within the apparatus. There could also be a multiple other forces between the two surfaces which have not yet been considered.

Figure 10: Patch effect.

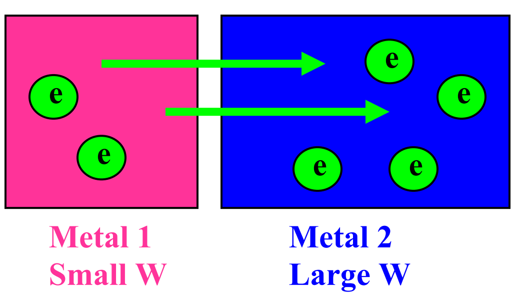


Figure 11: Electrostatic effects.

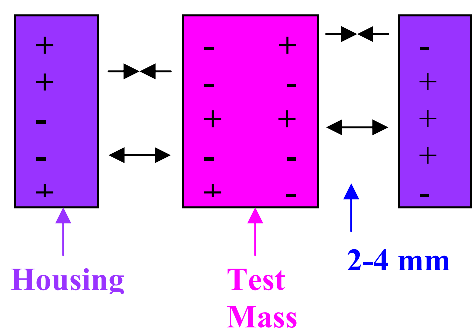


Figure 12: Outgassing.

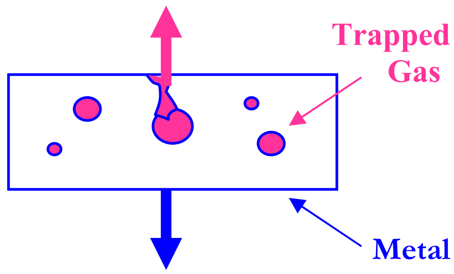
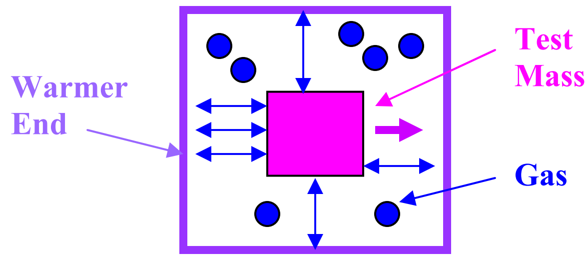


Figure 13: Radiometer effect.



In addition to being understood, these forces must be minimized so they will not interfere with gravitational wave detection.

2.3 Eöt-Wash LISA Torsion Pendulum

The Eöt-Wash LISA torsion pendulum is an instrument designed to understand and minimize the small forces between two closely-spaced surfaces. The pendulum is a gold-coated quartz plate which hangs on a thin tungsten fiber (Figure 14). As small forces displace the pendulum plate, the fiber twists. A measurement of the magnitude of the twist indicates noise from small forces on the pendulum. Lower noise signifies greater sensitivity of the pendulum (Figure 15).

A quartz gold-coated test plate can be moved close to the pendulum plate (Figure 14). As the separation between the two plates decreases, the twist of the tungsten fiber increases. This rise in the noise indicates that the pendulum plate can "feel" the presence of the test plate due to small forces between the plates. Forces due to outgassing and patch effects are major concerns. Analyzing and eliminating these small separation-dependent forces decreases noise.

Figure 14: LISA torsion pendulum.

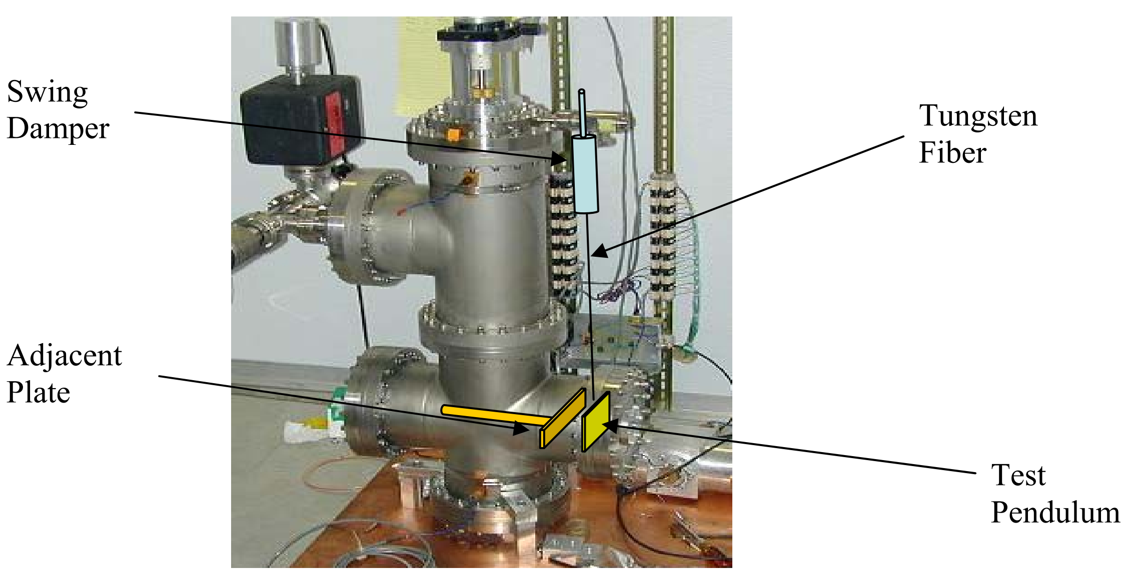


Photo from Jens Gundlach

Minimizing low-frequency noise is particularly important because LISA is sensitive to signals from binary systems at low frequencies (0.0001 Hz to 0.1 Hz). At first, binary systems orbit each other slowly. As they spiral into each other, they begin to orbit faster and faster, until they finally collide. Because binary systems spend significantly more time in slow orbit, there is likely to be many more of them in slow orbit than fast orbit present in the universe at any given time. A slow orbit results in a gravitational wave with a low frequency. LISA is designed to be sensitive to these low frequency waves because there are so many more of them to detect. Low-frequency noise would interfere with the measurement of these low-frequency signals. Therefore, the LISA torsion pendulum experiment is concerned with minimizing noise at low frequencies.

At the lower frequencies in the LISA range (0.0001 Hz to 0.01 Hz), the torsion pendulum has an intrinsic thermal noise. Noise from small forces cannot be reduced below this level (Figure 15). In order to measure this noise at such low frequencies, the separation between the plates is reduced to much smaller distances than the separation between the test mass and its housing in LISA. Separations as small as 25 μm will exaggerate the effects of the small forces present, and the data can be extrapolated back to larger separations like the 2-4 mm in LISA. The noise data indicates that the noise increases at smaller separations (Figure 16).

Figure 15: Pendulum sensitivity (noise with no adjacent plate present).

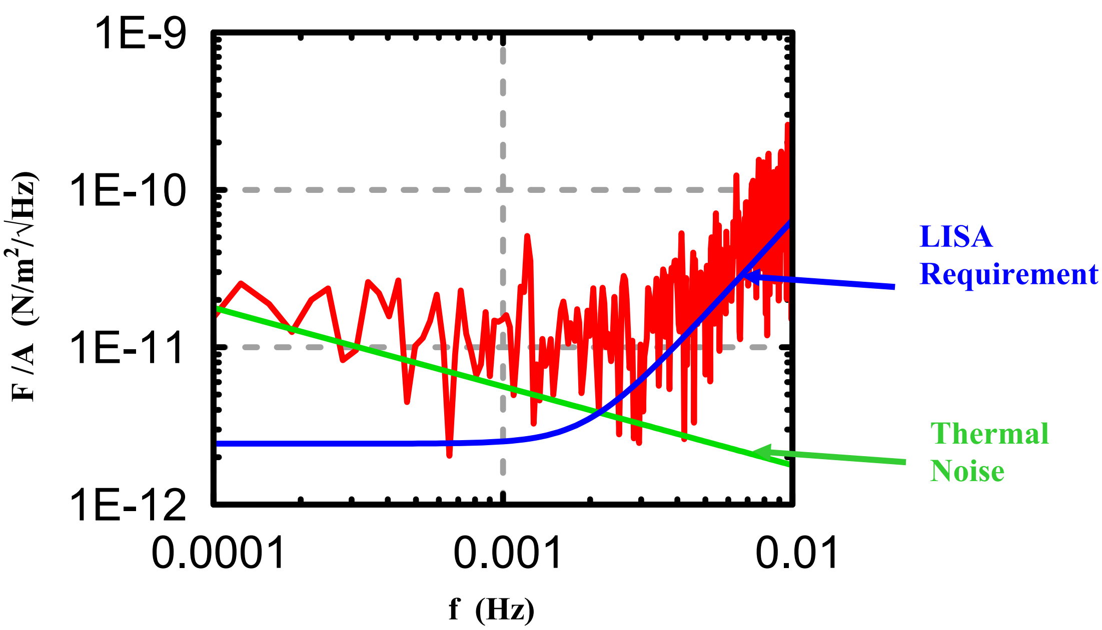


Figure from Jens Gundlach

Figure 16: Noise at closer plate separations.

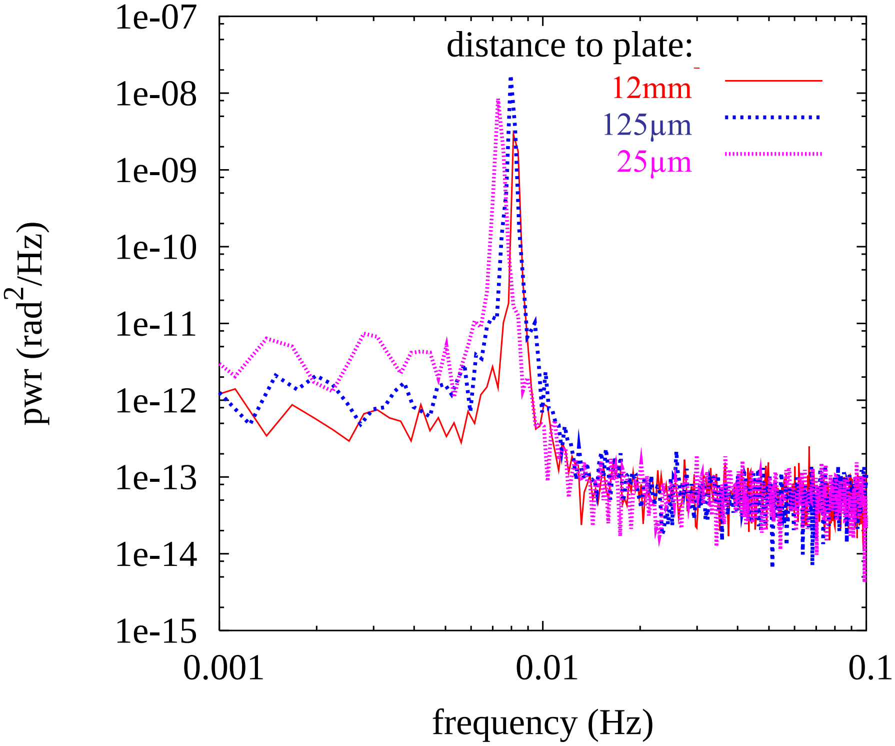


Figure from Jens Gundlach

Separation-dependent forces like outgassing and thermal effects contribute to noise at closer separations. Minimizing these small forces can help decrease noise.

Noise that is not due to the small forces under investigation can come from a tilt of the torsion pendulum apparatus. This noise is not a concern in the LISA project because it arises from the torsion pendulum itself. However, it appears in the signal, which increases the noise measured at low frequencies. If the effects of tilt are well-understood, they can be subtracted from the signal. Ideally, tilt should be entirely eliminated.

2.4 Torsion Pendulum Tilt

The LISA torsion pendulum is particularly sensitive to tilt. When the baseplate of the pendulum tilts, the entire apparatus tilts with it. The tungsten fiber from which the pendulum hangs is attached to the top of the apparatus. Ideally, the fiber would be perfectly cylindrical. In reality, the fiber has some irregularity in its shape, so it is somewhat similar to a flat ribbon. If the tilt is along the wide axis of the ribbon shape, the fiber will twist. This torque contributes to noise.

In addition, a tilt of the apparatus causes also causes a mechanical swing of the pendulum plate either towards or away from the adjacent plate. As the separation distance changes, the small forces between the two plates cause the pendulum to twist. For example, charge distribution over the plates is not perfectly uniform. As the pendulum swings toward the test plate, two like charges may be brought closer together. When they repel, the pendulum twists. Other electrostatic forces, thermal effects, and outgassing are more examples of forces which cause twist as separation distance changes. This twist contributes to noise.

Tilt contributes significantly to noise in the LISA torsion pendulum, and it must be monitored and minimized. The baseplate of pendulum stands on four vibrational isolation legs which compensate for the thermal fluctuations of the concrete floor. These legs contain elastomer parts which worsen the tilt problem. An effort to correct tilt of the baseplate motivates the design and construction of a rotating tilt sensor.

3 Rotating Tilt Sensor

The rotating tilt sensor is mostly aluminum. The sensor unit is mounted on a leveling platform inside a round box, and its electronics are mounted on the lid. The box is mounted in the upper shaft, which is fitted into the bracket. There are ball bearings between the inner edge of the bracket and the outer edge of the lower shaft. The bracket sits on the baseplate, which can be adjusted with two screws in order to fine-tune the axis of rotation.

Figure 17: Rotating Tilt Sensor

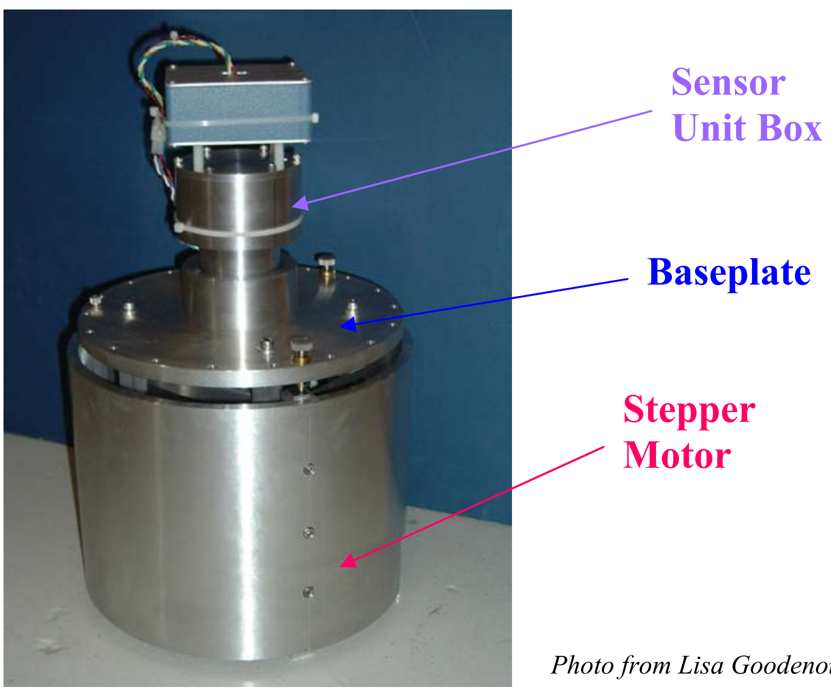


Photo from Lisa Goodenough

The LISA torsion pendulum experiment is particularly concerned with low frequency measurements (0.0001 Hz to 0.1 Hz). At these low frequencies, tilt sensors drift with time, which makes it difficult to measure absolute tilt. The rotating tilt sensor eliminates the effect of this drift, ensuring an accurate absolute tilt measurement.

3.1 Tilt Sensor Signal

The tilt sensor used in the apparatus is the 755-1172 model from Applied Geomechanics Incorporated. The sensor consists of a glass tube filled with a conductive fluid and a gas bubble (Figure 17). As the sensor tilts, the bubble moves within the fluid until it is perpendicular to the vertical line. As the bubble moves, the resistance between the two excitation electrodes and the pick up electrode changes linearly. The electronics of the tilt sensor output this change in resistance as a voltage. The voltage is multiplied by the calibration constant to give the degree of tilt.

Figure 18: Internal diagram of AGI tilt sensor.

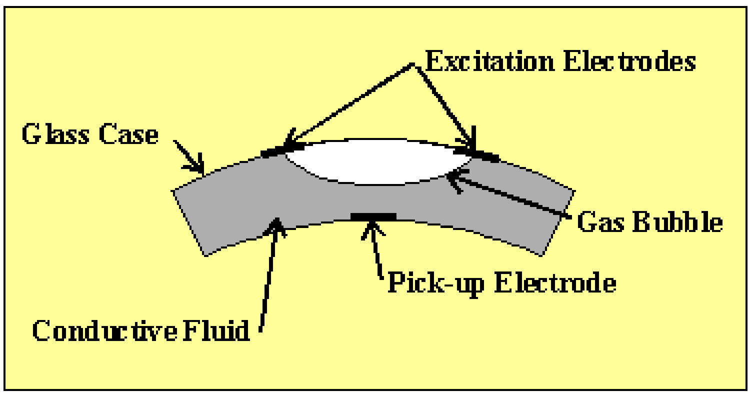


Figure from http://www.geomechanics.com/dspapp.cfm?appid=71.

As the apparatus rotates, the tilt sensor inside the box measures the magnitude of the tilt in each direction. If the plane has absolutely zero tilt, the sensor outputs a constant signal of zero volts as the apparatus rotates through one complete cycle. If the plane is tilted up, the sensor outputs a positive voltage at the maximum tilt. As the apparatus rotates, the tilt measured along the next axis is smaller, so the sensor outputs a smaller positive voltage. When the apparatus reaches the axis which is exactly perpendicular to the axis of maximum tilt, the tilt measured is zero, and the sensor outputs a signal of zero volts. As the apparatus continues to rotate, the tilt measured along the next axis is in the opposite direction, so the sensor outputs a negative voltage. When the apparatus reaches the axis of maximum tilt again, it has rotated 180°, and the sensor outputs the maximum negative tilt value. As the apparatus continues to rotate, the sensor outputs smaller and smaller negative tilt values until the apparatus once again reaches the axis perpendicular to the axis of maximum tilt. The apparatus has rotated 270°, and the sensor measures zero tilt. As the apparatus continues to rotate, the sensor outputs increasing positive voltage until the apparatus reaches the axis of maximum tilt where it started.

A plot of voltage versus time for one full revolution is a sinusoidal curve. The absolute tilt is given by the amplitude of the curve. A constant absolute tilt results in a sinusoidal curve with a constant amplitude. Because the magnitude of the tilt is extracted from the curve, the zero-point drift of the sensor itself does not mask the tilt. By rotating the tilt sensor unit, the effects of zero-point drift can be eliminated.

3.2 Instrument Calibration

The output signal of the tilt sensor is in voltage. This voltage must be multiplied by some calibration constant α in order to obtain the tilt in radians. The calibration constant was determined by using the leveling screws to tilt the baseplate of the apparatus by a known angle and recording the corresponding change in voltage. As the axis of rotation was deliberately moved further away from parallel with the vertical gravity vector, the sensor unit measured this known tilt and output a voltage. The calibration constant was extracted from this data using $\alpha = \Delta\theta/\Delta V$. Final calibration of the instrument under optimal conditions yielded $\alpha = 0.000998$ rad/V. AGI reported the tilt sensor's calibration constant as $\alpha = 0.0010028$ rad/V, which agrees with the experimentally determined number.

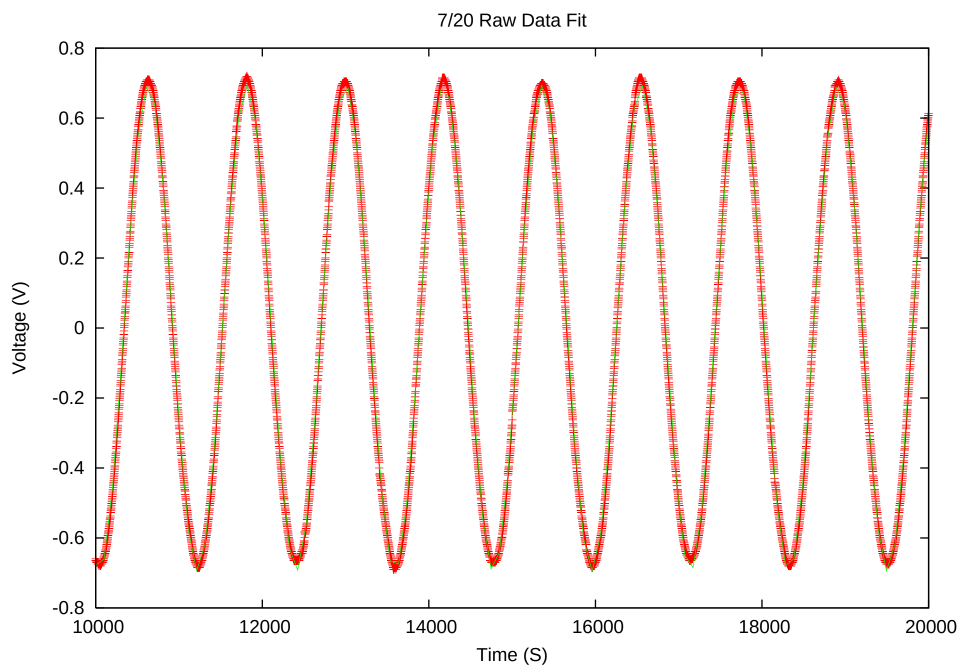
4 Results

The sensor unit inside the box was adjusted so that it was exactly perpendicular to the axis of rotation. This minimized offset in the data.

4.1 Raw Data

The baseplate of the apparatus was adjusted so the axis of rotation was not parallel to the vertical gravity vector. This deliberate tilt should result in a sinusoidal curve. Data was collected overnight, and is reported below (Figure 18).

Figure 18: Raw data.



This preliminary data was collected in a warm room on second floor which had foot traffic. Under these conditions, the noise level was quite high. After analysis of the preliminary data, the rotating tilt sensor apparatus was modified to eliminate slip of the ball bearings. Additionally, an optical interrupter switch was added to signal the beginning of a new revolution. The tilt sensor was moved into the laboratory on the first floor to a space with minimal traffic. The data collected under these optimal conditions is analyzed below.

4.2 Data Analysis

The baseplate of the rotating tilt sensor was adjusted so that the axis of rotation was parallel to the vertical gravity vector. Data was collected overnight, and the measured tilt of the floor was resolved into its x and y components using a sine and cosine curve fit. The calibrated fast Fourier transform (FFT) power spectrum for each component reveals the tilt along each axis. Data was simultaneously collected with a stationary tilt sensor in order to provide a comparison. The calibrated FFT power spectrum from the stationary sensor is also plotted on each figure.

Figure 19: Tilt Measured Along X Axis

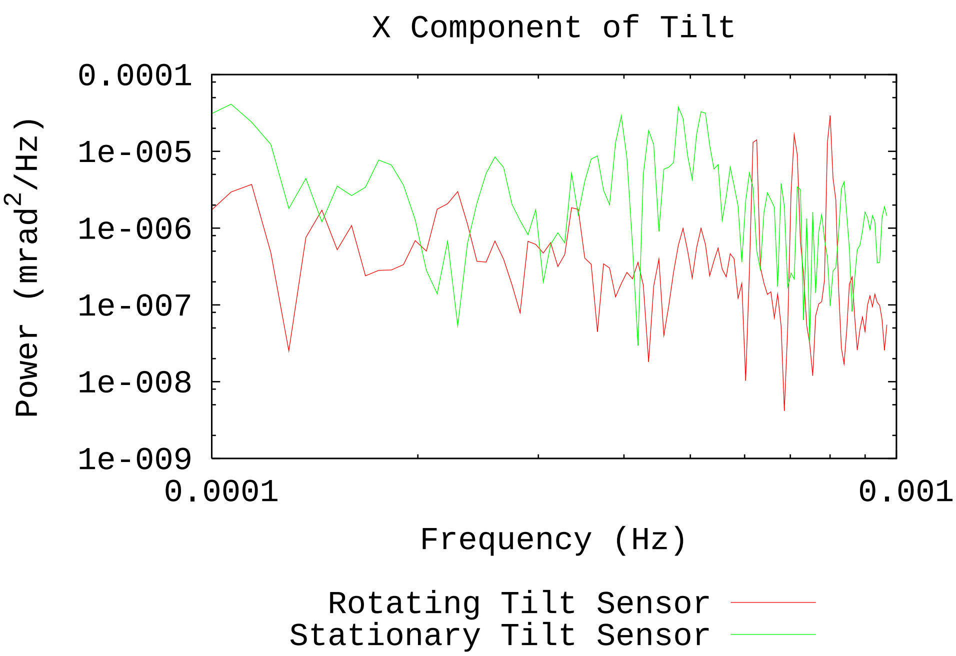
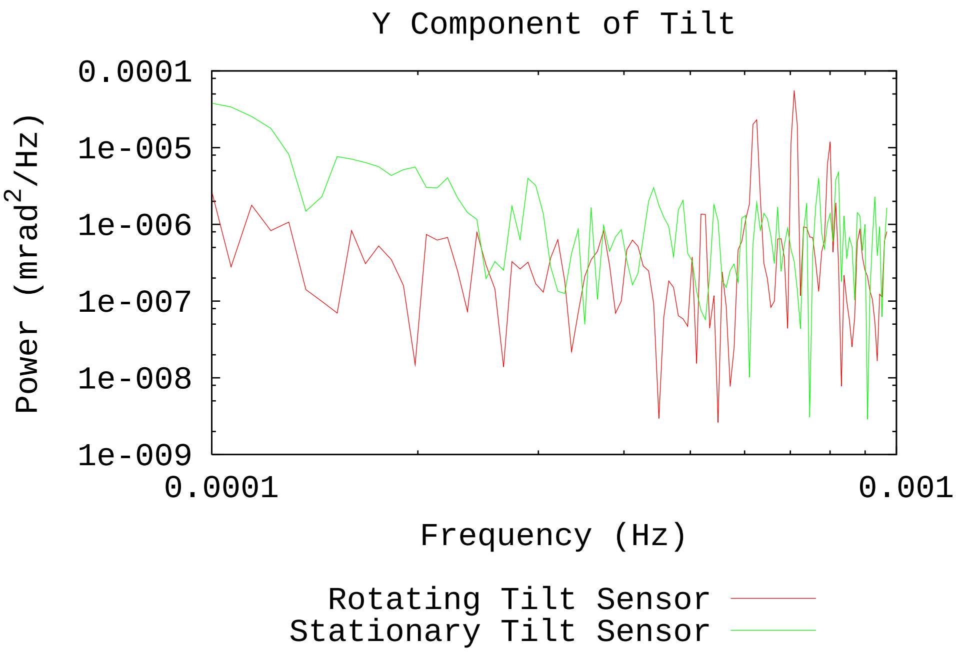


Figure 20: Tilt Measured Along Y Axis



Along the x axis, both sensors report approximately the same low-frequency tilt. Along the y axis, the rotating tilt sensor data is nearly a factor of ten below data from the stationary tilt sensor. It is probable that the floor tilts significantly more along the x direction than it does along the y direction. Zero-point drift of the stationary tilt sensor is masked in the x axis data by the much higher magnitude of absolute tilt along that axis. The absolute tilt is significantly smaller along the y axis, so the zero-point drift of the stationary tilt sensor overpowers it in the data.

The figures indicate that the rotating tilt sensor has a significantly lower noise level at low frequencies than the stationary tilt sensor. At a frequency as low as 0.1 mHz, the rotating sensor can measure tilt accurately within nanoradians.

5 Conclusion

The rotating tilt sensor successfully reduces zero-point drift, which enables a more accurate tilt measurement than a stationary tilt sensor. At 0.1 mHz, the rotating tilt sensor resolves tilt on the nanoradian level. This noise level is roughly four times lower than that of the stationary tilt sensor.

The rotating tilt sensor will be mounted on the LISA torsion pendulum with a feedback control system which will adjust the position of the baseplate based on tilt information from the sensor. This process will continually minimize tilt, which will significantly reduce noise from tilt effects on the torsion pendulum.

In addition to the LISA noise measurement torsion pendulum, the Eöt-Wash Group has three other torsion pendulum experiments which could use the rotating tilt sensor to continually minimize tilt. Because the rotating tilt sensor measures absolute tilt of the floor over time within nanoradians, it may have practical applications for geophysics.

6 References

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