New experimental technique for short-range gravity measurement

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Abstract. A new experimental technique for short range gravity measurements using picoprecision displacement sensor using digital image analysis is presented. We have developed a new experimental setup using torsion balance pendulum, aiming to test the Newton’s inverse square law at below millimeter scale. Weak equivalence principle can also be tested using the same experimental setup. Detector techniques and the detail of the experimental setup are described.

1. Digital Image Analysis System

Present experimental techniques are originally developed for a high energy collider experiment, as a geometrical detector position monitoring system [1]. For PHENIX experiment at RHIC (Relativistic Heavy Ion Collider) accelerator at Brookhaven National Laboratory, position monitoring resolution of 25microns is required for muon tracking chambers. To satisfy the requirement, a micron precision optical alignment system (OASys), which comprised of fiber optic light source, convex lens and CCD camera, is developed. Position determination resolution of 10nanometers is achieved, which is significantly better than the required resolution of 25 microns.

Triggered by the significant achievement at PHENIX, the authors developed a dedicated position monitoring system using digital video cameras, aiming to obtain better precision than at PHENIX [2]. Schematic diagram of the digital video system is shown in Figure 1.1. A position data is obtained as a video image, captured by the digital video camera. The video data are sent to PC via IEEE1394, then captured and recorded as a movie file in avi file format.
In order to extract the position data from the movie files, the avi movie files are converted into sequential static image files in bmp format. The intensity profiles are statistically analyzed in an offline analysis tool developed for this purpose, yielding position information. By using a video lens, position determination resolution of 100 pico-meters is achieved.

In Figure 1.2, data analysis chain is illustrated. At first, intensity histograms are obtained as sliced figures from the bmp static files which are generated by Adobe Premiere software. The object positions are determined as center of gravity positions. If we are interested in positions and angles of line-shaped objects, linear line fitting is applied for the sequence of the center of gravity points, as shown in Figure 1.3. Typical angular resolution of about $1.2 \times 10^{-6}$ degrees are achieved.
2. Principle of Short Range Gravity Experiment

Utilizing the surprisingly precise profile of the video position monitoring system, we have started to perform a series of gravity experiment at short range scale, where precision displacement measurement is required in order to extract the expected tiny gravity signals. To achieve the measurement, we employ a torsion balance pendulum, which is shown in Figure 2.1.

Figure 2.1: Principle of the gravity experiment using torsion balance pendulum.

Principle of the measurement is shown in Figure 2.1. Angular displacements between before and after moving the attractor mass positions are going to be measured as the gravity signal. It is because the balanced position of the torsion balance bar is expected at a position where spring force of the twisting wire and the gravitational force dragged by the attractor mass are getting equals. Therefore,
Gravitational force can be determined by measuring the displacement of the balanced positions. As a first order approximation, Hooke’s law can be assumed;

\[ N = \kappa \cdot \Delta \theta \]  

(2.1)

Here, \( N \) is the torque, \( \kappa \) is the spring constant and \( \Delta \theta \) is the angular displacement. Considering that the source of the torque is gravitational force \( F \), (2.1) can be expressed as followings using arm length of the torsion balance bar \( L \) and target-attractor distance \( r \) as;

\[ \kappa \cdot \Delta \theta = 2 \times G \frac{m_{\text{target}} m_{\text{attractor}}}{r^2} \times L \]  

(2.2)

, if we simplify the objects as point mass. From (2.2), we can determine the gravitational force by measuring the angular displacement \( \Delta \theta \). In order to extract the gravitational force, spring constant \( \kappa \) needs to be determined. We can experimentally determine the spring constant \( \kappa \) by measuring a periodic oscillation of the torsion balance bar. As shown in Figure 2.2, if we measured the oscillation period \( T \), \( \kappa \) can be determined as \( \kappa = 4\pi \frac{I}{T^2} \) using inertia moment \( I \) of the torsion balance bar.

![Figure 2.2: Periodic oscillation of the torsion balance bar. The spring constant \( \kappa \) can be determined from the oscillation period \( T \)](image)

If we use Tungsten 30microns wire with 80cm length, typical value of the obtained spring constant is \( \kappa = 60nNm \).  

(2.3)

Typical size of the gravitational force in the first generation setup, Newton-I, is about \( F = 1nN \), therefore, angular displacement is about \( \Delta \theta = 2 \times 1nN \times 5cm / 60nNm \sim 0.1\text{deg} \).

3. Newton-I Experiment

To perform the measurement, we have built the Newton-I experimental setup. Detailed structure of the Newton-I is illustrated in Figure 3.2. All the components are electrically connected, and made of non-magnetic metals (brass, aluminum, copper and lead). In order to shield a Coulomb force, metal electric shield is set covering the attractors. Position dependence can be examined by rotating the attractor table around the center for the test of inverse square law measurement. Composition dependence of gravitational constant can be measured by replacing the attractor material for the test of weak equivalence principle.
4. New Device: Newton-II

As described in the separate contribution [3], Newton-I experiment succeeded to confirm Newton’s law at centimeter scale. Especially, we succeeded to set most precise limit on the baryon number coupling force at shortest range scale, which is obtained from measurement of the composition dependence of gravitational constant. In Newton-I, largest error source comes from attractor replacement. In order to suppress the systematic error caused by attractor exchanging, next generation device, Newton-II, is developed. Newton-II is designed to be able to move the attractors rotating outside the torsion balance bar position, without changing the attractor materials by opening the vacuum chamber. As shown in Figure 4.1, we can measure gravity between different materials just by rotating the attractor turning table, without changing the setup.
Figure 4.1: Structure of Newton-II. Electric shield set covering the attractors are not drawn.

Figure 4.2: Expected signal from Newton-II.

Signal estimation using numerical calculation is performed, as shown in Figure 4.2. Position dependence and the material dependence can be measured at the same time without suffering from the systematic effects. Relative strength between different attractor materials provides precision information about the composition dependence of the gravitational constant. At the same time, curvature around the peak gives us the position dependence. In Newton-II, we will be able to test the weak equivalence principle in the shortest range, and the inverse square law in shorter range than Newton-I experiment.

5. Summary
A new experimental device Newton-I, is developed using digital video displacement sensing techniques with torsion balance pendulum. In order to suppress the systematic error, next generation device Newton-II is also developed, which aims to provide most precise test of weak equivalence
principle at shortest range scale. In addition, third generation device, Newton-III is being developed using completely different measuring principle. Data from Newton-II and Newton-III will be available soon.

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