Gravitation experiments during the total solar eclipse

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The variations of the apparent vertical direction of the gravity field were measured with horizontal gravimeters acting as tilt meters during the total solar eclipse in Turkey in March 29, 2006. Three separated locations within the path of totality were chosen for observations, two spaced apart along the center line, and one off the center line. No anomaly was observed at the furthest location from the center line. Aperiodic oscillations in tilt were recorded at the two locations on the center line. These may be related to the eclipse phenomenon. The average tilt amplitude deviation during the eclipse over all locations and in all directions was 150 nrad, which can be regarded as a mean upper limit for the eclipse related changes in the tilt.

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I. INTRODUCTION

The weakness of the gravitational force makes exploring its properties a challenging task. Even though the gravitational interaction has been studied for centuries, significant uncertainty is still present at extremely short or large scales. At the short end, uncharted territory begins at distances shorter than 0.1–0.01 mm, while the other end is marked by cosmic distances. Modern day cosmological observations rely heavily on the applicability of general relativity on cosmic scales and vice versa, large scale observations can be used to study gravity at large distances. On the theoretical side, many frameworks, e.g. string theories, lead naturally to gravitational interaction different from that of general relativity. For example, so-called extra dimensional theories typically modify gravity at very short distances.

In this light, it is interesting and natural to study the possibility that new gravitational effects can be discovered. Since the theoretical nature of possible new effects is unknown, modified gravitational theories may even give rise to effects not only on very short or cosmological scales, but also in between these extremes. The last few decades have indeed seen a variety of claims about possible anomalous behavior of gravity at intermediates ranges, observed during the course of a number of different types of laboratory investigations [1].

Since the 1950's there have been several reports on gravitational anomalies during solar eclipses. In the seminal work by Allais in 1954 [2,3], it was found that the oscillation plane of a paraconical pendulum was turned about 10 degrees during the eclipse. The turning of the oscillation plane was reported to approximately coincide with the beginning of the eclipse (the first contact of the moon), and at the end of the eclipse (the last contact of the moon) so that after the eclipse the oscillation plane returned to that before the eclipse. Similar types of anomalies were also reported by Savrov in eclipses in Mexico City in 1991 [4] and in Brazil in 1994 [4], although reported effects were close or even below the limit of the instrument resolution.

Saxl and Allen [5] observed significant changes in the oscillation period of their torsion pendulum during the total solar eclipse of 1970. The oscillation period suddenly increased at the onset of the eclipse, but curiously it remained unchanged after the eclipse. Experiments with a torsion pendulum during the eclipse in Finland in 1990 made by Kuusela [6], failed to show any significant modulation on the period related to the temporal phase of the eclipse. The same eclipse was also observed in Bielemorks with a torsion pendulum [7], and in Finland with an absolute gravimeter [8] and water tube clinometers [9] but all of the results were negative. New measurements with an improved torsion pendulum by Kuusela [10] in Mexico City in 1991 again gave negative results concerning the oscillation period. Interestingly, however, the position of the pendulum wire in the horizontal plane encountered shifts, seemingly related to the onset and end of the eclipse.

The latest positive results on gravity anomalies during the total solar eclipse have been observed with zero-length spring gravimeters, which directly measure the vertical component of the gravitational field. An experiment conducted in India in 1995 show a clear decrease of 10–12 μgal (1 $\mu\text{gal} = 10^{-8}\ \text{m/s}^2$) in the vertical component of the gravitational field at the onset of the solar eclipse [11]. The most striking gravimeter recording so far was made in Moho, China during the solar eclipse of 1997 [12,13]. In this study, a significant decrease in the strength of gravity was during two time periods: within 30 minutes before the first contact and 30 minutes after the last contact. The decrease in the gravitational field was about 7 μgal, 2 or 3 times the noise amplitude.

All of the gravitational anomalies observed during solar eclipses can be explained by the tilt of the apparent vertical direction, either because of the tilt of the instrument (or the base under the instrument) itself, the rotation of the gravity vector, or the generation of an additional horizontal component on the gravitational field. Unfortunately the vertical direction has not been measured during eclipse experiments with pendulums except in the experiment in 1991 by Kuusela [11], where the shifts in the position of the pendulum wire were direct indications of change in the vertical direction. Especially paraconical pendulums are very prone to any tilt if the azimuth of the oscillation plane is only measured from one side with respect to the usual pendulum rest position. In torsion pendulums, the tilt produces significant effects on the oscillation period if the period of the half cycle is measured as it was done in the experiments of Sax and Allen [6]. When the total cycle is measured, the effect of the tilt is much smaller, and typically no change in the period can be observed even if there are small but evident changes in the apparent vertical direction [11]. Since normal gravimeters measure the vertical component of the gravity field, the tilt of the field or the device also produces a drop in the apparent value of the gravity although gravimeters cannot directly detect the horizontal component. It also needs to be mentioned that very large effects, such as reported by Allais or Saxl and Allen, have never been experimentally repeated. Hence, we are led to believe that some uncontrolled factors have probably influenced their observations.

We designed an expedition to observe the total solar eclipse in Turkey on March 29, 2006 using a new approach. Our approach had two novel aspects that have not been utilized in previous experiments: the apparent vertical direction was directly measured and observations were made simultaneously in distant locations within the totality path. These new ingredients allow us to significantly improve the experimental procedure. Single positive results reported in past years have an evident weakness: the validity of the observation is not possible to estimate in lack of any comparative data. The use of equal instrumentation in several places is also essential since then we can truly explore temporal and spatial correlations of a possible gravity anomaly.

II. EXPERIMENTAL PROCEDURES

A. Construction of gravimeters

The construction of the magnetically coupled double pendulum gravimeter measuring the horizontal component of the gravitation field is shown in Fig. 1. It has two identical vertical bars, one supported from the top and the other from the bottom of the instrument frame. The bars can swing freely only in the vertical plane. On the end of the bars there are permanent magnets oriented in such a manner that they attract each other. In equilibrium position both bars are aligned vertically with the local vertical gravity $\boldsymbol{g}$. The pendulums oscillate around the stable equilibrium under small perturbations. If we assume that the potential energy of the magnetic interaction is $-k/r$ (assuming the interaction of monopoles), we get the period T of the oscillations

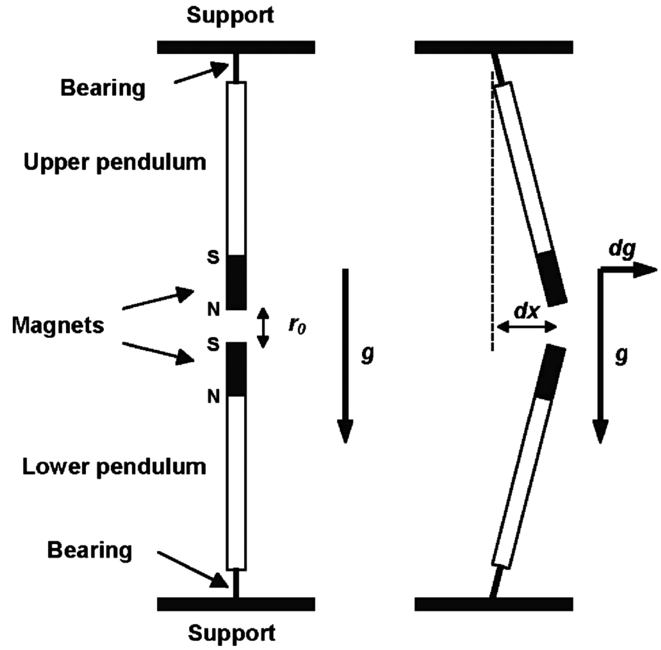

FIG. 1. The structure of the magnetically coupled double pendulum. If there is no horizontal gravitation component, the pendulums are in a vertical position (left figure). A small horizontal gravitation component produces large deflection (right figure).

$$T = 2\pi r_0\sqrt{hm/k}, \quad (1)$$

where r_0 is the distance between the magnets, h is the length of the bars, m is the mass of the magnet and the bar, and k is the magnetic coupling strength. If a constant horizontal force $\boldsymbol{dg}$ is applied, the restoring force from the top pendulum is cancelled by the destabilizing force of the bottom pendulum, and a corresponding horizontal shift will develop. The displacement dx of the pendulums is

$$dx = \frac{T}{2\pi}\sqrt{hdg}. \quad (2)$$

The displacement dx is proportional to the *square root* of the horizontal force $\boldsymbol{dg}$, which increases greatly the sensitivity. This was the key factor when choosing the type of instrument. If the displacement of the pendulums is measured in the horizontal plane, the strength of the horizontal force $\boldsymbol{dg}$ (or tilt of the device) can be determined. Equations (1) and (2) are valid only if the magnetic interaction is described as an interaction of monopoles. In practice the interaction of the real magnets, which have finite dimensions, is much more complex and the relation (2) cannot be realized, especially at very small tilt angles. However, we did not try to find a realistic model of the system since the period of the oscillations and the sensitivity to the horizontal force or tilt were determined experimentally.

The length of both pendulums was 100 mm, the masses were 12.99 g (the upper pendulum) and 11.36 g (the lower pendulum), and the distance of the magnets was 11.5 mm.

The structures of the pendulums were designed to have the equal moment of inertia. The coupling coefficient k was determined experimentally as a function of distance r, and it was 0.55×10^{-6} Nm^2 when $r = 11.5$ mm. With these parameters the period of the pendulums was 2.80 ± 0.10 s. The bearing of the pendulums is critical since the tilt angles are extremely small. Razor plates reclining in a narrow and shallow groove worked properly. We used the same material in the pendulums and their support structures in order to minimize thermal effects. Since the pendulums include magnets they are also sensitive to changes in the external magnetic field. We found that close shielding made of high-permeability materials disturbed the function of the gravimeters because of the induced residual magnetic fields on the shield material. Since the devices were designed to be portable it was not possible to use a large shield structure, and therefore we omitted the magnetic shields but added magnetometers to measure the external field.

The position of the upper pendulum was measured using the position sensitive photodetector. The position resolution of the detectors was 75 nm. The sensitivity of the gravimeters as a tilt device was determined by setting the devices on the adjustable rigid platform supported in three corners by sapphire balls. One of the balls was attached on the top of the piezoelectric actuator, and adjusting the length of the actuator by applied voltage the horizontal angle of the platform and therefore also the tilt of the device could be set. The angular resolution of the gravimeters was 20 nrad based on the peak-to-peak noise level of the detectors and electrical amplifier circuits. This tilt angle resolution corresponds to approximately 20 μgal horizontal gravitation force.

Each measurement system consisted of two double pendulum gravimeters whose planes of oscillation were perpendicular to each other. The system also included the temperature sensor (the resolution was 0.02 °C), the ambient pressure sensor (the resolution 0.2 mbar), and the two-axis horizontal magnetometer (the resolution 0.1 mgauss). The magnetometers were used both as a compass in each measurement location but also to detect any significant changes in the magnetic field which can affect on the gravimeters during normal operation. Gravimeters were tested in a controlled magnetic field, and the sensitivity to field strength was found to be 50 nrad/mgauss when the field was in the plane of the oscillation of the gravimeter pendulums, in the perpendicular plane the sensitivity was <0.1 nrad/mgauss.

The support plate of the device had four adjustable legs and a spirit level for coarse horizontal alignment. Each gravimeter has its own micrometer tilt adjustment (± 2 deg), which was used to adjust the period of the oscillation to be as close to 3.00 seconds as possible. Because of the nonlinear character of the double pendulum the oscillation period and also the corresponding sensitivity depend slightly on the basic tilt angle of the pendulums (i.e. the deviation from the vertical line) mainly because the distance of the magnets is changed. By setting the oscillation period of each device to be equal also the sensitivities could be adjusted to the same value. The oscillations of the pendulums were utilized only for adjusting the sensitivity, and actual recordings were not started until all oscillations had damped. The measuring systems were positioned in South-North direction with the help of the built-in compasses. During the record phase the positions of the pendulums of the gravimeters, temperature, pressure, and two magnetometer readings were recorded every 3.5 seconds by a laptop. The measurement systems were battery operated in order to assure clean and uninterrupted power supply.

B. Recording locations

Three equal measuring systems were located in Antalya (I; 36°54′45″ N, 030°41′23″ E), Manavgat (II;

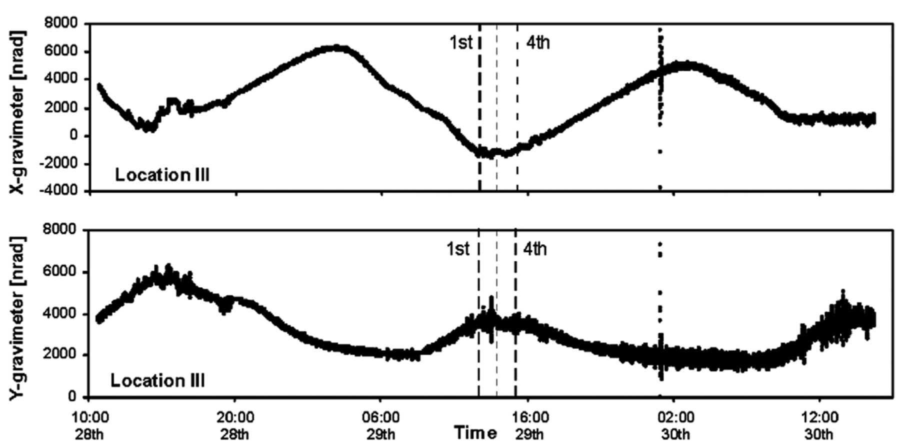

FIG. 2. The tilt angles of x- and y-gravimeters without any trend removing as a function of time at the location III. The first and fourth contacts of the solar eclipse are marked with thick dashed lines and the moment of totality with a thin dashed line. There are short gaps in the data because the data recording was stopped when the batteries were replaced and the devices were started again. The data segments were carefully pieced together and the gaps were linearly interpolated in order to maintain a synchronous time line.

36°47′12″ N, 031°26′35″ E), and Akseki (III; 37°02′55″ N, 031°47′24″ E). All places were within the totality path. The locations II and III were very close the center line but 50 kilometers apart, and the place I 60 kilometers from the center line, thus the locations were approximately in an L-shape configuration. Record sites were in buildings, either in the first or second floor in isolated rooms. Recordings were started on March 27, two days before the eclipse, and finished a day after the eclipse on March 30. Each day the recorded data was collected, the batteries replaced with new ones, and the function of the devices checked. On the eclipse day the first contact was at 09:37:32 (in U.T.; the location I), 09:38:28 (II), and 09:39:26 (III), the maximum eclipse at 10:55:59 (I), 10:56:57 (II), and 10:57:49 (III), and the fourth contact at 12:13:46 (I), 12:13:39 (II), and 12:14:19 (III). The duration of the totality of the solar eclipse was 3 minutes 10 seconds (I) and 3 minutes 45 seconds (II and III). The angular height of the Sun during totality was 55°.

III. RESULTS

As an example the original gravimeter data from the location III has been shown in Fig. 2. There are slow drifts

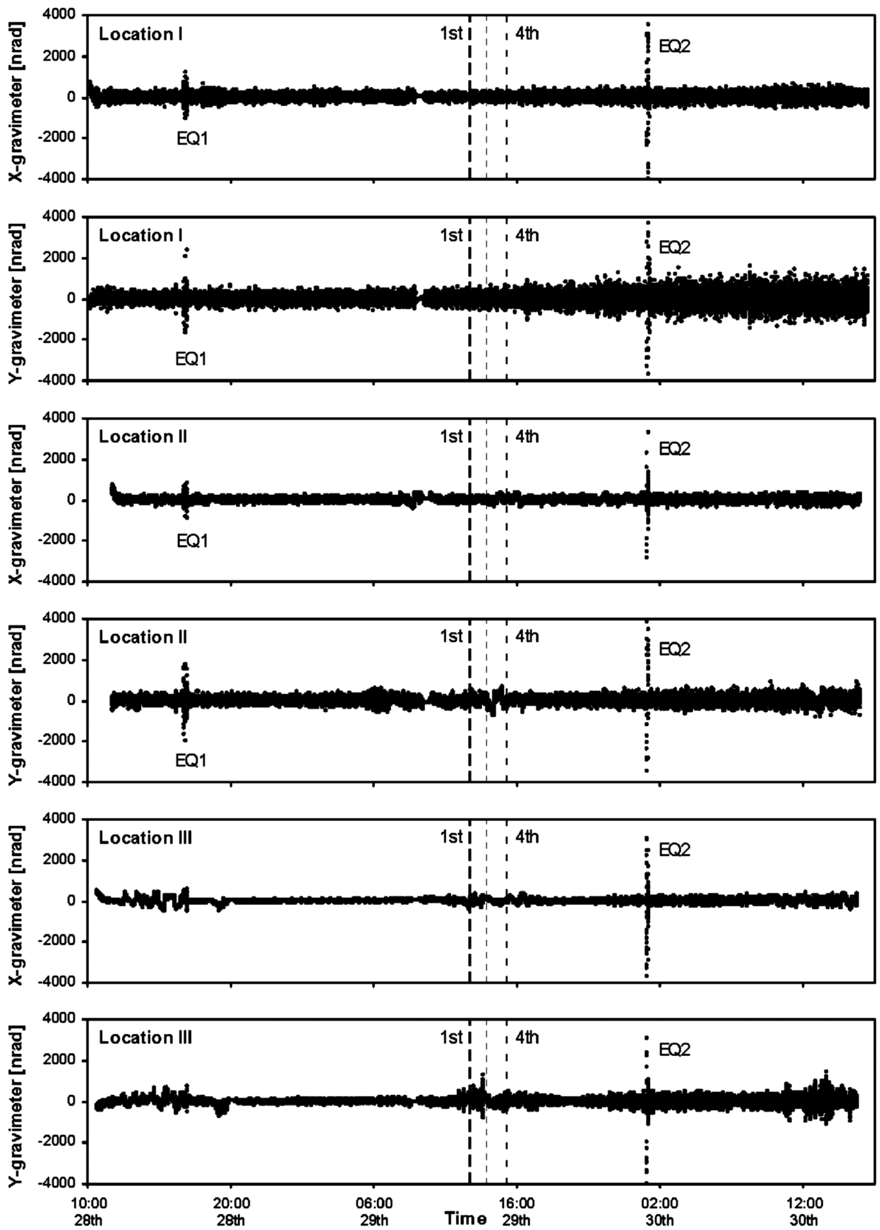

FIG. 3. The tilt angles of x- and y-gravimeters in all three locations as a function of time after removing slow drifts. The first and fourth contacts of the solar eclipse are marked with thick dashed lines and the moment of totality with a thin dashed line. The EQ1 and EQ2 mark two earthquakes.

due to tidal forces and changes in the ambient temperature. These drifts were most prominent in the location III, in all other locations they were significantly smaller. In order to focus on eclipse related changes the slowly wandering background has been removed by subtracting the baseline which was generated from the original signal by calculating the triangularly weighted moving average over 5000 seconds. This averaging window removes slow drifts but does not affect features whose characteristic time scale is shorter than the total temporal length of the eclipse phenomenon. The window width used in data analysis is not critical since results are essentially equal in the range of 2000–15 000 seconds. The gravimeter tilt data from all locations after trend removing are shown in Fig. 3 starting 26 hours before the first contact and ending 26 hours after the fourth contact. There are short gaps in the data because the data recording was stopped when the batteries were replaced and the devices were started again. The data segments were carefully pieced together and the gaps were linearly interpolated in order to maintain a synchronous time line.

In the location I (Antalya, outside the center line) no obvious eclipse related changes can be observed, neither in x- (South-North) nor y- (East-West) direction. The noise

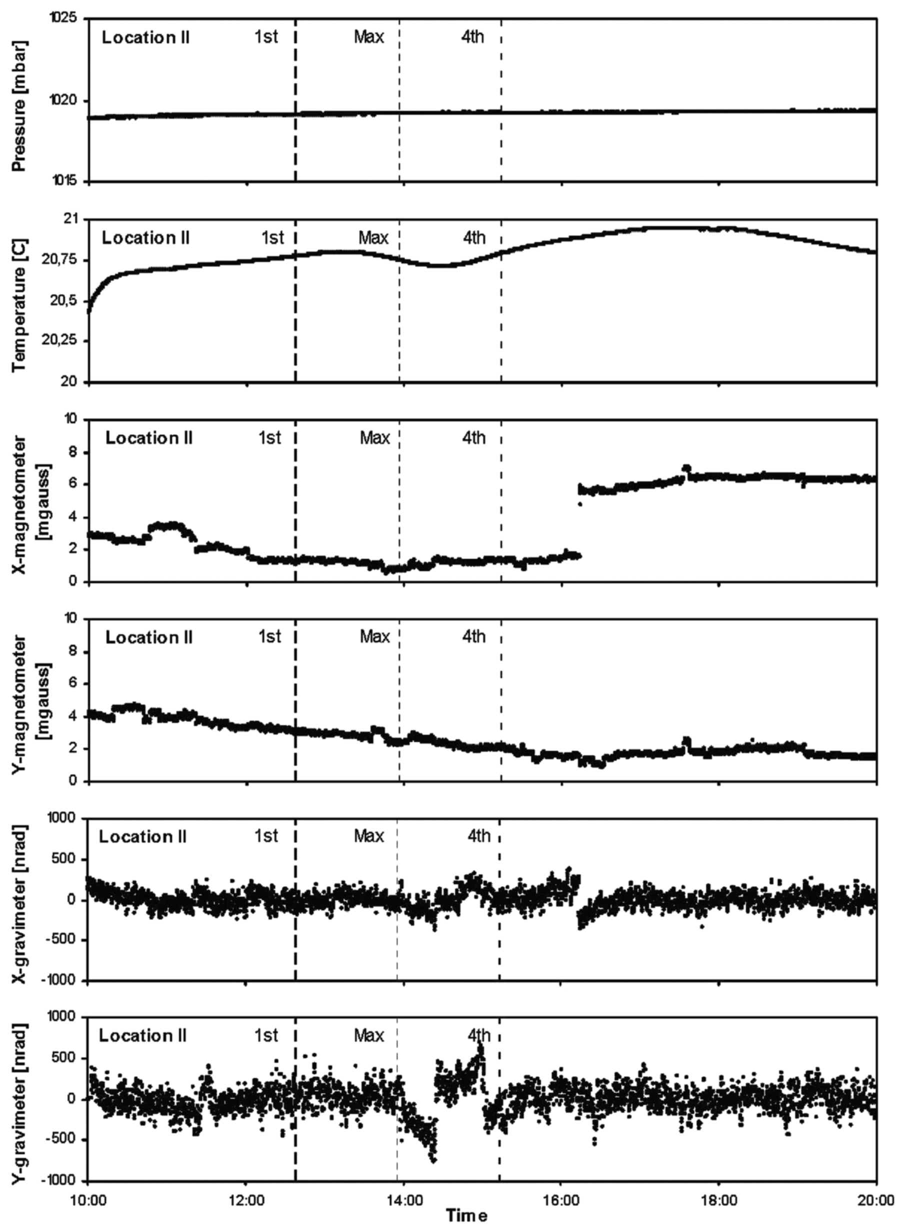

FIG. 4. The ambient pressure and temperature, the magnetic field in x- and y-directions, and the tilt angles of the x- and y-gravimeters as a function of time at the location II. The first and fourth contacts of the solar eclipse are marked with thick dashed lines and the moment of totality with a thin dashed line.

level is 90 nrad (x-direction) and 170 nrad (y-direction) during the eclipse based on standard deviation of the signal. For some unknown reason the noise level was always higher in the y-directions and it increased gradually in both directions, also in the recordings of other locations. There are two very short bursts in the data (marked with EQ1 and EQ2 in the Fig. 3), which supposedly were produced by earthquakes. The last one was identified by its timing and happened to be nearby the Syrian coastline.

In the tilt data of the location II (Manavgat, on the center line) there is some oscillation especially in the y-direction during the eclipse. Also the bursts from the earthquakes are clearly visible. The noise level just before the first contact of the eclipse is 90 nrad (x-direction) and 130 nrad (y-direction).

The noise level of the data from the location III (Akseki, on the center line) is the lowest, 40 nrad (x-direction) and 65 nrad (y-direction) measured before the first contact of the eclipse. Also in this data there are aperiodic oscillations during and nearby the eclipse but curiously also approximately 24 hours before and 24 hours after the eclipse. Only the last earthquake is visible.

In order to examine more closely the data during the eclipse a zoomed 10 hour segment of gravimeter data with ambient pressure, temperature, and magnetic field are presented in Fig. 4 (the location II) and Fig. 5 (the

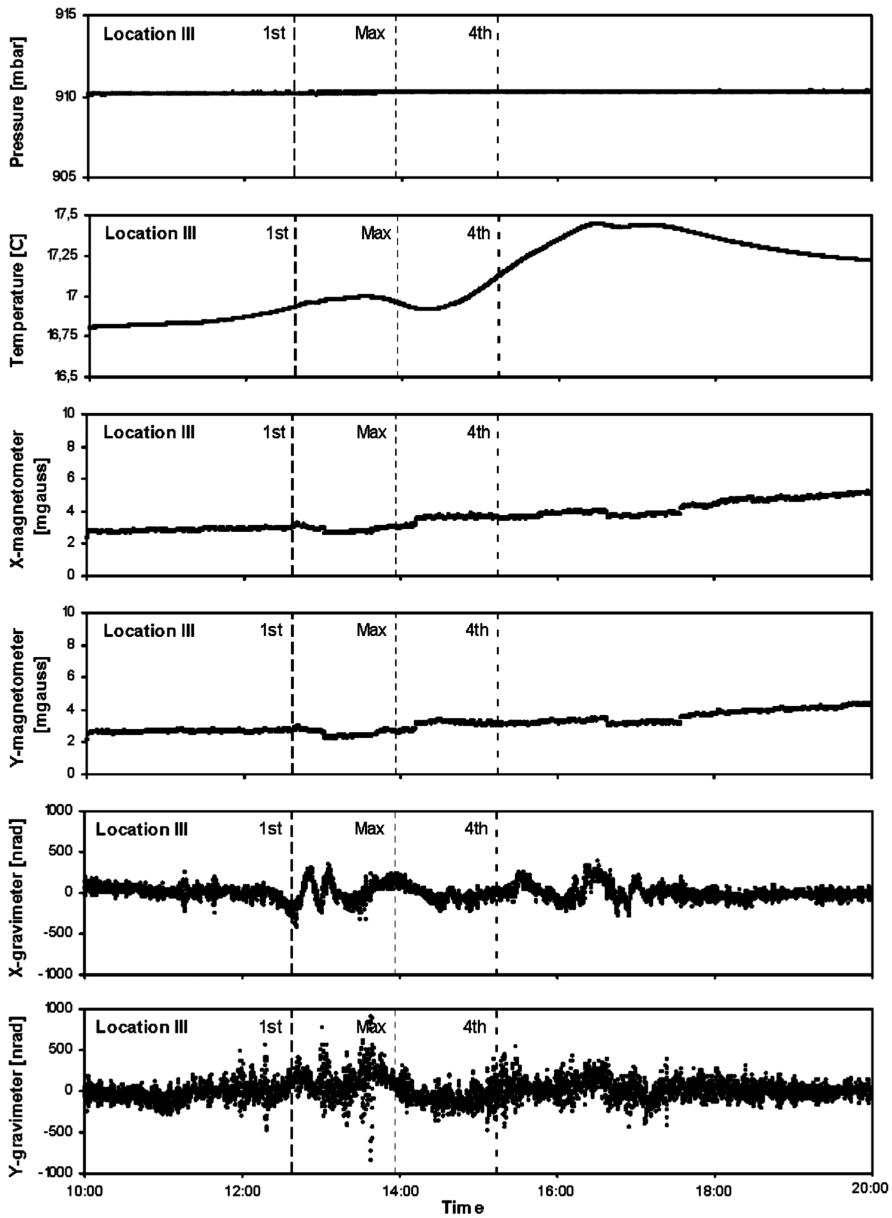

FIG. 5. Same as Fig. 3 but at the location III.

location III). The pressure, temperature, and magnetic field are presented without any filtering or trend removing. In the location II in the y-direction and in the location III in both directions there are abrupt changes or oscillations in the gravimeter signal during the eclipse, which are not clearly correlated with changes in magnetic field, temperature, or pressure. It should be noticed that the period of the tilt oscillations is in the scale of tens of minutes so that they cannot be originated from local disturbances like walking people, cars, etc. which can just increase the level of the short term noise. In general the ambient pressure is practically constant within the resolution limit of 0.2 mbar, and the changes in temperature are less than 0.25 °C. However, a small increase in temperature can be seen between the first contact and the maximum, and a small decrease between the maximum and fourth contact. In the location II data one jump in the magnetic field in x-direction after the eclipse has produced a stepwise decrease in the gravimeter signal (because the slowly changing baseline was removed this jump does not produce an infinite long step). The amplitude of this abrupt change is exactly what we can expect based on the tests of the gravimeters in the controlled magnetic fields. The origin of this jump in the magnetic field is unknown. The maximal peak-to-peak changes in the gravimeter tilt data of the location II and III, either due to tilt of the device or modulations in the gravitation field, are clearly higher than the average noise level, 300–500 nrad. Interestingly significant changes were observed only in the locations II and III, which lay on the center line, and not in the location I, which was within the totality path but on the edge of it. These changes in the tilt angle are almost in the same range as tilts of 1000–1500 nrad observed during the eclipse in 1991 in Mexico City [7] but not as clearly linked to the phases of the eclipse.

The tilt resolution of the gravimeters was clearly higher than the average noise level in all three locations, and therefore we can conclude that the overall sensitivity of the devices was high enough to detect any eclipse related anomalies in practice. Smaller changes could be detected only if some noise absorbers were used. However, such damping systems can produce unwanted oscillation modes and resonance effects. No tilt larger that 500 nrad in the time scale shorter than 5000 seconds was observed during the whole recording session of 3 days (excluding the bursts of the detected earthquakes) but most of the time the tilt noise was only a fraction of that. The average tilt amplitude deviation during the eclipse (from the 1st contact to the 4th contact) over all locations and in all directions was 150 nrad, which can be regarded as a mean upper limit for the eclipse related changes in the tilt. Since the most prominent local changes in the gravimeter tilt signals were mainly observed during and close to the eclipse period in the locations II and III, it is possible that they are related to the eclipse phenomenon. Long test runs in Finland revealed that such changes could not be originated from the instruments themselves but they must be real external effects.

IV. CONCLUSIONS

In summary, we have measured the apparent vertical direction of the gravity field using horizontal gravimeters as tilt meters in three distant locations within the totality path of the solar eclipse. In the locations close to the center line of the eclipse, deviations 2–3 times larger than the average noise level were observed during and nearby the eclipse, but in the location far from the center line no anomalous deviations were observed. Changes in the ambient temperature, pressure, or magnetic field cannot account for the observed anomalies in the time scale shorter than 5000 seconds. However, the detected signals are too small and they are not well correlated with the phases of the eclipse to reliably exclude external, but totally conventional explanations such as movements of the buildings or the ground, especially because we observed similar type of changes in one of the measurement locations also 20–24 hours before and after the eclipse. It is also possible that large changes in solar radiation energy during the eclipse could produce deformations in the structures of the buildings used in experiments although the changes in the atmospheric temperature were small. The average tilt amplitude deviation during the eclipse over all locations and in all directions was 150 nrad, which can be regarded as a mean upper limit for the eclipse related changes in the tilt. We can conclude that it is possible, but highly unlikely, that the observed very small changes could explain the previous observations of gravitational anomalies made with paraconical and torsion pendulums or vertical gravimeters.

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