1. Supporting text

1.1. Effect of underground water on gravity at Matsushiro

Underground water has a non-negligible effect on gravity through Newtonian attraction by its mass. In principle, any change in an underground water table caused by rainfall and drainage affects observed gravity. This local effect depends on climate, weather, geology, and geometric setting around the gravity station. Therefore, the effect can differ from station to station in magnitude and temporal dependence. Because the Matsushiro station is housed inside a tunnel dug along a hill, the effect of underground water can involve different processes from surface stations.

Residual gravity at the Matsushiro station correlates with rainfall (S1). In fact, the effect of rainfall is so significant at Matsushiro that a considerable part of the residual gravity changes is probably related to changes in the underground water table. There was rainfall of about 82 mm at Matsushiro just before the Tokachi-oki earthquake, so it is essential to make appropriate corrections for underground water effects in our study.

Preliminary analyses have revealed the following characteristics of rainfall effects on gravity at Matsushiro. First, unlike at many other stations, a decrease in gravity is observed following rainfall. A similar phenomenon has been found also at the underground station in Moxa, Germany (S2). Second, gravity reacts to rainfall almost immediately with no time lag. These facts suggest that Newtonian attraction by the incremental water mass above the gravimeter is a dominant effect. Third, the instantaneous magnitude of gravity change is approximately proportional to the
instantaneous amount of rainfall, and nearly independent of prior amounts of rainfall. The constant of this proportionality is about 0.039 µGal mm\(^{-1}\), which is close to the gravity change (0.042 µGal mm\(^{-1}\)) caused by an infinite sheet of a water layer. Fourth, the gravity excursion due to rainfall decays very slowly and almost linearly with time. The rate of this decay appears independent of the amount of rainfall. This phenomenon may be interpreted as a function of water drainage or percolation at a steady rate over and/or inside the hill.

All these observations suggest that the supply of water mass over the hill by rainfall, its percolation into the hill, and drainage are dominant processes that result in the observed gravity changes. This would be verifiable if we could accurately monitor groundwater fluctuations associated with rainfall. However, it is difficult to measure groundwater fluctuations inside the hill directly; in fact, gravity observations are perhaps the best method to do so. Therefore, we must resort to a phenomenological approach. We adopt a simple tank model, which is a slight modification of an accumulation and discharge model of groundwater (§3). In our model, rainfall produces a decrease in gravity proportional to its amount. This decays linearly with time until it reaches zero. Effects of rainfall events at different times are simply superposed. Rainfall data are available every 10 minutes for input to the model.

To put this into a more quantitative context, the gravity change \( g(t) \) due to rainfall is described by a differential equation:

\[
\frac{dg(t)}{dt} = \gamma \Theta(-g(t)) - \alpha r(t)
\]  

(S1)

where \( r(t) \) is rainfall rate at time \( t \) in mm s\(^{-1}\) and \( \Theta \) is a step function. \( \alpha \) is a constant of proportionality between rainfall and gravity, and \( \gamma \) is the gravity recovery rate after rainfall. Both \( \alpha \) and \( \gamma \) are positive. Using this equation, we can calculate the temporal changes of gravity using rainfall data.

As an example of the rainfall correction, we show rainfall and residual gravity data, both uncorrected and corrected, for four months in 2002 (Fig. S1). Rainfall data are shown in terms of hourly total in mm, and model parameters \( \alpha \) and \( \gamma \) have been adjusted from the data empirically so that the model reproduces the observed trend well. For our
data, choice of $\alpha = 4 \times 10^{-10} \text{ ms}^{-2} \text{ mm}^{-1}$ and $\gamma = 3 \times 10^{14} \text{ ms}^{-3}$ yield the best results. This simple model works quite well; we could modify it by using more “tanks” to represent more complicated temporal behavior, but for our purposes, it is unnecessary to introduce higher degrees of freedom in the model.

We then apply the same model to data for the 2003 Tokachi-oki earthquake (Fig. S2). Before the rainfall correction is applied, the residual gravity is affected significantly by rainfall prior to the earthquake. Fitting a quadratic function to the uncorrected data yields $0.35 \times 10^{-8} \text{ ms}^{-2}$ for the change in gravity. After we apply the rainfall correction, the estimate of the gravity change is reduced to $0.10 \times 10^{-8} \text{ ms}^{-2}$.

1.2. Effect of tilt of the gravimeter at Kyoto

In normal operation, an automatic tilt compensation system consisting of two thermally expansive elements (thermal levelers) and two orthogonally aligned tiltmeters inside the gravimeter controls the vertical alignment of the SG. This mechanism is believed to contribute to better instrument performance, especially when tilt of the basement is unstable. On the other hand, a lasting concern has been that activation of the thermal levelers may lead to some degree of degradation in the instrumental noise spectrum, through possible crosstalk between vertical and horizontal accelerations.

The SG at the Japanese Antarctic station (Syowa) once experienced a serious problem with its tilt compensation system, and was operated without automatic control of alignment of the gravimeter for a limited period ($\S4$). Although the thermal levelers were disabled at that time, they were not detached mechanically. As a result, alignment of the gravimeter was subjected to the influences of ambient temperature through thermal expansion/shrinkage of the thermal levelers as well as the tilt of the basement. The temperature changes introduced false signals into gravity. A trial is underway ($\S4$) to recover gravity signals free from tilt effects for that period, using data from tiltmeters. Results are promising and point to the possibility that SGs could be operated without automatic tilt compensation systems.

This experience led us to conduct another experiment on the SG at Kyoto. By both
disabling and mechanically detaching the thermal levelers, thermal expansion/shrinkage of them does not have any effect on tilt of the gravimeter. Without feedback from the thermal levelers, the tilt of the basement relates directly to the tilt of the gravimeter. In fact, the tilt signals indicate relatively large undulations in mainly diurnal periods, perhaps related to thermal strain of the building in which the gravimeter is installed.

The 2003 Tokachi-oki earthquake occurred after this modification of the gravimeter. Therefore, analysis of the gravity data from the Kyoto SG requires a correction for the tilt effect. The dependence of gravity on tilt is approximately quadratic with respect to tilt angles from the vertical. We assume that the tilt effect is described by

$$g(t) = a(x(t) - x_0)^2 + b(y(t) - y_0)^2 + c$$

(S2)

where $g(t)$ is gravity, $x(t)$ and $y(t)$ are the error signals (in V) from the tiltmeters for X and Y axes, $x_0$ and $y_0$ are the null positions of tiltmeters, and $a$, $b$ and $c$ are constants. It is also implicitly assumed that the tilt error signal, called tilt balance, is proportional to the tilt angle. This right-hand side can be expanded into a quadratic function of both $x(t)$ and $y(t)$ with five unknown parameters. Due to the geometry of the gravity sensor, $a$ and $b$ are positive for the SG, unlike usual gravimeters. In principle, if the gravity sensor is horizontally symmetric and the two tiltmeters are identical, $a$ and $b$ are identical. In practice, a small difference in $a$ and $b$ may exist due to some variations between theoretical and actual conditions. So we treat them as independent parameters. By fitting this model to the residual gravity, we can extract the contribution of tilt to the observed gravity and obtain gravity changes free from tilt effects.

The model function and residual gravity agree well (Fig. S3). Gravity changes do not need to be completely reproduced by tilt effects, because other factors contribute to gravity. Tilt data for the Y component are not available after 10:00 on 28 September (UTC) because of malfunctions. Because the optimal model parameters indicate slight changes with time, we selected a short timespan for fitting the model. The tilt undulation in the X component is mostly responsible for the tilt effect. Estimates for the coefficients $a$ and $b$ are $3.5 \times 10^{-8}$ ms$^{-2}$V$^{-2}$ and $-23.5 \times 10^{-8}$ ms$^{-2}$V$^{-2}$, respectively. Although the precise reason for the reversed sign of the Y component is unknown, the Y component may not be well constrained because of the much smaller magnitude of the tilt signals. Some
nonlinearity in the tiltmeters may also be partly responsible.

With this correction, the effect of tilt on gravity is reduced considerably. The residual gravity data still contain almost diurnal undulations. This is either due to imperfect removal of the tilt effect or to other environmental disturbances such as atmospheric pressure. These may contribute to the error in the final estimate of coseismic gravity change of approximately $0.1 \times 10^{-8} \text{ms}^{-2}$.

1.3. On instrumental offset of superconducting gravimeter

It is known that an SG often indicates an instrumental offset in a gravity signal when subjected to strong mechanical shock caused by an earthquake or maintenance work. In most cases, however, the offset is so large (typically tens or hundreds of $\mu$Gal) that it is easily distinguishable from a real signal. Empirically speaking, there appears to be a threshold of applied acceleration in generating an instrumental offset; when acceleration exceeds it, an irreversible change in the magnetic supporting system of the SG may take place, resulting in an offset of unpredictable magnitude. Because the effect of strong acceleration on the gravity sensor has not been investigated quantitatively, it is not known precisely how large an external acceleration, in what component (vertical, horizontal, or perhaps rotational) and at what frequency, causes an instrumental offset.

At the time of the 2003 Tokachi-oki earthquake, all the SG stations in Japan, especially Esashi, underwent large disturbances due to passage of seismic waves. It is a serious question whether or not those disturbances caused instrumental offsets in the gravity sensors. In this case, the observed offsets in gravity signals are $1 \mu$Gal at most, much smaller than instrumental offsets typically observed on strong earthquakes. This fact may be regarded as an indication that the gravity sensors survived the accelerations caused by the seismic waves from the Tokachi-oki event.

To quantify this argument, we try to deduce an empirical criterion on the occurrence of instrumental offsets to show that the acceleration of the Tokachi-oki event was below the threshold. We use data from the dense seismic observation network called K-NET (S5). The sensors deployed in K-NET are strong-motion acceleration seismographs with
an eigenfrequency at 450 Hz (S6). The data are digitally sampled at 100 Hz for three components, but they are lowpass filtered with a cutoff frequency at 30 Hz. The K-NET station which is nearest to the Esashi SG station is Mizusawa (IWT011), about 15 km apart from Esashi. During the period from July 1997 through December 2003, there are 37 events in which acceleration, either vertical or horizontal, larger than 5 Gal was registered at Mizusawa. For each event, we calculated spectra of three components of acceleration seismograms. During the same period, the SG at Esashi suffered from 12 times of instrumental offsets associated with earthquakes.

The selected earthquakes are plotted according to their spectral power in vertical and horizontal components which is averaged over one third octave bandwidth around a specified center frequency (Fig. S4). When we see the spectra at 1 Hz (Fig. S4A), the 2003 Tokachi-oki earthquake is one of the largest events during this period. Some events which are smaller in terms of spectral power at 1 Hz have caused instrumental offsets. However, at this frequency, there is no clear threshold with respect to the generation of an instrumental offset. On the other hand, when seen at 20 Hz (Fig. S4B), the Tokachi-oki earthquake has relatively small power compared with other events. Such a difference is due to the fact that a large earthquake tends to have more spectral power in lower frequencies. With some exceptions, the events seem to be classified roughly into two regimes, with or without instrumental offsets, according to the spectral power. The Tokachi-oki earthquake falls into the latter regime, though close to the border. This result suggests that higher frequency components of acceleration may be responsible for the occurrence of instrumental offsets, as easily imagined. This also provides a supporting evidence for the absence of an instrumental offset in the Esashi data at the Tokachi-oki earthquake. It is not obvious from the present analysis which component, vertical or horizontal, has a larger effect on the instrumental offset.

Similarly, no instrumental offset is expected for the SGs at Matsushiro and Kyoto, because ground acceleration was much smaller at these stations than at Esashi.
2. Supporting figures

Fig. S1. (A) Residual gravity from Matsushiro before (blue) and after (red) rainfall correction. (B) Hourly rainfall (light blue) and contribution of rainwater to gravity calculated with a tank model (magenta).
Fig. S2. Same as Fig. S1, but for the period encompassing the 2003 Tokachi-oki earthquake.
Fig. S3. (A) (blue) Residual gravity from the Kyoto SG after removal of tides and atmospheric effects. (red) Effect of tilt on gravity estimated by fitting the model of eq. (S2). (B) Error signals from the tiltmeters for the X component (green) and Y component (magenta).
Fig. S4. (A) Mean power density of ground acceleration at 1 Hz for the earthquakes that registered acceleration over 5 Gal at the Mizusawa station of K-NET. The horizontal acceleration denotes whichever is larger, east-west or north-south component. Red dots represent those events on which the SG at Esashi showed an instrumental offset. The green dot is the 2003 Tokachi-oki earthquake. Other events are represented by blue dots. (B) Same as (A) but at 20 Hz.
3. References


S4. S. Iwano, Y. Fukuda, Phys. Earth Planet. Inter. in press.


S7. We used strong-motion data from the K-NET maintained by National Research Institute for Earth Science and Disaster Prevention.