Absolute gravity measurements in New Zealand

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Although absolute gravimetry based on the measurements of length and time is an ideal tool for monitoring phenomena with long term stability, only a few countries possess absolute gravimeters. New Zealand (NZ) does not possess an absolute gravimeter, and all the absolute gravity measurements so far made were carried out by foreign institutions. Among them, the majority of the measurements, including the NZ first absolute gravity measurement in 1995, were carried out by US or French groups at Christchurch on the way to McMurdo Station in Antarctica.
A remarkable measurement was carried out by Colorado University and Otago University at NZ South Alps in 2000. NZ South Alps locates at the southeastern side of Alpine fault which divides Pacific sea plate and Australian plate. The formation of South Alps was considered to be caused by large scale uplift along the transform fault. Therefore the absolute gravity measurement was aimed at revealing the formation mechanism.
Except the measurements at Christchurch, absolute gravity measurements in NZ had not been carried out for a long time afterwards, particularily, no measurement was carried out in North Island. In February 2015, Geological and Nuclear Science (GNS) and Land Information New Zealand (LINZ), collaborating with Geoscience Australia(GA), were carried out absolute measurements by using FG5-237 of GA at three existing absolute gravity points in South Island and five newly established gravity points in North Island (Stagpoole et al., 2015). In addition, Colorado University and Otago University carried out absolute gravity measurements in South Alps by using FG5-111 during the period of December 2014 and January 2015 after an interval of 15 years (Bilham et al., submitted).
As mentioned above, several absolute gravity measurements have been recently carried out. However the results obtained are not enough for the studies, and the importance of the absolute gravity measurements in NZ including the measurements in South Alps is unchanged. Moreover NZ collaborators desire to continue the repeated measurements. Therefore, collaborating with the NZ researcher, we are going to push forward the research along the proposed plan. The following is a summary of the absolute gravity measurements conducted in January and March 2016.
The absolute gravimeter employed in this study was FG5-210 of Kyoto University. It was shipped from Japan in middle of December 2015, finished the import procedure to NZ by the end of December 2015, and derived at the gravity station at Warkworth VLBI observatory of Auckland University of Technology (AUT) on January 11, 2016.
In the case of trouble during the transportation, we divided the measurement schedule into two periods, namely, January and March. In January, we vacuumed the dropping chamber, tested and aligned the instruments, and conducted the measurements until January 16. Although there were some small problems, we finally obtained 33 sets (3300 drops) of data. The preliminary obtained gravity value was only 2.80 ugal larger than that obtained by GA in last year. It suggests the measurement was successful. The instrument was kept in high vacuum condition until March. It will be checked in Warkworth and employed for the measurements at the gravity points in North Island and carried to South Island via Wellington for the measurements in Christchurch and South Alps as well.

In this presentation, we report the results of these measurements and the outline of the future observation plan.
Acknowledgements: This study was partially supported by JSPS KAKENHI Grant No. 15H05205. We thank Prof. Roger Bilham of Colorado Univ., Dr. Christopher Pearson of Otago Univ. and Dr. Vaughan Stagpoole of GNS for their helpful and valuable comments to the research plan.

Keywords: absolute gravity measurements, Southern Alps, gravity changes, absolute gravity reference system

Continuous relative gravity observation at Sakurajima Volcano: Disturbance corrections of tilt and gravity time series

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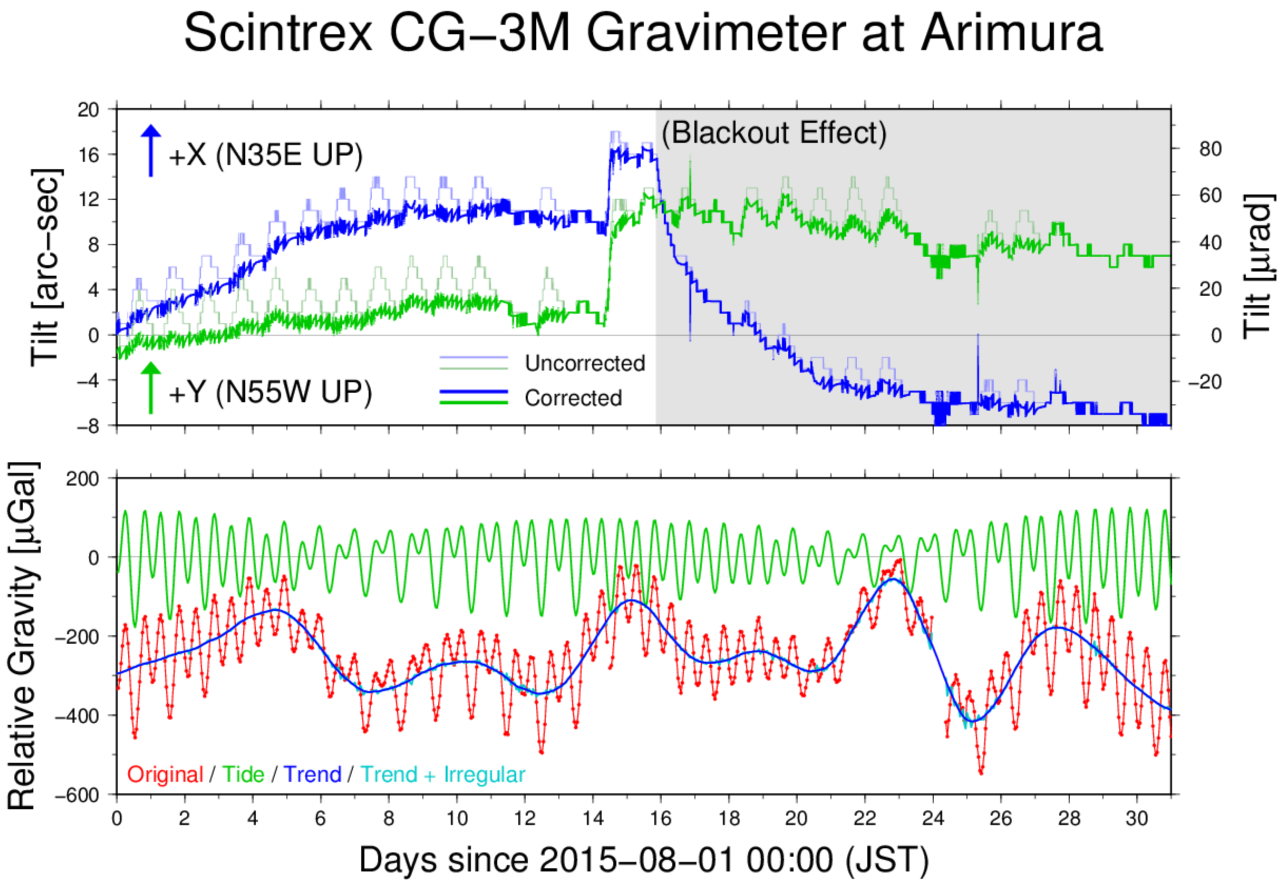
Gravity observation is one of the most effective methods to monitor mass movements in volcanoes. Gravity changes due to volcanism have been observed mainly with campaign gravity measurements using portable relative gravimeters (e.g., Furuya et al., 2003) and with continuous absolute gravity measurements (e.g., Kazama et al., 2015). However, most of the previous studies only have focused on the clear volcanic gravity signals with periods of more than a day, because the short-period gravity data tends to become noisier due to the low sampling rate of the gravity observations. Since other geodetic data have already revealed broadband volcanic signals with periods of seconds to years (e.g., Iguchi et al., 2008; Hotta et al., 2016), short-period volcanic gravity changes should be monitored to understand more about the volcanic activities in terms of mass movement.
We were thus motivated to collect the continuous gravity data with the sampling rate of one minute, using a Scintrex CG-3M relative gravimeter at Arimura Observatory, Sakurajima Volcano (Kagoshima Prefecture, Japan). The gravimeter was first installed in May 2010 and continues collecting the gravity data as of January 2016. It also records the minutely tilt values of the gravimeter, which are utilized to correct the apparent gravity changes due to the tilt. This presentation mentions how to correct some disturbances in the gravity/tilt data as follows, and the volcanic gravity/tilt signals will be discussed at the presentations in the “Active volcanism” session.
Instrumental drift and tidal effect in gravity data: We first corrected the large instrumental drift (rate: more than 300 micro-Gal/day) from the original gravity data by subtracting the long-period gravity change calculated with the cubic spline curve, which was obtained from the 2-day average of the original gravity data. We also corrected the tidal gravity changes (amplitude: up to 300 micro-Gal) with periods of less than a day, using the BAYTAP-G software (Tamura et al., 1991). In the lower panel of the attached figure, the red curve shows the corrected gravity change from which the long-period instrumental drift was removed, and the blue curve also shows the corrected gravity from which both of the drift and tidal effect were removed. The blue curve contains the non-periodic gravity changes associated with volcanism, along with the periodic gravity change with periods of less than a few days.
Insolation effect in tilt data: The gravimeter tilted diurnally during sunny days, possibly because the insolation tilted the building of Arimura Observatory slightly. In order to correct the insolation effect in the tilt data, we first estimated the diurnal tilt variation for each component of the N35E-S35W and N55W-S55E axes, by averaging the daily tilt variations on 1 to 11 August 2015. We then corrected the insolation-derived tilt disturbances by removing the estimated diurnal tilt variations from the original tilt data. The light and dark lines in the upper panel of the attached figure show the tilt time series before/after the insolation effect was corrected, respectively. Significant tilt changes associated with the volcanic event on 15 August 2015 can be identified clearly, owing to the correction of the insolation effect. Note that the tilt changes in the second half of August 2015 might be affected by the air temperature change in Arimura Observatory, because the blackout on the night of 16 August turned off the air conditioners in the observatory.

Keywords: relative gravity, gravity change, tilt change, Sakurajima Volcano, instrumental drift, tide


Scintrex CG–3M Gravimeter at Arimura
+X (N35E UP)
+Y (N55W UP)
(Blackout Effect)
Uncorrected
Corrected
Tilt [arc–sec]
Tilt [μrad]
Relative Gravity [μGal]
Original / Tide / Trend / Trend + Irregular
Days since 2015–08–01 00:00 (JST)

Gravity observations around the Ontake Volcano (Campaigned absolute and Continuous relative)

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We have been conducting absolute gravity measurements at the foot of the Ontake Volcano (approximately 10km away from the mountain top in the direction of southeast) since 2004. We initially intended to detect gravity changes of hydrothermal origin in and around the seismic swarm area. Therefore, those observations were not suited to detect mass change just beneath the mountain top. However, according to the phreatic explosion in 2014, we searched new observation hubs closer to the mountaintop and have started to carry out hybrid gravity observation and continuous relative gravity measurement. As of this moment, we have not detected remarkable gravity change caused by volcanic activity. But, we have accumulating some important findings such as the relationship between accumulated precipitation for a few days and campaigned observation values of absolute gravity, atmospheric correction (attraction and loading deformation) at a highland, and so on. Taking these into account, we will report trials of sophistication of mobility-based observation by combination of continuous spring-type relative gravity and absolute gravity measurement campaigns.
Acknowledgements: This work is collaborated by Y. Miyagi (NIED) and Nagoya Univ. staffs (especially, M. Furumoto, T. Sagiya, T. Okuda, and S. Horikawa). We are grateful to the Mitake education office in Kiso town, Ontake Golf & Resort Hotel, and Ontake Resort Inc. for providing observation facilities.

Keywords: gravity measurement, Precipitation, atmospheric correction, volcano

Sea level oscillations observed with an iGrav SG at Tomakomai, Hokkaido, Japan

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A superconducting gravimeter installed near the coast may detect gravity effects induced by sea level variation. For example, Nawa et al. (2003) show the relationship between sea level variation and gravity variation from a superconducting gravimeter installed at Syowa Station, Antarctica. These effects are interpreted to be due to loading and attraction by seawater in Lutzow-Holm Bay around the station (Nawa et al., 2007). We tried to extract gravity changes induced by sea level variation from the gravity data acquired by an iGrav superconducting gravimeter newly installed at Tomakomai, Japan (Sugihara et al., 2015). As a result, at the period of passing low pressure in the vicinity of Hokkaido (e.g. several days in April and December 2015), we could detect signals corresponding to the sea level oscillations of the period 74 minutes.

Acknowledgement
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Keywords: superconducting gravimeter, noise, seiche, atmospheric pressure

Effect of underground water on superconducting gravimeter observation at Ishigakijima

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Superconducting gravimeter observation at Ishigakijima, Japan was launched in 2012 with the purpose of detecting potential signals associated with slow slip events. To date, we have not been very successful in distinguishing slow slip signals from surface water disturbances, because interactions between the ocean and the underground water make it difficult to model their effects on gravity. In 2015, there were relatively dry periods at Ishigakijima, which were broken by the approach of typhoons. In these events, observed gravity changes were correlated with the sea level, highly likely to indicate its relation with the underground water level. On the other hand, the data from soil moisture sensors at the gravity station showed that the soil water near the surface was independent of the underground water. Based on these observations, we will present results of detailed analysis taking into account the interactions between the ocean, underground water and atmosphere, and their effects on gravity.
We thank Okinawa-ken Nagura Dam Kanrisho for providing dam observation data. This work was supported by JSPS KAKENHI Grant Number 26289350.

Keywords: superconducting gravimeter, Ishigakijima, underground water

Independent Component Analysis application to the gravity observation data

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ICA (Independent Component Analysis) is a multivariate method to separate signals mixed with different rates assuming independent signals are uncorrelated each other and have a large negentropy. ICA can be applied to the gravity observation data because the gravity signals are regarded as a mixed data of different sources. Some previous studies applied ICA to the satellite gravity data (Guo et al., 2014, Forootan et al., 2011 etc.) and other geodetic data successfully. ICA is expected to be applied for the gravity observation data as well. We presented in 2015 JpGU meeting that ICA worked more effectively for separating the small signals of 3 gPhone gravimeters data than PCA (Principal Component Analysis) did. However, the separated signals by ICA do not automatically guarantee any geophysical meanings, because ICA is just a statistical method. Thus, the applicable limit of ICA should be estimated in advance. Therefore we conducted several tests of ICA applicability using synthetic gravity data sets. The results showed that ICA can separate periodic variations, long term variations and trends, while it hardly separate almost gaussian signals with large differences in amplitudes. There are still problems in evaluation of the results, particularly with noise signals. By improving these points, we will try more detail and practical evaluations of ICA applicability in the future.

Keywords: Gravity, Independent Component Analysis

Gravitational gradient changes of mega-thrust earthquakes observed by GRACE

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The earthquakes change the gravity, which means the gravitational gradient is also changed. Gravity Recovery And Climate Experiment (GRACE) have been providing insight into the gravity changes by earthquakes and the data can also be used to reveal the gravitational gradient changes. For example, Wang et al. [2012] reported gravitational gradiet changes following the 2004 Sumatra-Andaman earthquake on the GRACE CSR RL04 data. In this presentation, I will introduce the co- and postseismic gravitational gradient changes by four huge earthquakes, i.e., the 2004 Sumatra-Andaman earthquake, the 2010 Maule earthquake, the 2011 Tohoku-Oki earhquake, and the 2012 Indiean Sea earthquake observed by GRACE, comparing to the gravity changes and the gravitational gradient changes of the Tohoku-Oki earthquake observed by GOCE.

Revisiting estimates of glacier mass balance in Asian High Mountains from satellite gravimetry

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The advent of GRACE, the dedicated gravity satellite mission, has enabled continuous and remote measurement of the glacier mass balance in Asian High Mountain Ranges (HM Asia). Matsuo & Heki (*EPSL* ,2010) first attempted to estimate the glacier mass balance in this region using GRACE data and reported the average ice loss rate of -47 Gt/yr for the period 2003-2009. On the other hands, Jacob et al.(*Nature,* 2012) also conducted the GRACE-based estimate for this region and reported the average ice loss rate of -11 Gt/yr for the period 2003-2010. According to Matsuo & Heki (*SEPPYO* ,2014), the discrepancy between these two estimates can be attributed to the following two factors: groundwater signal leakage from the irrigated region in Northern India and inter-annual variability in glacier mass balance. Therefore, in order to correctly estimate the glacier mass balance in HM Asia, it is required to properly separate the groundwater signals from the target region and utilize the long-term GRACE data as long as possible. In this study, we re-estimate the glacier mass balance in HM Asia by employing new GRACE data, hydrological model, and data processing technique.

Keywords: Space geodesy, Glacier, Climate change, GRACE, Gravity

Investigation of method that makes Japanese old and dense gravity data consistent with Japan gravity standardization net 2013

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Geospatial Information Authority of Japan (GSI) have established a new gravity standardization network of Japan, named the Japan Gravity Standardization Net. 2013 (JGSN2013), from the latest absolute and relative land gravity measurements covering the whole country. The accuracy of JGSN2013 is evaluated around 10μGal in standard deviation from the residuals of network adjustment and the leave-one-out cross validation, and this means JGSN2013 achieves more accurate gravity standard than the former gravity standard, the Japan Gravity Standardization Net. 1975 (JGSN75), by an order of magnitude. GSI also conducted relative gravity measurements at benchmarks and some of triangular control points from 1967 to 1993 in order to obtain dense spatial distribution of surface gravity and also utilize them for orthmetric height correction of levelling survey. The data obtained by the measurements comes to 14,000 in total, refers JGSN75 and has been utilized for calibration of measurement devices etc. as nationally authorized gravity standard.
This gravity data refer to JGSN75, which was established in 1976, thus are not consistent with recent measurements referring JGSN2013 and the difference sometimes exceeds range of the measurement error. The major sources of the difference are difference in measurement procedure or difference of referred standard, temporal vertical variation of ground at observed sites caused by crustal deformation or pumping of groundwater. The maximum difference between JGSN75 and JGSN2013 at the gravity station of GSI is over 100μGal.
GNSS-derived orthmetric height determination has been recently developed. As a result, the importance of land gravity data densely covering the whole country has been gradually increasing because the data has been increasingly utilized as fundamental data for modeling of geoid, a reference surface for orthometric height. The latest, Highly-reliable land gravity data covering the country are essential for improving accuracy and reliability of geoid model. However, it is almost impossible to obtain new data referring JGSN2013 with in several years by newly conducting time- and cost-consuming gravity measurement for the whole country.
To resolve these problems, a method that makes JGSN75 gravity consistent with JGSN2013 gravity is developed. In this research, difference between two gravity reference system is explained with two causes thus, (A): “observation error that is originally included in JGSN75” and (B): “effects of crustal deformation that is imposed on observation point while old and new observation interval”. (B) can be estimated using spirit leveling data and GNSS continuous observation data for determination of variation of observation point and its effect for gravity value. Furthermore, co-seismic and post-seismic gravity change are estimated using rectangular fault model and viscoelastic relaxation model calculation. These crustal deformation effects are subducted from difference gravity data and we obtain (A). And we can adapt appropriate method for interpolation of difference of gravity data that are corrected using (B).
By this research, gravity change that are caused by crustal deformation is estimated. And relation of old and new gravity data is revealed. Thus old and dense gravity data recover accuracy. Consequently, basic data for developing more precise geoid are provided.

Keywords: Japan gravity standardization net 2013

A mathematical simulation of the dynamics of local Earth gravity direction referring to the Earth surface normal

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Based on the development of measurement and information technology, geodetic measurements are continually reported with high quality. ITRF2008 [1] claims a believed origin accuracy at the level of 1 cm over the time-span of 26 year of SLR observations, and further 1.2 ppb (8 mm) accuracy is achieved by integrating other three techniques together: GNSS/GPS, VLBI and DORIS. With latest technical improvements, even better accuracy could be expected in the new solution of ITRF2014 [2].
It is often expected, that geodetic measurements with high accuracy should be helpful in understanding the geo-physical principle of Earthquake. Therefore many comparative analyses have been carried out aiming at constructing a correlation between recorded giant earthquakes and the temporal variations of some geodetic measurements. The conclusions from these analyses are generally frustrating, that the observed discrepancies of measurements, e.g., Earth gravity changes, ``reflect the difference in the geodynamical settings of the studied earthquakes'' [3]. Such a frustration often leads to the widespread argument that predicting Earthquake is impossible.
The gap between the plausible achievements in geodetic measurement and the frustrating conclusions by using them for interpreting earthquakes, could be explained by the *Nyquist-Shannon* sampling theorem: to detect a single event without prior knowledge, its temporal-spatial domain should be sampled with an adequate frequency. In geo-science the situation is far from being satisfied. Normally an earthquake is a local event which accidentally happens at a particular time moment covering a close neighborhood of its epicenter. Densely sampling the dynamical behaviors on Earth is often a suffering task because of two factors: 1) the scale, and 2) the system reference. A typical velocity of plate tectonic movements which varies from 1-10 cm/year is indistinguishable from random noise in most of daily observations; The system reference of geodetic observation is often set either as man-made satellites, or as natural space objects like lunar or extragalactic reference, which are neither convenient nor flexible for local and dense geo-observations.
This paper suggests a new geo-observation in which the reference system is set as the local geometry of the Earth's surface. There are two distinct vectors existing on Earth’s surface: the surface normal, which is defined as a geometric descriptor, and the direction of the Earth's gravity force, which is defined as the gradient of the Earth's gravitational potential pointing to the Earth mass center. It is expected to get information of the mass distribution below the Earth's crust layer. A mathematical simulation is carried out with typical Earth parameters; A conceptual measurement model is described to measure the subtle angular difference between the above two vectors, where the angular difference is converted to a spatial distance according a dedicatedly designed system. Laser interferometer together with an ultra-high precision camera system provides a sub-nanometer measurement accuracy, which in principle could be measured over time span of hours, even minutes. Without systematic ambiguities like un-modelled forces in space, signal delay in ionosphere, the suggested concept physically is promising for a complementary geo-measurement besides the current mainstream techniques.
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Keywords: Earth gravity direction, Earth surface normal, Geodetic measurement

Gravity potential measurement using optical lattice clocks and its applications to geodesy, seismology and volcanology in the future

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Gravity potential measurements using optical lattice clocks based on the general relativity are going to achieve a relative precision of an order of 10^{-18} in a few hours, corresponding to an order of centimeters in terms of height. Relativistic geodesy using optical lattice clocks allows us to directly determine the gravity potential at the Earth’s surface, which is expected to improve a static geoid model serving as the reference of height, combined with other geodetic data. However, in plate subduction zones like Japan where crustal deformation is active compared with the stable continents, time variations in the gravity potential caused by tectonic phenomena should also be considered. In this presentation, geophysical impacts of monitoring temporal potential changes with a precision of 1 cm are discussed. Measured potential variations are much more sensitive to height changes of observation sites than to the underground mass redistributions. This means that optical lattice clocks can be used as an altimeter, which enables us to evaluate height changes observed with space geodetic techniques. The height changes determined from the potential measurement are free from the errors due to atmospheric phase delays in the GNSS. A more reliable and faster determination of height may improve a precision of monitoring water vapor in the atmosphere in the context of the GNSS meteorology. Gravity measurement is also sensible to height changes. However, it suffers from groundwater disturbances near the surface, which is almost negligible when measuring the gravity potential variation. Therefore, optical lattice clocks, when combined with gravity measurement, will help real-time monitoring of movements of crustal fluids such as magma, by correcting for apparent gravity changes due to rapid height changes.

Keywords: optical lattice clock, geoid, gravity, relativity

Gravity potential determination based on Doppler cancelling technique: simulation experiments using high-frequency-stability microwave links between satellites and ground stations

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In this report we present simulation results for determining the gravity potential (geopotential) using high-frequency-stability microwave links between satellites and ground stations. Based on gravity frequency shift principle and Doppler cancelling technique, the geopotential difference between a satellite and a ground station can be determined, and consequently the geopotential difference between different ground stations can also be determined via satellites. Suppose the relative inaccuracy of the clocks on board satellites and at ground stations is about 10^{-17} level, our simulation experiments show the following results: (1) if two ground stations are connected via one satellite, the standard deviation is around 3 m^2/s^2 (equivalent in height 0.3 m); and (2) if two ground stations are connected with a network of satellites up to 5, the standard deviation can be largely improved, reaching around 1 m^2/s^2. With quick development of time-frequency science, portable and commercial optical atomic clocks with inaccuracy of 10^{-17} or better will appear soon. Hence, our proposed approach is prospective in the near future, especially for effective real-time geopotential determination, height measurement and global height datum unification in 1 cm level.
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Keywords: geopotential determination, optical atomic clocks, microwave links, Doppler cancellation technique, gravity frequency shift, satellite

