Evaluation of Systematic Errors in the Compact Absolute Gravimeter TAG-1 for Network Monitoring of Volcanic Activities

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Abstract

Volcanic activities sometimes involve gravity changes, and this research is intended to establish an observation network surrounding an active volcano using compact absolute gravimeters. To simplify the configuration of absolute gravimeters, they are preferably operated with a light source distributed from a telecom band (wavelength of 1.5 μm) laser through optical fibers. To evaluate the accuracy of the absolute gravimeter with the telecom band laser, we conducted observations using a prototype gravimeter (TAG-1) with frequency-stabilized lasers at both 1.5 μm and 633 nm, and compared these results with the expected gravity at the site. Initially, both results showed offsets $-187 \text{ Gal}$ and $-9.6 \text{ Gal}$ for the 1.5-μm laser and the 633-nm laser, respectively ($1 \text{ Gal} = 10^{-8} \text{ m/s}^2$). By correcting the systematic errors of the photo detectors measured by the synthetic chirp signal, the obtained absolute gravity was consistent with the expected value for both wavelengths; offsets from the expected gravity were reduced to $6.6 \text{ Gal}$ and $5.4 \text{ Gal}$ for 1.5 μm and 633 nm, respectively. We also evaluated the errors associated with long-distance transmission of the 1.5-μm laser using a reeled optical fiber (26 km) and an optical amplifier and found no degradation in the gravity data from the case of short transmission (10 m). These results allow networking of compact absolute gravimeters connected by telecom optical fibers that are operated using a common laser and expansion to volcanic areas to monitor the gravity change associated with volcanic activities.

Keywords

Absolute gravimeter · Frequency stabilization · Telecom band laser · Volcanic observation

1 Introduction

Volcanic activities often involve earthquakes, crustal deformation, magnetic anomaly, and other geophysical phenomena. Gravity change is a direct probe of the mass movement of magma that is monitored for the prediction of volcanic eruptions and to evaluate the transition of volcanic activities. Both types of gravimeters, relative gravimeters and absolute gravimeters, have been used, and the latter can measure long-term gravity changes without any instrumental drift with reference to an accurate wavelength of the frequency-stabilized laser. However, owing to the complex mechanism, large size, and high cost, absolute gravimeters have not commonly been used for volcanic observations. This research is intended to establish a network of compact absolute gravimeters for volcanic observations.

To construct this observation network, absolute gravimeters are preferably operated with telecom band (wavelength of 1.5 μm) lasers distributed to each gravimeter via optical
fibers because conventional lasers (wavelength of 633 nm) cannot be transmitted to distant sites because of the loss of optical fibers; which is typically 15–30 dB/km for 633-nm light, and 0.2–1 dB/km for 1.5-μm light. To evaluate the accuracy of the absolute gravimeter with a telecom band laser, we conducted observations using a prototype gravimeter (TAG-1) with frequency-stabilized lasers at both 1.5-μm and 633-nm wavelengths, and compared these results with the expected gravity of the site.

2 Gravity Change Associated with Volcanic Activities

Sakurajima is one of the most active volcanos in Japan. A devastating eruption occurred in 1914, and small eruptions still continue. It has been determined that the amount of magma in the magma chamber beneath the mountain is coming to that of 1914. Okubo et al. (2013) observed gravity changes associated with the volcanic eruption of Sakurajima using an absolute gravimeter. The gravity change was 10 μGal (1 Gal = 10⁻⁸ m/s²) at a distance of 2 km from the crater; this is only one factor larger than the background noise level due to local disturbances such as groundwater (Kazama and Okubo 2009). Therefore, observations near the crater and networking with a number of gravimeters surrounding the crater will significantly enhance the detectability of magma motion near the source by averaging the local disturbances using a number of sensors.

3 TAG-1 Gravimeter

Araya et al. (2014) developed a compact absolute gravimeter, TAG-1, and we used it for the evaluation of the availability of network monitoring of volcanic activities. To evaluate the accuracy of the absolute gravity with the telecom band laser, we conducted observations using TAG-1 with frequency-stabilized lasers at wavelengths of 1.5 μm and 633 nm, and compared these results with the expected gravity of the site. Figure 1 shows a picture and a schematic diagram of the TAG-1 gravimeter. It is comprised of a dropper for the free-fall mass and a built-in accelerometer for correction of seismic vibrations. By applying the built-in accelerometer and the small dropper, TAG-1 is compact and transportable for observations.

The laser light is introduced into the optical unit through the optical fiber and is incident to vacuum chambers confining the free-fall mass (Free-fall mirror) dropper and a reference pendulum (Reference mirror), both of which include retro reflective mirrors forming an interferometer. The interfered light is guided to photo detectors (PDs) through optical fibers. TAG-1 uses a quadrature interferometer for the displacement measurement of the free-fall mass, and the optical phase is calculated from the detected signals (Heydemann 1981; Svitlov and Araya 2014). From the quadratic dependence of the displacement with respect to time, the absolute gravity can be obtained. Effects of ground vibration acceleration on the gravity are corrected using data from the build-in accelerometer using the reference pendulum.

TAG-1 can be operated at both wavelengths of 1.5 μm and 633 nm by using the PDs and the optical unit designed for each wavelength. InGaAs-type and Si-type PDs are used for the wavelengths of 1.5 μm and 633 nm, respectively. Beam verticality can be adjusted so that the measuring laser beam and beam of the auto-collimator reflected on a reference alcohol surface are in parallel. For the vertical adjustment at the invisible 1.5-μm wavelength, the measuring laser beam is monitored using an IR (infrared) viewer.

4 Observation Using a Conventional 633-nm Laser and a Telecom Band (1.5 μm) Laser

We performed gravity measurements in a basement room of the main building of the Research Institute of Electrical Communication (RIEC), Tohoku University, using TAG-1 operated with both a conventional iodine-stabilized 633-nm He–Ne laser (wavelength of λᵢ = 632.99081163 nm), and a telecom band (1.5 μm) laser (λ₁₅ = 1,538.803242 nm, Fig. 2) which was frequency-stabilized using the acetylene linear absorption spectrum with a linewidth of 500 MHz (Kasai et al. 2016) and whose frequency accuracy is estimated to be 10⁻⁹ (Nakagawa and Onae 2004); the latter may realize the long-distance distribution of the light source and networking of gravimeters. The systematic errors in operation for both wavelengths were evaluated.

The free-fall mirror was dropped every 2 min. The obtained data were corrected for seismic noise measured by the build-in accelerometer. Figure 3 shows the measured gravity using the conventional 633-nm laser and the 1.5-μm frequency-stabilized laser. The theoretical gravity variation is shown by the red line based on calculated tidal gravity and the absolute gravity measured by the relative measurement from a gravity reference point, as described in the following
Fig. 1 Picture (upper) and schematic diagram (lower) of the TAG-1 gravimeter. The optical unit shown in dashed red line in the lower figure can be replaced depending on the laser wavelengths.
section. Slow tidal gravity variations were commonly observed for both cases, while offsets were apparent. The offsets averaged in the periods were $-187 \ \mu\text{Gal}$ for the 1.5-$\mu$ m laser and $-9.6 \ \mu\text{Gal}$ for the 633-nm laser. This may be due to the PDs because mechanical and optical configurations are essentially the same for both cases, and the laser wavelengths are well defined. We evaluated the systematic error of TAG-1 caused by the frequency response of the PDs.

5 Systematic Error Evaluation of the PDs

Because the frequency of the fringe signal is almost proportional to the velocity of the free-fall mass, the response of the PD causes a systematic error in the gravity measurement (Niebauer et al. 1995). To evaluate the error directly, synthetically modulated laser light that simulates the interferometer fringe was applied to the PD, and the difference in obtained gravity values from the measurement and from calculations could be regarded as estimates of the systematic error. The free-fall mass in gravity, $g$, generates a chirp interferometer signal with a frequency rate of $\frac{df}{dt} = \frac{g}{\lambda}$, where $\lambda$ is the wavelength of the laser. Therefore, chirp frequency rates of 13.07 MHz/s and 30.96 MHz/s produce $g = 9.8 \ \text{m/s}^2$ for $\lambda = 1.5 \ \mu\text{m}$, and 633 nm, respectively. The laser intensity was modulated using an electro-optic amplitude modulator for the 1.5-$\mu$ m evaluation, while a laser diode was used for the 633 nm light source. In each case, the chirp signal was applied using a function generator whose clock and data sampling clock were both locked to the same Rb time base. For the measurement of the 1.5-$\mu$ m laser, the chirp frequency was set to change from 0.1 MHz to 2.6 MHz in 0.2 s, and it
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Fig. 4 The observed gravity (blue/light blue dots, left axis) and the estimated error of the PDs obtained from the synthetic chirp signal (green dots, right axis). Observed 1 and observed 2 are calculated from the 1.5-μm datasets within 0:30–1:30 and 1:30–2:30, respectively, on 19 December, 2017, as shown in Fig. 3.

The observed data, calculated with \( t_0 > 60 \) ms and \( \Delta t = 80 \) ms, were corrected using the estimated errors, as shown in Fig. 5. The observed data corrected using the estimated errors for the 633-nm and 1.5-μm lasers. The theoretical tides were removed from the data and then averaged. The expected level based on the relative measurements were referenced to AOB-B, as shown by the red dashed line. To see the consistency of the corrected gravity, two data sets for each laser were calculated and showed similar results.

The observed data, calculated with \( t_0 = 80 \) ms and \( \Delta t = 60 \) ms, agreed with the error estimation of the PDs. The estimation shows small systematic errors for whole \( t_0 \), and smaller \( t_0 \) gives smaller gravity acceleration; the decrease of observed gravity at 1.5 μm in Fig. 3, calculated with \( t_0 = 10 \) ms and \( \Delta t = 150 \) ms, is consistent with this estimates of errors of the PDs.

The laser light at 1.5 μm was introduced through short (10 m) or long (26 km) optical fibers. In this experiment, we used a reeled optical fiber in the laboratory. As shown in Fig. 7, the measured absolute gravity did not change and showed no degradation even when the laser was provided through a 26-km-long optical fiber and an optical amplifier. Nevertheless, to estimate errors in a practical system in the field, environmental effects on the optical fibers, such as vibration and thermal disturbances, need to be measured.
6 Conclusions

The compact absolute gravimeter, TAG-1, was successfully operated with both 633-nm and 1.5-μm lasers. By correcting systematic errors of the PDs measured using a synthetic chirp signal, the obtained absolute gravity was consistent with the expected value for both wavelengths; the systematic error of 1.5-μm PDs was estimated to be as much as $-190 \, \mu\text{Gal}$ without the correction. These results can lead to networking of compact absolute gravimeters connected via telecom optical fibers operated using a common laser and can be expanded to volcanic areas to monitor the gravity change associated with volcanic activities.
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References

Araya A, Sakai H, Tamura Y, Tsubokawa T, Svitlov S (2014) Development of a compact absolute gravimeter with a built-in accelerometer and a silent drop mechanism. In: Proceedings of the International Association of Geodesy (IAG) symposium on terrestrial gravimetry: static and mobile measurements (TGSMM-2013), 17–20 September 2013, Saint Petersburg, pp 98–104

Heydemann PLM (1981) Determination and correction of quadrature fringe measurement errors in interferometers. Appl Opt 20:3382–3384

Kasai K, Yoshida M, Nakazawa M (2016) 295 mW output, frequency-stabilized erbium silica fiber laser with a linewidth of 5 kHz and RIN of $-120 \text{dB/Hz}$. Opt Express 24:2737–2748

Kazama T, Okubo S (2009) Hydrological modeling of groundwater disturbances to observed gravity: theory and application to Asama Volcano, Central Japan. J Geophys Res 114:B08402

Nakagawa K, Onoe A (2004) Developments of optical frequency standards for wavelength-division-multiplexing (WDM) optical fiber communication systems. IEEJ Trans Fundam Mater 124:52–55

Niebauer TM, Sasagawa GS, Faller JE, Hilt R, Klopping F (1995) A new generation of absolute gravimeters. Metrologia 32:159–180

Okubo S, Kazama T, Yamamoto K, Iuchi M, Tanaka Y, Sugano T, Imanishi Y, Sun W, Saka M, Watanabe A, Matsumoto S (2013) Absolute gravity variation at Sakurajima Volcano from April 2009 through January 2011 and its relevance to the eruptive activity of Showa crater. Bull Volc Soc Japan 58:153–162

Svitlov S, Araya A (2014) Homodyne interferometry with quadrature fringe detection for absolute gravimeter. Appl Opt 53:3548–3555

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