Testing Gravitational Physics with Superconducting Gravimeters

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Superconducting gravimeters are the most sensitive instruments to measure surface gravity changes at low frequencies. Currently, about twenty five superconducting gravimeters are operating in the world and their global network has been developed. We investigate possible applications of the superconducting gravimeters to tests of gravitational physics. Previous experimental searches for spacial anisotropies in the gravitational constant G and for gravitational waves, performed with gravimeters in 1960's to 1970's, can be improved by applications of the current superconducting gravimeters. Also, we describe other proposed applications of testing the universality of free-fall and searching for composition-dependent dilatonic waves, and discuss future works necessary for these geophysical tests.

§1. Introduction

Superconducting gravimeters are the most sensitive instruments of measuring gravity at low frequencies. They have been used for tests of gravitational physics and geophysical studies (Ref. 1) and references therein). The global network of superconducting gravimeters, the Global Geodynamics Project (GGP) network,[2)] has been developed since 1997. Currently, about twenty-five superconducting gravimeters join the GGP network (see §3 for the distribution of the GGP stations). The GGP network allows us to study gravity signals in global nature with increased sensitivity. It has been successfully used for geophysical studies.[3)] Its applications to gravitational physics were suggested,[1),4),5)] but they have not been studied in detail yet. In this paper, we will focus on possible applications of the global network to gravitational physics.

Brief descriptions of the instrument and the GGP network are given in §§2 and 3, respectively. We will see previous applications of superconducting gravimeters in gravitational physics and discuss possible future applications of superconducting gravimeters and the GGP network in gravitational physics in §4.

§2. Superconducting gravimeters

The superconducting gravimeters were developed by Goodkind and Prothero at the University of California, San Diego (UCSD), in the late 1960's.[1),6)] The fundamental design described in their first report[6)] has not been changed, but its performance has been improved since then at UCSD and GWR Instruments.[7)] Currently, commercial superconducting gravimeters are available at GWR Instruments.

Two new superconducting gravimeters have been installed at the Laboratory of Geodesy and Geodynamics (LOGG) in Hsinchu Taiwan (24.8°N, 121°E) in March 2006. They were manufactured by GWR Instruments. A photograph of one of

Fig. 1. A photograph of the superconducting gravimeter (No. 48) and its data acquisition system, installed at LOGG in Hsinchu Taiwan. The sensing unit (Fig. 2) is placed in the liquid helium dewar (the blue tank in this photograph) and operates at liquid helium temperatures (~ 4.2 K). (See the online edition for the color version of this figure.)

the superconducting gravimeters (No. 48) is shown in Fig. 1. A schematic view of the sensing unit of the superconducting gravimeter is shown in Fig. 2 (quoted from Ref. 1)).

In a superconducting gravimeter, instead of the spring used in a mechanical gravimeter, its proof mass (a superconducting sphere) is levitated by magnetic fields, induced in superconducting levitation coils (see Fig. 2). The proof mass is about 2.5 cm (one inch) in diameter and its weight is between 4 and 8 g.[1)] By adjusting the currents of the levitation coils, the magnetic stiffness (spring constant) can be tuned to be nearly zero. The motion of the proof mass, in response to changes in ambient gravity, is monitored by capacitive sensors that surrounds the proof mass. In operation, the proof mass is kept at the same position through a feed-back system. Because of the stability in the super currents in the levitation coils and the smallness in stiffness, superconducting gravimeters provide stable and sensitive gravity measurements. The sensitivity of a superconducting gravimeter, installed at a quiet site, is better than ~ 1 n gal or 10^{-11} m s^{-2} for a year-long measurement at various frequencies and its stability is better than a few μ gal (10^{-8} m s^{-2}) per year for resent instruments. A more detailed description of superconducting gravimeters is

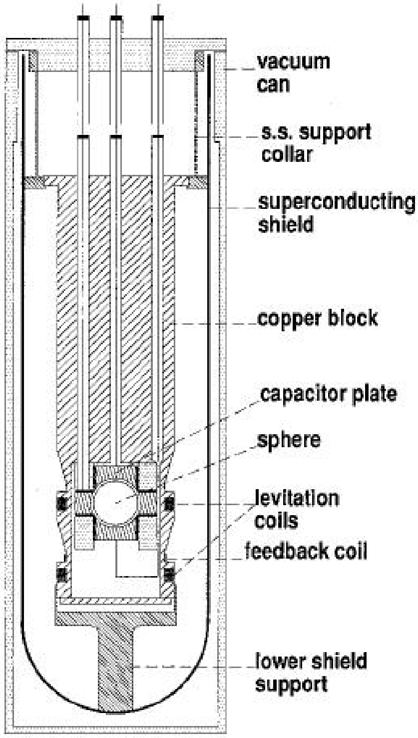

Fig. 2. A schematic cross-section of the sensing unit of a superconducting gravimeter (quoted from Ref. 1)).

given in Ref. 1).

§3. The GGP network

The GGP network[2)] has been developed since 1997 to study geophysical signals in global nature, for example, the inner core oscillations, polar motion and wobbles.[8)] The map of the GGP stations is given in Fig. 3. Currently about twenty five stations join the GGP network. From Fig. 3, one can see that the GGP stations are widely distributed, from north to south and east to west on the globe.

§4. Applications in gravitational physics

Superconducting gravimeters have been applied to tests of gravitational physics since 1970's. One of the earliest works in the context is the search for anisotropies in locally measured values of the gravitational constant G,[10)] which are predicted by some gravitation theories.[11)–13)] It is pointed out that this search can be improved with the use of longer records of gravity data from multi-stations.[1)] We will discuss the possible improvement in §4.1.

Other experiments, which have been performed using superconducting gravime-

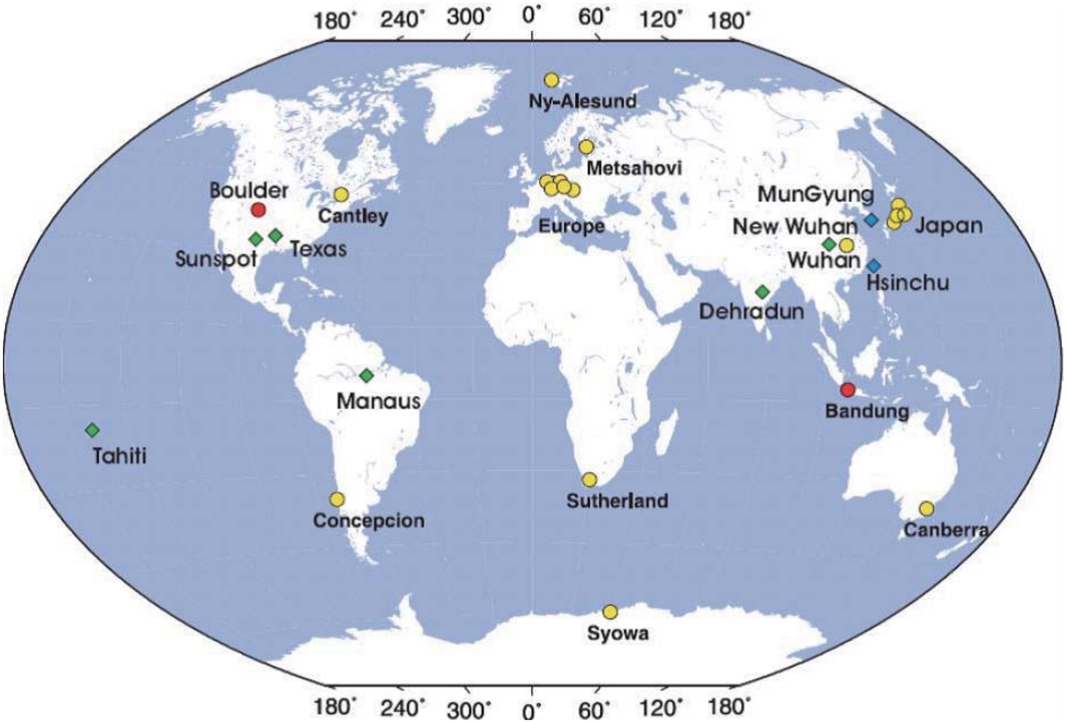

Fig. 3. The map of the GGP stations, quoted from Ref. 9). Yellow circles indicate the stations that are currently operating. Red circles indicate the stations that recently stopped operation. Green diamonds indicate the stations that are going to install superconducting gravimeters in the near future. Blue diamonds indicate the stations that newly installed superconducting gravimeters. (See the online edition for the color version of this figure.)

ters, are testing the inverse-square law in a laboratory scale (0.4 to 1.4 m)[14] and in the geophysical window (10 to 10^3 m),[15),16)] a determination of the gravitational constant G,[17] and searching for gravitational waves using the Earth as the receiver.[18),19)] We will describe the gravitational-wave search in more detail in §4.2.

As for future experiments, we will briefly describe two proposals: testing the universality of free-fall[4] (§4.3) and searching for composition-dependent dilatonic waves (§4.4).

4.1. *Search for spacial anisotropies in G*

Unlike Generals Relativity, some theories of gravitation predict spacial anisotropies in locally measured values of the gravitational constant G (Refs. 11)–13) and references therein). Among these theories, some allow the existence of preferred frames in the universe, and such anisotropies in laboratory-measured values of G arise from the translation and rotation of the Earth relative to the assumed preferred frames (preferred-frame effects). In another type of theories, anisotropies in G are caused by a nearby gravitating body, such as the Galaxy (the Galaxy induced anisotropy or preferred-location effects). These anisotropies lead to anomalous tidal effects, which can be searched for with gravimeters.

Will has examined Earth-tide data obtained from mechanical gravimeters and found that they agree with Newtonian predictions within two percent.[11] This indicates that the magnitude of the anomalous tidal effects should be less than $10^{-9}g$, where $g \approx 9.8$ m s^{-2} is the Earth's surface gravitational field. With this experimental limit, he obtained upper limits on the preferred-frame effects and the preferred-location effects, which are parameterized by α_2 and ξ in the parameterized post-Newtonian (PPN) formalism,[*] respectively: $\alpha_2 < 3 \times 10^{-2}$ and $\xi < 10^{-2}$.[11]

Warburdon and Goodkind[10] searched for such anomalous tidal effects in their gravity data of superconducting gravimeter and placed more stringent upper limits: $\alpha_2 < 4 \times 10^{-4}$ and $\xi < 10^{-3}$. This upper limit on ξ is currently the most stringent constraint on the PPN parameter (see Table 4 on p. 43 in Ref. 20) for current limits on the PPN parameters).

Later, it is shown that α_2 can be constrained to be order of 10^{-7} from the close alignment of the Sun's spin axis with the solar system's planetary angular momentum after 5 billion yr.[21] Also, it is shown that α_2 should be determined to a few parts in 10^{-5} using Lunar Laser Ranging (LLR) data,[22] and its preliminary estimate is given as $\alpha_2 = (2 \pm 2) \times 10^{-5}$ in Ref. 23).

With the use of longer records of gravity data from the GGP stations and the improved knowledge of geophysical and environmental disturbances, we could improve the estimates of the upper limits placed by Warburdon and Goodkind. From recent observations, it is shown that the noise level of a superconducting gravimeter located at a quiet site is about a few ngal ($10^{-12}g$)[24] at the signal frequencies of the preferred-frame and preferred-location effects. This is about three orders of magnitude improvements in gravity measurements in comparison with the experimental data used by Will in early 1970's. With this current noise level, we could obtain upper limits on both of α_2 and ξ in order of 10^{-5}, which is comparable with the expected sensitivity from the LLR data. Further analyses are necessary to obtain accurate estimates.

4.2. *Search for gravitational waves*

In the early stage of experimental studies on detecting gravitational waves, a pioneer of gravitational-wave research, Weber, proposed to search for normal modes of the Earth, exited by incident gravitational waves.[25] The first upper limits on the flux of gravitational waves were placed by checking the excitation of the normal modes, using seismological data[26] and a mechanical gravimeter,[27] in 1960's. In the early 1970's, possible excitations of the normal modes were observed with a superconducting gravimeter,[18],[19] but the results have not been confirmed by following experiments.

This approach of searching for gravitational waves is sensitive at low frequencies (about 0.3 mHz or 54 min in period for the ${}_0S_2$ mode); it allows to investigate lower frequencies than other ground-based gravitational-wave detectors (i.e. laser interferometers and resonant-mass detectors), whose sensitive frequency ranges are about 10 to 1000 Hz.[28] Superconducting gravimeters are suitable for the normal-mode

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[*] See Ref. 20) and references therein for detailed descriptions of the PPN formalism.

method because of their good sensitivity at the low-frequency range. Superconducting gravimeters were improved from the one used for the gravitational-wave search in early 1970's[18),19)] and the GGP network is now available. Our knowledge of low-frequency normal modes and the Earth model has been being improved in geophysics.[29),30)] Therefore, it might be interesting to reinvestigate the normal-mode method using current superconducting gravimeters and the GGP network.

In the frequency range of the normal-mode method, there are stringent upper limits on the cosmological stochastic gravitational waves by the Nucleosynthesis and recent measurements of the cosmic microwave background: $\Omega_{gw} h_{100}^2 \lesssim 10^{-5}$.[31),32)] As for astrophysical stochastic gravitational waves, the Doppler tracking of the Cassini spacecraft has placed an upper limit: $\Omega_{gw} h_{100}^2 \lesssim 0.1$ at ~ 0.3 mHz.[33)] To provide a significant contribution to the filed, we have to achieve a comparable sensitivity with the Doppler tracking result.

The normal-mode method has fundamental difficulties to separate the expected signals of gravitational waves from seismic noise and geophysical effects, such as excitations of the normal modes by silent earthquakes.[34)] However, with the use of the GGP network, we could identify some localized disturbing effects and remove them from the gravity data. Further investigation is necessary.

Also, scalar gravitational waves, predicted by scalar-tensor theories of gravitation (e.g. Brans-Dicke's theory), can be searched for by checking excitations of spherically symmetric modes of the Earth, during quiet periods. Some efforts of studying the twenty-minute breathing mode, ${}_0S_0$, have been done by Block, Weiss and Dicke in an early stage of gravitational-wave research.[35)] This mode can now be studied with improved sensitivity by using current superconducting gravimeters and the GGP network.

4.3. *Test of the universality of free-fall*

The Earth's inner core is weakly coupled to the rest part of the Earth by mainly gravitational forces. If there were a violation of the universality of free-fall, because of their different chemical compositions and/or of different mass fractions of binding energies, the inner core and the rest part of the Earth would fall at different rates towards the Sun and other sources of gravitational fields.[4)] The differential acceleration would result in surface-gravity effects, which can be searched for using superconducting gravimeters. Based on a simple Earth model, it is shown that the universality can be tested to a level of 10^9 with a superconducting gravimeter.[4)] To be comparable with current best limits on tests of the universality,[36)] the sensitivity has to be improved by more than three orders of magnitude. There are several possibilities to improve the sensitivity. One way is to apply advanced data analysis methods to extract weak signals. According to a non-linear damped-harmonic analysis method used in geophysical studies, it is possible to improve the sensitivity by a factor of ~ 10.[37)] Another way may be to carry out coincidence measurements with two superconducting gravimeters located ideally opposite sides of the Earth near the equator. If there were a violation towards the Sun, the expected magnitude of the violation signal at the two superconducting gravimeters is the same but the sign should be opposite. By combining such coincidence signals, we could double the magnitude of the expected signals and the sensitivity would be improved by a factor of 2.

Because of the inclination of the Earth's rotation axis, the maximum violation signals towards the Sun can be expected at observatories located on the equator in Spring and Autumnal equinox points, and on Tropic of Cancer or Capricorn in Summer and Winter solstices.[4)] Our site in Taiwan is one of the ideal locations for this approach in Summer and Winter. If the noise level of data from our site is high, it might be better to use data from low noise sites considering the degrees of signal compensation depending on the latitude and longitude of the sites. Further studies are necessary to figure out the optimal schemes for global observations and noise reduction.

A more detailed description of this geophysical test of the universality in given in Ref. 4).

4.4. *Search for dilatonic waves*

Composition-dependent dilatonic waves are predicted by unified theories of strings.[38)] When such dilatonic waves pass the Earth, because of the difference in dilatonic charge (namely, the difference in the chemical compositions) between the Earth's inner core and the rest part of the Earth, there would be relative motions between them.[5)] Such relative motions would result in surface gravity changes, which can be searched for by superconducting gravimeters. This method has its best sensitivity at the resonant frequency of the translational motions of the inner core:$\sim 7 \times 10^{-5}$ Hz, which is lower than the sensitive frequencies of previous proposals using gravitational-wave detectors: ~ 10 to 1000 Hz. Using available results of surface-gravity measurements with superconducting gravimeters and assuming a simple Earth model, preliminary upper limits on the energy density of dilatonic waves can be obtained at the low frequency. However, the results are currently limited by the uncertainty in the Earth model. A more detailed description of this method and the preliminary results are given in Ref. 5).

§5. Summary and discussion

We have discussed the following geophysical tests of gravitational physics in the previous sections: searching for preferred-frame and preferred-location effects (§4.1), searching for gravitational waves and scalar gravitational waves (§4.2), testing the universality of free-fall (§4.3) and searching for composition-dependent dilatonic waves (§4.4). These discussed applications are summarized in Table I.

From the third column of the table, one can see that the frequencies of the searched for effects are low: $\sim 10^{-5}$ to 10^{-3} Hz. In the low frequency range, superconducting gravimeters are the most sensitive instruments.

Those searched for effects are all thought to be very small. In order to have significant contributions to the field of gravitational physics, it is essential to improve the sensitivity. Key researches and developments to improve the sensitivity may be (1) developing data analysis methods to extract weak signals, (2) figuring out the optimum use of the global data, (3) carrying out coincidence measurements and (4)

Table I. Summary of the geophysical tests of gravitational physics, discussed in §4. The second and third columns indicate the expected dominant phenomena and their periods, respectively.

Searched for signals	Expected phenomena on the Earth	Periods
Preferred-frame effects (α_2)	Anomalous tides	12 hours
Preferred-location effects (ξ)	Anomalous tides	12 hours
Gravitational waves	Excitation of the ${}_0S_2$ mode	54 minutes
Scalar gravitational waves	Excitation of the ${}_0S_0$ mode	20.5 minutes
Violation of the universality of free-fall	Translational motions of the inner core	$\sim$ 24 hours
Composition-dependent dilatonic waves	Excitation of translational motions of the inner core	4-6 hours

improving the Earth model.

As mentioned earlier, data analysis methods to extract weak signals have been being studied in geophysics.[37] Their analysis shows that it is possible to improve the sensitivity by about one order of magnitude, by applying the advanced data analysis method. We could improve the sensitivity of the geophysical tests by applying the advanced analysis method.

In order to make the optimum use of the global data form the GGP network, we have to consider the optimum geometrical configuration of the stations, which are most suitable for each test. Some of the discussed effects exhibit latitude and/or longitude dependencies. For example, violation signals of the universality of free-fall vanish near the poles; observatories located near the equator are favored for this test (see §4.3).

Another point to be considered for the optimum use of the global data is the noise levels of the sites. The noise levels depend on the instruments and geophysical locations.[24] We should choose low noise sites in favored locations for each test.

By carrying out coincidence measurements with multi-station, we could improve the sensitivity. Analysis methods for coincidence measurements in the GGP network has to be developed.

As we have seen in §§4.1 and 4.2, previous searches for the anistropies in G and gravitational waves have been done in 1960's–1970's. Studies on the normal modes and Earth tides have been improved significantly since then. Also, the instruments and the global network have been developed; the sensitivity of gravity measurements at the signal frequencies was improved by about three orders of magnitude. Therefore, we can expect significant improvements on the previous results. However, as discussed earlier, there are some geophysical effects that mimic the expected signals. It is essential to model the unwanted effects and remove them from the data, to achieve a good sensitivity.

The test of the universality of free-fall and search for dilatonic waves attempt to monitor the translational motions of the inner core. One of the targets of the GGP network is the study of translational motions of the inner core (the Slichter triplet[39]); geophysicists have been searching for the Slichter triplet to determine physical properties of the Earth's interior.[40] Therefore, the GGP network and other technologies developed for the Slichter-triplet search can be applied to the test of the universality and search for the dilatonic waves. However, physical properties of the Earth's interior is not well known. The uncertainties in the Earth model would limit these experiments.

Fortunately, there are intensive efforts being made with new technologies to improve the Earth model. For example, recent advances in particle physics are providing new tools to see the Earth's interior. Some of the examples are the detection of the antinutrinos from natural radioactivity in the Earth with KamLAND[41] and studies on neutrino oscillation tomography of the Earth's interior.[42] Also, laboratory experiments at high pressure and high temperature are being performed to determine the viscosity of the core.[43] A new geophysical approach of coincidence measurements with a laser strainmeter system and a superconducting gravimeter is being carried out at the Kamioka Observatory in Japan,[44] to study the normal modes, the Slichter triplet, silent earthquakes and other geophysical phenomena. With these researches employing new technologies, one can expect that our knowledge on the Earth model and geophysical phenomena will be improved significantly in the near future.

§6. Conclusions

Superconducting gravimeters have been proved to be stable and sensitive in geophysical studies and also they have been used to study gravitational physics since 1970's. By using the Earth as the test body, we have investigated possible applications of the global network of the superconducting gravimeters to gravitational physics.

We have discussed possible improvements on the previous search for anistropies in the gravitational constant G. With the GGP network and improved knowledge on disturbing effects, we have seen that it would be possible to achieve a comparable sensitivity with the LLR.

We have proposed to reinvestigate the normal-mode method of searching for gravitational waves and scalar gravitational waves, which have been attempted by pioneers of gravitational-wave research in 1960's to 1970's, by making use of the advanced technologies in superconducting gravimetry.

Also, we have described the proposed applications of testing the universality of free-fall and searching for composition-dependent dilatonic waves, using the Earth as the test body and the superconducting gravimeters as the displacement sensor.

These geophysical tests would ultimately be limited by the uncertainties in the Earth model. However, future improvements can be expected from progress in new technologies and further studies going on in geophysical studies.

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