Centenary Researches on Earth Tides in Kyoto University (1909 - 2008)

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Abstract: This paper is a short historical review of centenary researches on Earth tides carried out in Kyoto University during the period of 1909 - 2008. Geophysical researches in Kyoto University started in 1909 when Toshi Shida arrived at Kyoto. He installed the tiltmeters of the E von Rebeur-Paschwitz type and the Pendulum seismographs of the Wiechert type at the Kamigamo Geophysical Observatory. Based on the data obtained from these instruments, he accomplished many pioneering achievements in geophysics. Among them, he first carried out tidal tilt observation in Japan and proposed the third parameter in spherical elasticity known as "Shida Number". First observation of tidal strains was carried out by Kenzo Sassa by employing extensometers of the Sassa type. Recent researches in the field of Earth tides with originalities in Kyoto University are tidal gravity measurements with superconducting gravimeters in Japan and Indonesia and development of laser interferometric devices for precise measurements of tidal strains. Combined use of laser strainmeters and superconducting gravimeter in Kamioka will be an effective tool to investigate physical properties of Earth's interior.

KEYWORDS: Tiltmeter, Extensometer, Laser strainmeter, Superconducting gravimeter, Shida Number

1. Introduction

Geophysical researches in Kyoto University started in 1909 when Toshi Shida (1876-1936) got his post as an associate professor in the Kyoto Imperial University (predecessor of Kyoto University). He graduated from the Institute of Physics of the Imperial University of Tokyo in 1901 and arrived at Kyoto Imperial University in September, 1909. After arriving at Kyoto, Shida immediately installed the tiltmeters of the E von Rebeur-Paschwitz type and the Pendulum seismographs of the Wiechert type at the Kamigamo Geophysical Observatory located about 4 km away from Kyoto University in direction of the north-northwest. Based on the data obtained from these instruments, Shida accomplished many pioneering achievements in geophysics;

(i) Precise observation of tidal tilts and proposal of the third parameter in spherical elasticity (Shida Number),
(ii) Discovery of quadrantal push-pull distribution of the first motion of seismic P waves,
(iii) Verification of deep earthquakes,
(iv) Proposal of a plan to detect free oscillation of the Earth.

Among these, topics (i) and (iv) are shown in the following chapters. In this chapter, we mention (ii) and (iii) briefly. With regard to (ii), Shida first pointed out the quadrantal push-pull distribution of the first motion of seismic P waves. Based on seismograms obtained at the Kamigamo observatory and other seismic observation network belonging to the Central Meteorological Observatory of Japan, Shida found out the quadrantal pattern of P-wave first impulses. This result was first reported at the meeting of the Tokyo Mathematico-Physical Society in April, 1917. Just after the meeting, a destructive shallow earthquake of M=6.3 occurred in Shizuoka Prefecture on May 18, 1917. Shida collected seismograms of this earthquake and confirmed that the distribution of P-wave first motions shows simple pattern of push-pull distribution divided by two orthogonal nodal lines (Shida 1929). Nowadays, it is well known that the first impulses of the seismic P-waves show a quadrantal pattern with compressional or dilatational distribution. This is a simple way to know the earthquake source mechanism.

In the research of deep earthquakes (iii), Kiyoo Wadati of Meteorological Agency of Japan is famous by his successive papers (Wadati, 1928 1929, .1931, 1935). He showed the convincing evidence of earthquakes occurring deeper than 300 km in and around Japan by employing the seismic data obtained from the dense seismic observation network of the Central Meteorological Observatory of Japan. He distinguished the existence of a deep earthquake zone crossing the central Honshu, which was later called the Wadati-Benioff zone (a seismic zone with an inclined surface from the trench toward the continental margin).

Prior to Wadati's work, Shida pointed out the existence of deep earthquakes in the lecture given at the opening ceremony of the Beppu Geophysical Laboratory, Kyoto Imperial University on 28 October, 1926. In this lecture, he indicated the deep earthquake zone traversing central Honshu. Before the lecture, Shida examined in detail the arrival times of the seismic P waves observed at various stations in Japan and found some abnormal earthquakes at which the time-difference of arrival-times among various stations in Japan were very small compared with those of ordinary earthquakes. Moreover, the arrival-times of these earthquakes observed at far-field stations in foreign countries were ten seconds or more earlier compared with those of ordinary earthquakes. Meanwhile, a strong earthquake shook the central Honshu on 27 July, 1926. Based on data of the P wave initial motions obtained from different stations in Japan, Shida fixed the hypocenter of this earthquake near Lake Biwa, northeast in Kyoto. The depth of the epicenter was determined to be about 260 km. Shida came to the conclusion that deep earthquakes must have taken place in the Earth. The reprint of this lecture concerning the deep earthquakes was published ten years later (Shida, 1937). Shida hesitated to publish the result as the scientific papers, and only his lecture note is remaining. The following comments have been left in his lecture note about this. "The Earth must be statically stable in a zone deeper than 120km according to the isostatic theory, and it may be difficult to consider that the brittle fractures such as those occurring near the surface would occur in the deep zone near the depth of 300km. Therefore, it is necessary to renew the knowledge of the source mechanism of deep earthquakes and the detailed structure inside the Earth. Time has passed while I was keeping collecting various materials and preparing a high-pressure experiment device to know physical properties in the upper mantle." Deep earthquakes with origins deeper than 60 km are approximately one-quarter of all earthquakes. Existence of deep earthquakes became one of the important grounds to find out the subduction zone in plate tectonics.

In 1929, Toshi Shida was awarded the 19th Imperial Prize from the Japan Academy on the title of "Investigations on the Rigidity of the Earth and on Earthquake Motions". In addition to his excellent achievements in research and education, Shida established the Beppu Geophysical Observatory in 1926, the Aso Volcanological Observatory in 1928, and the Abuyama Seismological Observatory in 1930. Since then, useful geodetic and seismological data have been obtained in these observatories until now.

In this paper, early research achievements on Earth tides performed by Toshi Shida and his successors (Kenzo Sassa and Eiichi Nishimura) are introduced first. Then some recent research activities in Kyoto University in the field of Earth tides, especially, tidal gravity measurements using superconducting gravimeters and development of laser interferometric devices for precise measurements of tidal strains are explained in the following chapters.

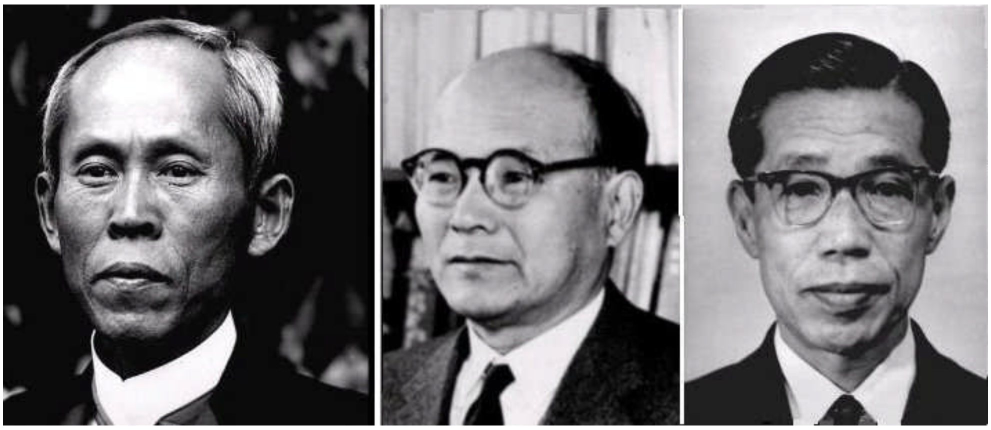

Figure 1. Pioneering leaders in the research field of Earth tides in Kyoto University. From left to right: Toshi Shida (1876-1936), Kenzo Sassa (1900-1981) and Eiichi Nishimura (1907-1964).

2. First observation of Earth tides in Japan and proposal of "Shida Number"

Figures 2 and 3 show the general view of the observation room of the Kamigamo Geophysical Observatory and the arrangement of instruments in the observation room, respectively (Shida, 1912). The observation room stands on a small hill of Paleozoic rock in the northern part of Kyoto city. The natural rock of Paleozoic foundation was excavated to the depth of 3.5m over an area of 6m x 10m, and the floor was covered with concrete about 30cm thick except for the granite stone pillars on which instruments were installed.

As shown in the right side of Figure 3, the observation room was divided into two parts by two stone walls across stairs. In the eastern room (right upper part of Figure 3), the vertical seismograph of the Wiechert's inverted pendulum type with 1300kg-weight was installed at the NE corner, and his horizontal seismograph with 1000kg-weight was installed at the SE corner. The western room (right lower part of Figure 3) was used for the tiltmeter observation.

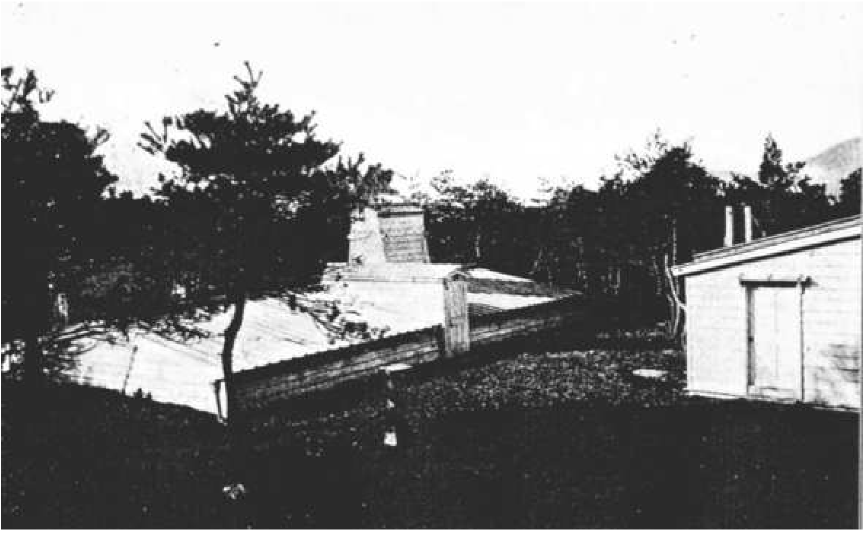

Figure 2. General view of the Kamigamo Observatory in 1910 (After Shida,1912).

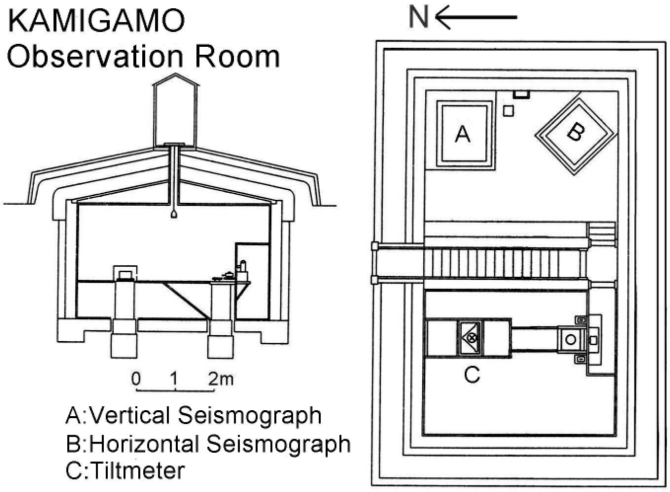

Figure 3. Construction of the observation room and arrangement of instruments (After Shida,1912)
(Left: side view (from west side), Right: plan view)

Using the tiltmeters of E von Rebeur-Paschwitz type in Kamigamo, Shida carried out first observation of tidal tilts in Japan. Based on tiltmetric data obtained from January 1910 to April 1911, he estimated the diminishing factor (***D***). At the first time, he was disappointed because ***D*** value obtained at the Kamigamo Geophysical Observatory was greatly different from those obtained at stations in Europe. This is due to the difference of loading effects of ocean tides. Japan is surrounded by ocean and seas, and the loading effect in Japan is extremely large compared with those in European continent. He considered this weak point positive and succeeded to estimate the rigidity of Earth’s crust from tidal loading effect at Kamigamo. After eliminating the tidal loading effect, he obtained the value of $\boldsymbol{D}$ =0.79, which is similar to those obtained in Europe, though it was still larger than the expected value.

The name of Shida is famous as the Shida Number in tidal studies. As well known, the tidal response on the Earth's surface can be represented by three dimensionless parameters in spherical elasticity. They are Love numbers $\boldsymbol{h}$ and $\boldsymbol{k}$, and Shida Number $\boldsymbol{l}$. Love (1909) showed that the disturbing potential can be represented with sufficient approximation by a spherical harmonic function of the second order, and all the deformations produced in the Earth by this potential may be represented by the same harmonic function multiplied by a numerical coefficient suitable for each aspect of the phenomenon. As the numerical coefficients, Love introduced two parameters ($\boldsymbol{h}$ and $\boldsymbol{k}$). Shida (1912) pointed out that a third number parameter ($\boldsymbol{l}$) should be necessary to obtain a complete representation of the phenomenon.

The tiltmetric observation started by Shida was succeeded by Eiichi Nishimura. He installed the fused silica tiltmeters of horizontal pendulum type at several stations in Japan and investigated local effects on tidal tilt observations over many years. In 1941, Nishimura carried out tiltmetric observation at Barim (N48° 18’, E122°10’, h=790m) in the China continent in order to obtain an accurate $\boldsymbol{D}$ value (Nishimura, 1950). The station is distant more than 1000km from the nearest sea. The observation room was in an old copper mine surrounded by hornfels. Using data obtained from tiltmeters installed at the 70m from entrance of the tunnel (44m in depth from the surface), Nishimura estimated the following $\boldsymbol{D}$ value;

$$\boldsymbol{D} = 0.661 \pm 0.024$$

This value was almost corresponding to a theoretically expected value. It took about 30 years to obtaining this reasonable value after Shida had started the tidal tilt observation at Kamigamo in 1910.

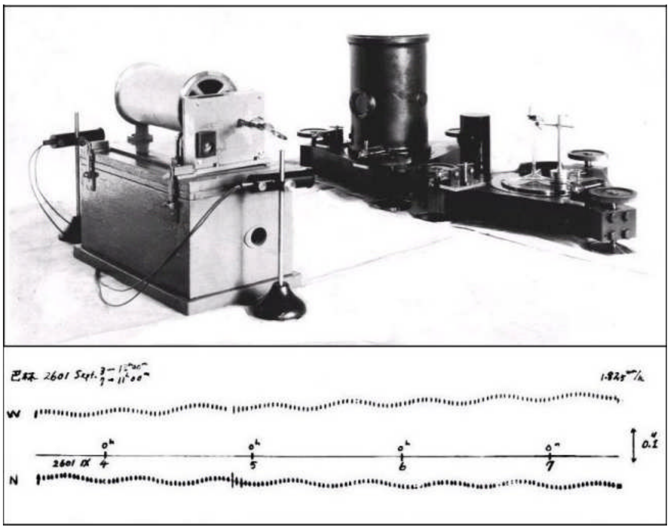

Figure 4. Fused silica tiltmeters of horizontal pendulum type used at the Barim station (upper) and example of tiltmetric records (lower).

3. Early proposal of observing free oscillations of the Earth

Existence of free oscillations of the “elastic” Earth had been theoretically predicted since the latter half of 19th century. However, observational verification of this had to wait until 1960 when the great Chilean earthquake of Mw=9.5 occurred off the east coast of Chili.

In order to observe the free oscillations of the Earth, it is inevitable to develop the instruments having high sensitivity in the range of periods from several minutes to 1 hour. Ordinary seismographs are not sensitive to such long periods. Before the Chilean earthquake of May 22, 1960, following effective instruments had been developed: (i) Benioff extensometers (Benioff, 1935, 1959), (ii) Press-Ewing long-period seismometers (Press, *et al*., 1958) and (iii) LaCoste and Romberg gravimeters (Clarkson and LaCoste, 1957). Using these instruments, convincing evidence of Earth's free oscillations was established in 1960s.

Prior to this, Toshi Shida considered to observe free oscillations of the Earth and designed a new observation system in 1920s (Shida, 1925). The system was a modified Galitzin's seismometer consisting of an extremely over-damped 5-minutes horizontal pendulum and a double coil galvanometer of low resistance, the needle of which was a Boys quartz fiber torsion balance with a 20-minutes period. Unfortunately, Shida and his group could not complete this observation system due to mainly financial difficulties.

After the World War II, Maurice Ewing and Frank Press of Columbia University in U.S.A. developed the long-period seismograph in the latter half of the 1940's and succeeded to observed free oscillations of the Earth (Benioff *et al*., 1961). Their device so called the Press-Ewing seismograph was based on the almost same principle as that proposed by Shida in the first half of 1920s. The Press-Ewing seismograph consisted of a 30-second pendulum and a 90-second galvanometer.

During the Chilean earthquake on May 22, 1960, Ichiro Nakagawa observed free oscillations of the Earth at Kyoto by employing two Askania Gs-11 gravimeters of #105 and #111 (Nakagawa, 1962b). He improved the Pertzev's tidal filter (Nakagawa, 1961, 1962a).

4. First observation of tidal strains of the Earth

Shida also considered a linear extensometer to observe tidal strains and free oscillations of the Earth as shown in Figure 5 (Takemoto, 2007). This idea was latter improved by Kenzo Sassa and Izuo Ozawa, and was efficiently employed to observe the tidal strains of the Earth.

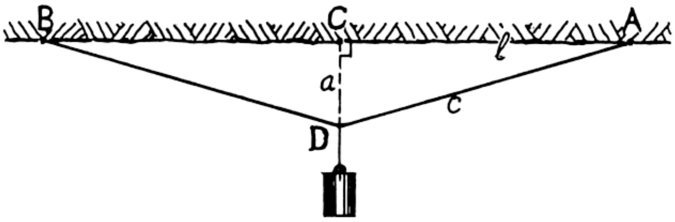

Figure 5. Schematic representation of a wire extensometer designed by T. Shida.

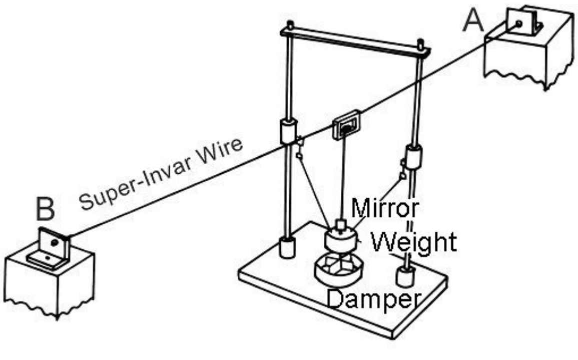

Figure 6. Schematic representation of a wire extensometer of the Sassa type.

Kenzo Sassa developed an extensometer using a flexible wire as a length standard to measure the relative displacement between two piers fixed into the bedrock (Figure 6). In this device, a super-invar wire 1.6mm in diameter is fixed at both ends to concrete piers standing opposite each other at a distance of 20m. A weight of 350g is suspended from its center with an elinvar wire. Changes in the distance between the two piers cause an up-and-down movement of the weight. This motion is transformed into rotation of the weight through a bifilar suspension consisting of two super-invar wires 0.03mm in diameter. Photographic recording is done with an optical lever using a small mirror mounted on the weight. Using this mechanical-optical extensometer, Sassa first succeeded to observe the tidal strain changes of the Earth in Ikuno and Makimine stations in 1943. Accordingly, the experimental investigation of the strain-tensor components of Earth tides started. Sassa and Ozawa installed the same type extensometer in Osakayama Observatory in 1947 and continued long-term tidal strain measurements. They first reported these result of tidal strain measurements at the IAG General Assembly held in Brussels in1951 (Sassa *et al.*(1952) and Ozawa (1952)).

Izuo Ozawa devised many kinds of mechanical extensometers with photographic recording systems. Figure 7 shows a high-sensitive super-invar bar extensometer with magnifier of Zollner suspension type (Ozawa, 1961). He continued precise tidal strain measurements in Osakayama, Kishu and Suhara in Japan over many years. In 1971, a super-invar bar extensometer of Ozawa type was installed in the Walferdange laboratory in Luxembourg (Ozawa *et al.*, 1973). This instrument was used to estimate the ***l*/*h*** ratio (Melchior and Ducarme, 1976).

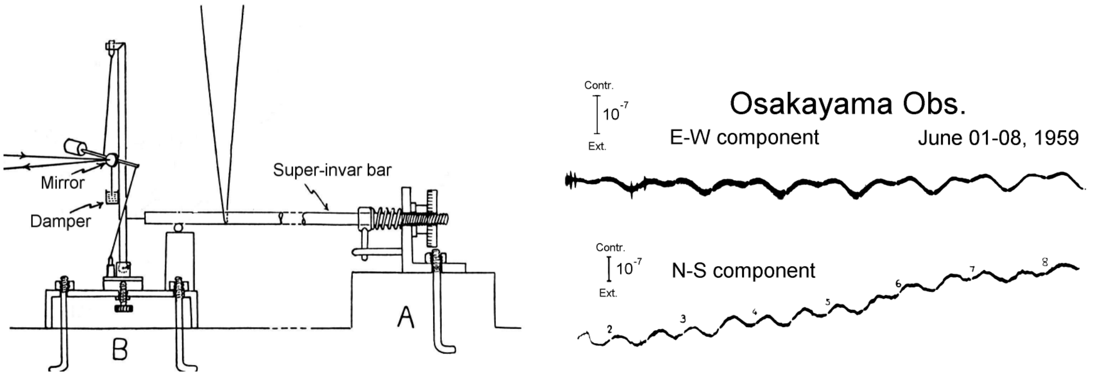

Figure 7. Schematic representation of a super-invar bar extensometer with magnifier of Zollner suspension type designed by I. Ozawa (left) and example of tidal strain records (right).

A continuous monitoring of crustal movements by tiltmeters and strainmeters has been considered to be an effective measure of earthquake precursors particularly on short time scales of hours to days. An early contribution in such an approach was due to Sassa and Nishimura (1951). They first reported anomalous changes of ground-strains and tilts observed before occurrences of some destructive earthquakes at observatories located near the source regions. Among them, a typical example was a precursory tilting motion associated with the 1943 Tottori earthquake of M=7.2. During 6 hours prior to the occurrence of the earthquake, an anomalous tilting motion with the order of 0.1” (0.5 μ rad.) was observed with a tiltmeter of the horizontal pendulum type installed at 800m under the ground surface in Ikuno mine located about 60km away from the epicenter. Although there remained some uncertainties to conclude it as a precursor, it played an important role in Japan for promoting the national project for earthquake prediction which started in 1965. Since then, many observatories and supplementary stations for monitoring crustal movements have been established in Japan. More than 100 stations are operating under the national project for earthquake prediction. Despite such a dense arrangement of stations equipped with improved instruments, we have not been able to detect “reliable precursors” immediately before the occurrence of earthquakes.

In the early morning of January 17, 1995 (in Japanese Standard Time), a destructive earthquake of M_w=6.9 occurred near the Kobe City. The death toll from the earthquake reached more than 6,300 due to collapse of buildings and bridges, fires and diseases induced by the earthquake. We have carried on continuous observation of crustal strains with a laser strainmeter at the Rokko-Takao station in Kobe since 1989 (Takemoto *et al.*, 1998b, 2003). The distance from the station to the epicenter is about 20 km and the station is located almost above the fault plane. Based on the laser strainmeter data, we searched for anomalous strain changes before and after the earthquake mainly focusing to the period of one week before the earthquake, but could not find out distinct evidences. It will be difficult to find out reliable precursors immediately before the occurrence of earthquakes from continuous monitoring of crustal movements by tiltmeters and strainmeters.

5. Tidal observation with superconducting gravimeters

Two superconducting gravimeters (Model TT-70: #008 and #009) were introduced into Kyoto University in 1988. Since then, continuous observation of gravity changes by employing two superconducting gravimeters had been carried on in Kyoto until December 1997 (Takemoto *et al*., 1998c). During the period, we investigated instrumental noise (Higashi, 1996), atmospheric effect (Mukai *et al*., 1995a, 1995b) and the effect of ambient temperature change on gravity measurements (Mukai *et al*., 1995c). In December, 1997, one (#008) of the two superconducting gravimeters in Kyoto was shifted to Bandung in Indonesia under the cooperation between the Graduate School of Science, Kyoto University and the Volcanological Survey of Indonesia (now, Directorate of Volcanology and Geological Hazard Mitigation), Ministry of Mines and Energy of the Republic of Indonesia (Takemoto *et al*., 1998d). We installed the SG #008 in the underground observation room where Baron Melchior and his colleagues carried out gravity observation in 1987 by employing the LaCoste & Romberg gravimeter:L336 (Melchior *et al*., 1995). The Bandung station (BA) was located at 06°53'47"S, 107°37'54"E, and 713m above the sea level. The SG #008 was installed on the concrete base of 1.2m x 1.2m which was constructed 1 m below the floor on the under layer of very thick volcanic deposit of sand and other volcanic products. The distance from the nearest sea is about 50km. The Bandung station was the only one station existing near the equator in the GGP network and provided important gravity data from December, 1997. After eliminating tidal changes and long-term drift from the SG data in Bandung, we found that the gravity residual is correlated with ambient groundwater changes. The rise of 1m of the groundwater level increase the gravity residual of 4.2-4.4μGal with a time lag of about 13-20 days (Takemoto *et al*., 2002).

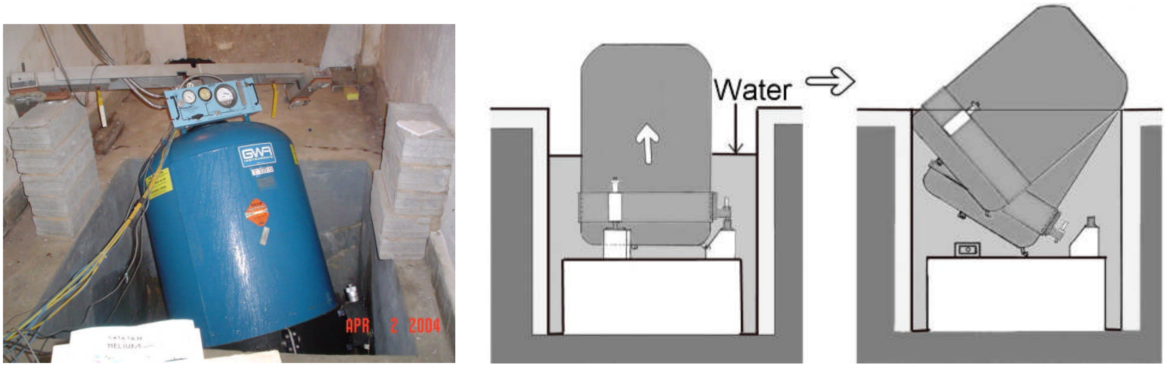

Figure 8. Accident of SG#008 due to heavy rainfall of March 27, 2004.

On March 27, 2004, the SG in Bandung suddenly broke down due to the natural disaster of flood after heavy rainfall of 140mm/hour. The SG floated due to the buoyancy of the flowing water (Figure 8). We thus continued the effort to repair the instrument but it was unfortunately impossible. We were obliged to close the SG station in Bandung in 2004.

Then we searched for possibility to restart SG observation in Indonesia because it was the only SG station that existed near the equator. In consideration of various conditions, we decided to shift another superconducting gravimeter of CT type, which was used in Aso volcano from 1996, to the National Coordination Agency for Surveys and Mapping in Indonesia (BAKOSURTANAL) in Cibinong, Indonesia. In 2008, Yoichi Fukuda and Toshihiro Higashi of Kyoto University installed the SG in the newly constructed gravity measurement room in the building belonging to BAKOSURTANAL (6°29'28"S, 106.50'56"E, h=138m) and we can restart the SG observation in Indonesia.

6. Application of laser interferometric devices to precise observation of Earth tidal deformations

In order to observe crustal deformations, various types of extensometers (strainmeters) have been developed during the last half of 20th century (e.g. Sassa type and Ozawa type extensometers). These meters are essentially using solid materials of low thermal conductivity as a "length standard" for measuring a relative displacement between two piers fixed into the bedrock (see Figure 6). Super-Invar wires (rods) or fused quartz tubes are commonly used as the length standard.

On the other hand, the appearance of the laser at the beginnings of 1960s opened up new possibilities in crustal strain measurements. Using the coherent and stable laser source, interferometric strainmeters have been developed (e.g. Berger and Lovberg (1969). The laser interferometric strainmeter enables the small strain to be measured quantitatively in terms of the wavelength of the laser light without using a length standard of any solid materials.

In Kyoto University, the laser interferometric device was used for calibrating conventional rod type extensometers at first. Then, laser strainmeters of the Michelson type were installed at the Amagase Crustal Movement Observatory, Kyoto in 1977 (Takemoto, 1979). The same type laser strainmeter was installed at the Rokko-Takao station in 1988 (Takemoto *et al*., 1998b). As mentioned before, precursory strain changes could not be detected before the earthquake of January 17, 1995, but we could estimate the fluid core resonance using the data of the laser strainmeter installed at the Rokko-Takao tunnel in Kobe (Mukai *et al*., 2004).

On the other hand, a new technique based on holographic interferometry was developed for measuring crustal deformations (Takemoto, 1986, 1990). The holographic recording system, consisting of an He-Ne gas laser and associated optical elements, was first installed in a tunnel at the Amagase Crustal Movement Observatory in 1984. Tunnel deformations caused by tidal and tectonic forces were precisely determined using 'real-time' technique of holographic interferometry. In this procedure, a hologram of the tunnel wall within a section 1-2 m in diameter was directly recorded on a photographic plate and then the plate was carefully reset in the same position at which the hologram had been taken. When the reconstructed image of the hologram was superimposed on the current image of the tunnel wall, many interferometric fringes could be seen through the hologram. The fringe displacement, formed by the deformation of the tunnel, was continuously recorded on a video cassette tape using a video camera and a time-lapse video recorder. The change in the fringe patterns was analyzed using the image-processing system. Tidal deformations obtained from the holographic method were consistent with the strain changes observed with laser strainmeters in the same tunnel. These observational results substantiated the tunnel deformation estimated by the finite-element calculations.

The holographic system, however, has a margin for improvement in use of the long-term strain measurements because the fringe pattern observed through the photographic plate gradually blurs over the course of the time. Thus, a clear record of holographic interferometry cannot be obtained even over a week. Therefore, we attempted to use the Electronic Speckle Pattern Interferometry (ESPI) technique, in which the interference fringe pattern can be produced without using photographic processing but instead using electronic processing (Takemoto *et al*., 1998a). This attempt, however, did not succeed due to technical difficulty in detecting slowly moving crustal deformation.

In 2002, we installed a 100m laser strainmeter system in a deep tunnel about 1,000m below the ground surface at the Kamioka mine, Gifu, Japan (Figure 9). As shown in Figure 10, the system consists of three types of independent interferometers: (1) an EW linear strainmeter of the Michelson type with unequal arms, (2) an NS-EW differential strainmeter of the Michelson type with equal arms and (3) a NS absolute strainmeter of the Fabry-Perot type. These are configured in L-shaped vacuum pipes, each of which has a length of 100 m. (1) and (2) are highly sensitive (order of 10^{-13} strain) and have wide dynamical range (10^{-13} -10^{-6}). (3) is a new device for absolute-length measurements of a long-baseline (100 m) Fabry-Perot cavity with a precision of the order of 10^{-9} by the use of phase-modulated light (Takemoto *et al*., 2004, 2006). The laser source of strainmeters (1) and (2) is a frequency-doubled YAG laser with a wavelength of 532 nm. The laser frequency is locked onto an iodine absorption line and a stability of 2×10^{-13} is attained. (3) uses another laser source of the same type as used for (1) and (2).The light paths of the laser strainmeter system are enclosed in SUS304 stainless steel pipes. The inside pressure is kept to be 10^{-4} Pa. Consequently, quantitative measurement of crustal strains of the order of 10^{-13} can be attained by employing the laser strainmeter system of (1) and (2) at Kamioka. This resolving power corresponds to that of a superconducting gravimeter. The noise level recorded at Kamioka is lowest in the range of 10^{-3} to 10^{-1} Hz among laser strainmeters now operating in the world.

Figure 9. View of the 100m laser strainmeter system in the Kamioka mine, Gifu, Japan.

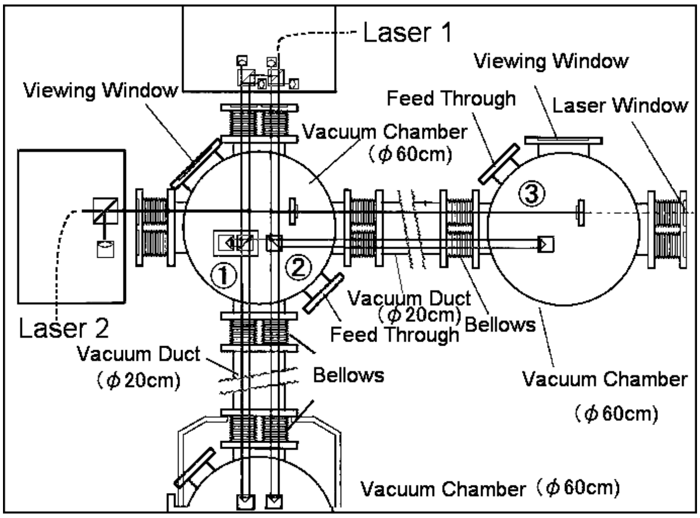

Figure 10. Schematic view of the laser strainmeter system at Kamioka consists of three types of laser interferometers. (1) A simple Michelson type interferometer of unequal arms installed in the EW direction. (2) An equal arm laser interferometer detecting difference of linear strains in the NS and EW directions. The third type (3) is a new device for absolute-length measurements of a long-baseline (100 m) Fabry–Perot cavity with a precision of the order of 10^{-9} by the use of phase-modulated light.

Figure 11 shows the strain seismograms obtained from the Kamioka laser strainmeters ((1) and (2)) at the time of the great Sumatra-Andaman earthquake of December 26, 2004. In this figure, the left side is a high-passed and the right side a low-passed (1000sec) record, respectively. We can recognize that the maximum amplitude of seismic wave is in the order of 1μ strain (left side) and coseismic strain step is in the order of 1 nano strain at the epicentral distance of 5600km.

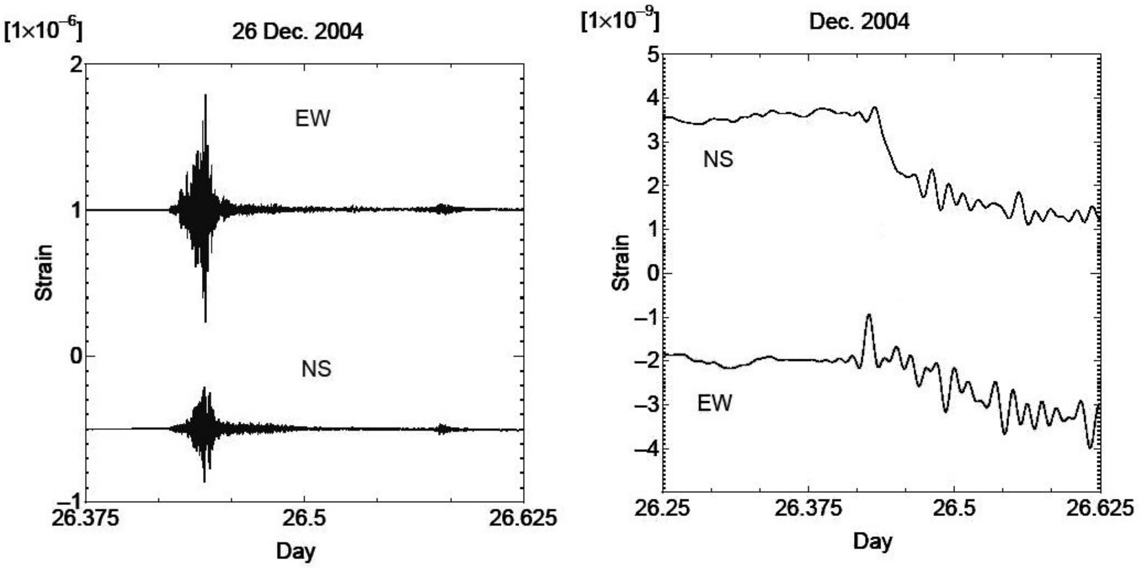

Figure 11. Strain seismograms of the great Sumatra-Andaman earthquake of December 26, 2004 observed at Kamioka.

In 2004, the Superconducting Gravimeter (T016) which had been used in the Showa station in Antarctica was installed in the same tunnel in Kamioka mine. Figure 12 shows the comparison of the tidal strain changes in NS and EW directions obtained from laser strainmeters and the gravity changes obtained from the superconducting gravimeter. Figure 13 shows the comparison of spectra obtained from laser strainmeters and the superconducting gravimeter after the earthquake (M=7.4) of Jan. 06, 2006 occurred at South Sandwich Islands. We can expect that combined use of laser strainmeters and superconducting gravimeter nearby installed will be an effective tool to investigate keen geophysical problems such as to separate “spheroidal modes” and “torsional modes of Earth’s free oscillations and to search for Slichter triplet.

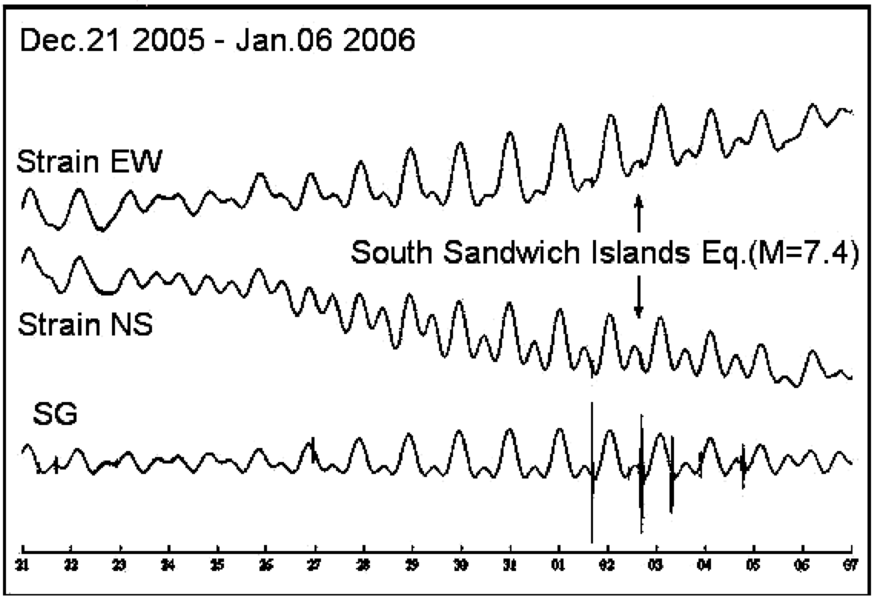

Figure 12. Comparison of tidal changes observed with laser strainmeters (NS and EW) and superconducting gravimeter installed in the same tunnel in Kamioka.

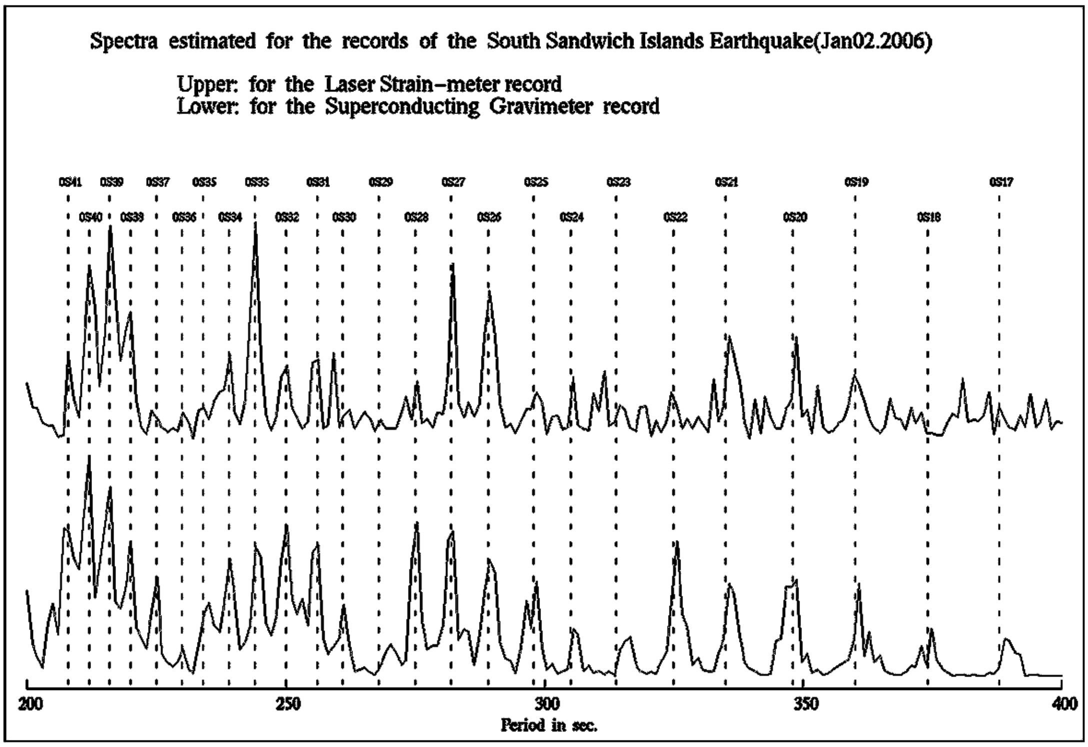

Figure 13. Comparison of spectra obtained from laser strainmeters and the superconducting gravimeter at the earthquake (M=7.4) of Jan. 06, 2006 occurred at South Sandwich Islands.

Concluding remarks

In this paper, some of centenary researches on Earth tides carried out in Kyoto University during the period of 1909 - 2008 are presented. Early remarkable achievements are the proposal of "Shida Number" and the first observation of tidal strains by employing the Sassa type extensometers. Since then, we have continued studies on Earth tides based on observational data. Now, laser strainmeters and superconducting gravimeters are efficient tools to investigate Earth tides. Combined use of laser strainmeters and superconducting gravimeter will produce many new findings in geophysics. In the near future, the data obtained from these high-sensitive terrestrial instruments should be compared with the geodetic satellite data to improve geodetic and geophysical investigations.

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