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Geodesy in Japan: legends and highlights

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Abstract

Here, I review modern history of geodesy and geodynamics in Japan, highlighting a few episodes during the last two centuries. The review starts with the first measurement of the meridional arc length in Japan by Tadataka Ino (1745–1818) early in the nineteenth century, done as a part of the mapping campaign of the country. Next, I mention the first international recognition of Japanese geodesy realized by the discovery of a new term in the Earth's polar motion by Hisashi Kimura (1870–1943) at the beginning of the twentieth century. Finally, I review an unsuccessful campaign to detect present-day continental drift in Japan shortly before World War II, conducted by the Geodetic Committee of Japan being inspired by the hypothesis of active opening of the Sea of Japan by Torahiko Terada (1878–1935).

Keywords: Geodesy, History, Japan, Arc length, Polar motion, Continental drift, GNSS

Dawn of geodesy in Japan: first meridional arc length measurement

Figure 1 summarizes the geodetic episodes that I introduce in this article, and first of all, I focus on the first geodesist in Japan. The last samurai government of Japan (the Edo Bakufu in Japanese) closed the country in 1639, prohibiting most interactions with foreign countries, and the stable feudal regime lasted until the Meiji Restoration in 1868. The government had an astronomical bureau (the Tenmon-kata) responsible for compilation of calendars. People in the bureau acquired necessary expertise in astronomy from literature published in seventeenth–eighteenth centuries in China based on knowledge brought by Jesuit missionaries from Europe.

Tadataka Ino (1745–1818) retired from his family business as a merchant in Sawara (currently in the Chiba Prefecture, Kanto) at the age of 50. He moved to Edo (Tokyo) and started to study astronomy and geodetic surveying under Yoshitoki Takahashi (1764–1804), the leading astronomer in the bureau nearly 20 years younger than T. Ino. They were interested in determining the meridional arc length of the Earth because they needed accurate dimension of the Earth to compile a calendar predicting precise dates and times of lunar/solar eclipses. Although

the arc lengths were available in Chinese books, Ino and Takahashi recognized their inconsistency between literature and uncertainty in the conversion to the units of length formerly used in Japan. An accurate value of the arc length was also necessary for astronomical calibration of latitudes in making precise maps.

Takahashi and Ino submitted a proposal to perform a geodetic survey from Edo to the northernmost part of the main island (Honshu) of Japan, and Ezo (Hokkaido). The government approved their proposal, considering its importance from the viewpoint of foreign affairs. At that time, occasional interactions with Russians occurred in and around Ezo, and the government recognized it an urgent need to have precise geographic knowledge of the country. Such a social situation matched the personal interest of people in the astronomical bureau.

Ino and his team conducted the first survey in 1800 and obtained a preliminary quantity for the meridian arc length by comparing the astronomical latitude differences and the distances measured by ground surveying. Next year, his mapping mission was upgraded to an official national project. His team finished the first comprehensive surveys of NE Japan and submitted the maps to the government in 1804. By compiling the data observed until then, he determined the one-degree meridional arc length in Japan as 110.75 km (originally published in a Japanese unit of length). This is only ~0.2% shorter than the modern value 110.95 km (Fig. 2).

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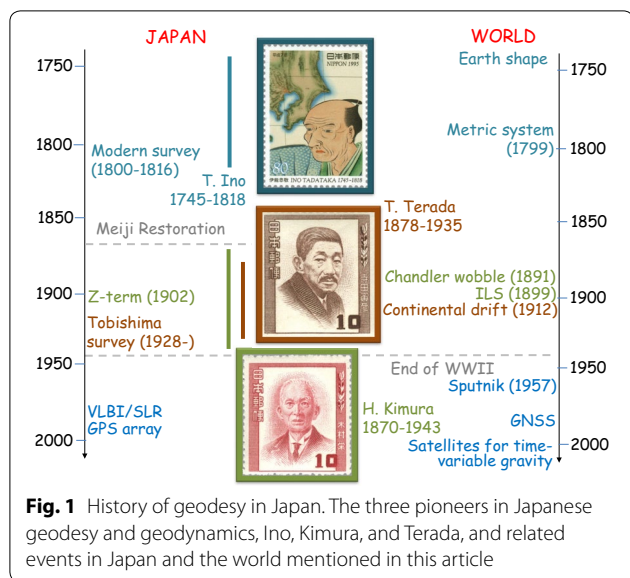


Fig. 1 History of geodesy in Japan. The three pioneers in Japanese geodesy and geodynamics, Ino, Kimura, and Terada, and related events in Japan and the world mentioned in this article

Neither Ino nor Takahashi was aware of the ellipticity of the Earth when they started the survey, i.e., they assumed the spherical Earth. In the closed Japan, the government only allowed direct contacts with Dutch traders through a tiny window at Nagasaki, Kyushu. For example, the Dutch version of the French book *Astronomie* (ver.2) (Lalande 1771) was imported to Japan as *Astronomia of Sterrekunde*, published in 1773. Y. Takahashi obtained the book in 1803 and immediately understood the importance of its contents. Over subsequent years, his group translated it into Japanese and shared the latest astronomical and geodetic knowledge in Europe (including the shape of the Earth) within their community. It is important to note that Takahashi and Ino indeed measured the arc length in Japan but not for studying the

Earth's elliptical shape with the latitude dependence of the arc length.

Takahashi passed away in 1804, but Ino and his group continued geodetic surveys, also in SW Japan, subsequent to those in NE Japan. The prime meridian was defined at Kyoto, the ancient capital of the country. Ino conducted astronomical measurements to calibrate latitudes in mapping NE Japan. However, SW Japan elongates in east–west, and he needed to calibrate the ground geodetic survey results by performing astronomical longitude measurements. An accurate chronometer was necessary for precise longitude measurements, but it was not available then in Japan. Instead of it, Ino and his group tried to determine the longitude differences in SW Japan in 1805 by comparing the occultation times of the Galilean satellites of Jupiter at remote points. In doing that, they employed the procedure explained in Lalande (1771), brought to Japan in a Dutch version only 2 years before. They continued observations of these Jovian satellites for 6 years but were not able to obtain enough data to calibrate longitudes in SW Japan (Kazu 2005).

They continued the survey in SW Japan, and the final version of the whole map of Japan, known as *Dai-nihon-enkai-yochi-zenzu*, was submitted to the government in 1821, 3 years after Ino passed away. Japan resumed foreign diplomacy shortly before the Meiji Restoration in 1868, the turning epoch to a modern country, and the maps made by Ino served as the basis of a series of national maps that the new government started to issue in 1877. The quality and technical aspects of these maps are discussed in detail in Oda (1974). Ino is also known in Japan as a hero who lived two lives, as a merchant and a geodesist, proving that 50-year old is not too late to become a geodesist.

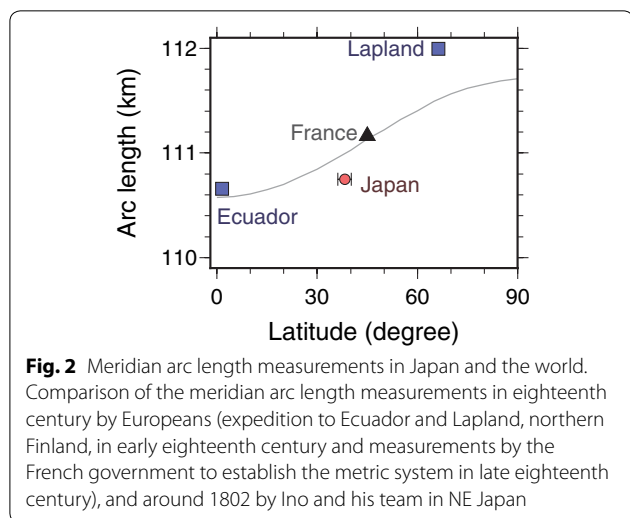


Fig. 2 Meridian arc length measurements in Japan and the world. Comparison of the meridian arc length measurements in eighteenth century by Europeans (expedition to Ecuador and Lapland, northern Finland, in early eighteenth century and measurements by the French government to establish the metric system in late eighteenth century), and around 1802 by Ino and his team in NE Japan

First international recognition of Japanese geodesy: Z-term of polar motion

It is common nowadays that Japanese earth scientists publish papers in English journals, some of which may become internationally recognized and frequently cited. A paper written by Hisashi Kimura (1870–1943) in 1902 would be one of the earliest examples. It was written in response to unduly low rating to Japanese data in an international observing campaign of latitude variations.

In the last decade of the nineteenth century, Friedrich Küstner (1856–1936) in Germany and Seth Chandler (1846–1913) in America independently discovered the Earth's polar motion, which was theoretically predicted by Leonhard Euler (1707–1783) back in 1756. First, Küstner reported a quasi-annual latitude variation of 0.2 arcseconds in 1888. The International Association of Geodesy (IAG) coordinated an observing session in 1891 and confirmed that this variation was a polar

motion from the phase reversal of the latitude variations observed in Hawaii and Germany. Chandler (1891) found a new period of ~ 14 months of latitude variation in addition to the annual term. We now know that such “Chandler wobble” and annual polar motion can be driven by mass redistribution within the Earth.

This new period was significantly longer than 305 days predicted by Euler based on the ellipticity of the rigid Earth. The difference was soon explained by Simon Newcomb (1835–1909) (Newcomb 1891) by considering the elastic deformation of the Earth by centrifugal force around the moving pole. Considering the scientific importance of the Earth’s polar motion, IAG launched the first global-scale international geodetic campaign in 1899 as the International Latitude Service (ILS). They planned to deploy telescopes (zenith telescopes dedicated to measure latitude variations) along the latitude $39^\circ 08' \text{ N}$ to reduce systematic errors by adopting the same set of stars for latitude observations.

The new government established after the 1868 Meiji Restoration vigorously imported up-to-date science and technology to catch up with Europe and America. The Geodetic Committee of Japan welcomed it when ILS selected Mizusawa, NE Japan, as a latitude observatory in Far East. Despite the offer by ILS to send a Western expert to Japan, they appointed H. Kimura, a young astronomer from the Imperial University of Tokyo, as the director of the observatory. The latitude variation $\Delta\theta$ is expressed as a function of longitude ϕ and the X and Y components of the polar motion toward longitudes 0° and 90° , respectively, i.e.,

$$\Delta\theta = X \cos \phi + Y \sin \phi. \quad (1)$$

After analyzing the data since 1899 in 1901, the ILS central bureau at Potsdam, Germany, found that the Japanese data show larger post-fit residuals derived with Eq. (1) than those of the other observatories. They sent a letter to the chair of the Geodetic Committee of Japan suggesting the poor performance of the Mizusawa observatory. They also announced to reduce the weight of the Japanese data in estimating X and Y . H. Kimura immediately scrutinized the zenith telescope and observing procedures but did not find any flaw. Being confident in the accuracy of the Japanese data, he doubted the validity of Eq. (1) itself. He found that a new longitude-independent annually varying term, the Z-term in Eq. (2), could largely reduce the residual (Fig. 3),

$$\Delta\theta = X \cos \phi + Y \sin \phi + Z. \quad (2)$$

He published his idea in European (Kimura 1902a) and American (Kimura 1902b) journals (this was not a

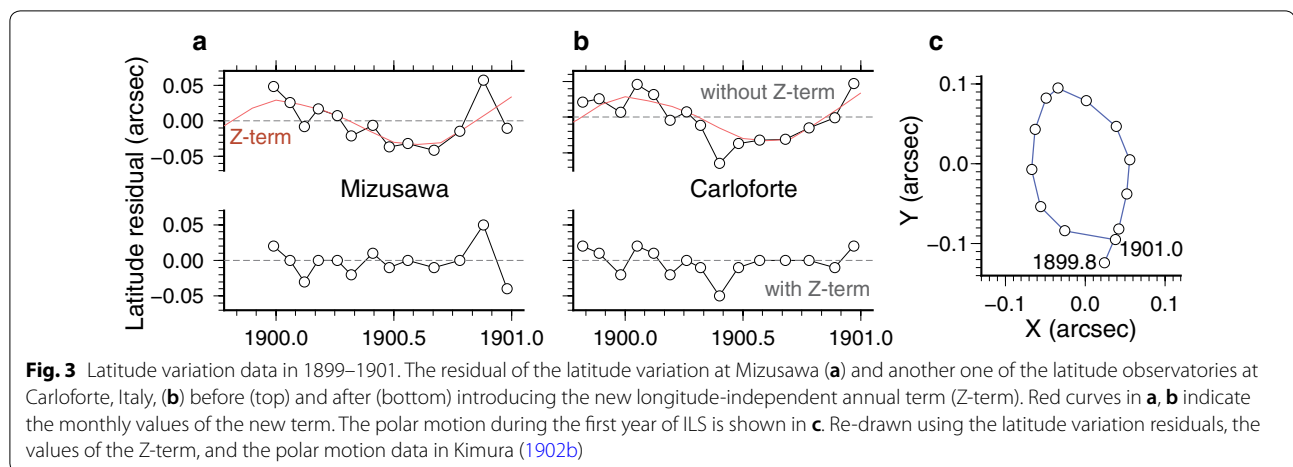
misconduct then). The ILS central bureau admitted and accepted the new term (Z-term).

The Japanese observatory (International Latitude Observatory of Mizusawa, ILOM) served as the ILS central bureau during 1922–1934 with H. Kimura as the director. This dramatic “turnover” of offence and defense was recognized as a brilliant achievement in Japan. In fact, Kimura was one of the first recipients of two newly established prestigious awards, the Imperial Prize of the Japan Academy in 1911 and the Order of Culture in 1937. The whole story can be found in a book published commemorating one century of latitude observations in Japan (National Astronomical Observatory 1999).

The Z-term apparently implies that all the observatories move northward/southward in winter/summer by $\sim 1 \text{ m}$ ($\sim 0.03 \text{ arcsec}$). Numbers of hypotheses were proposed to explain this seasonal term, e.g., north–south movement of the Earth’s center of gravity (detected by space geodesy as a phenomenon with a much smaller amplitude in 1990s, see, e.g., Dong et al. 1997), an artifact caused by atmospheric refraction, and so on. These hypotheses, however, failed to explain the observed Z-term quantitatively. It took ~ 70 years that the geophysical mechanism of the Z-term has been revealed by Yasujiro Wako (1928–2011) (Wako 1970), who noticed that the previously unmodeled behavior of the semiannual nutation can be interpreted as the Z-term.

Long-term movement of the celestial pole of the Earth has been known as the precession since the times of the Greeks and Romans. The spin axis of the Earth is oblique to the normal direction of the orbital plane of the Moon or that of the ecliptic plane of the Sun, and the luni-solar torque exerted on the elliptical Earth drives the precession. The torque changes in various periods, e.g., by the change of the angle between the tilt of the spin axis and the two tide-generating bodies. They cause short-term oscillations of the spin axis referred to as forced nutation. The polar motion causes longitude-dependent latitude variation as shown in Eq. (1), but the nutation causes uniform shift of the apparent positions of the stars for all longitudes. When ILS started, people considered that the nutation had been “known”, i.e., they implicitly assumed that it had been possible to calculate it with sufficient accuracy to isolate “unknown” polar motions. Actually, however, the nutation had not been modeled sufficiently. The semiannual nutation is the component with the second largest amplitude, and the Z-term was mainly because of the unmodeled behavior of this component particularly due to the resonance with the free core nutation (FCN), a phenomenon occurring for a rotating body with a fluid core like the Earth (Fig. 4).

FCN is driven by inertial coupling between the core and the mantle at their boundary and has a period of



~460 sidereal days (e.g., Wahr 1981). Excitation of FCN has not been confirmed clearly by geodetic observations (cf. Shirai et al. 2005). Nevertheless, FCN significantly influences phases and amplitudes of forced nutation components through the resonance with FCN (fluid core resonance, FCR), especially the annual and semiannual components.

The Z-term comes from the deviation of actual semiannual nutation from the model without assuming a fluid core. Figure 5 illustrates how the unmodeled semiannual nutation makes the Z-term signature, i.e., a longitude-independent seasonally varying term. One important factor was that the observatories switched the set of target stars every month to realize midnight observations throughout a year. A longer duration of observation makes it easier to discern nutation and polar motion, and the finding by Wako (1970) owes much to the extension of the observing period from 4 to 6 h realized in 1955. By the way, FCR influences the annual term more than the semiannual term. However, the amplitude of the annual term is small, and it does not cause signatures like the Z-term.

The Earth model has been improved between the times of Kimura (1902a, b) and Wako (1970). Molodensky (1961) quantified how FCR influence forced nutation terms. The theory was sophisticated by Sasao et al. (1980), who also formulated the FCN dissipation by electromagnetic and frictional core–mantle coupling. In 1980s, optical telescopes were replaced by very long baseline interferometry (VLBI), and accurate measurements of the Earth’s rotation enabled Herring et al. (1986) to find a few milliarcseconds of the deviation in the annual and semiannual nutation from the standard model incorporating FCR. Gwinn et al. (1986) interpreted this “new Z-term” reflects

the difference of the core–mantle boundary ellipticity from the hydrostatic equilibrium.

First geodetic campaign in Japan to aim at detecting possible continental drift

The most popular topic in Japanese geodesy nowadays is crustal movements. In fact, nearly half of the papers presented in recent fall meetings of the Geodetic Society of Japan discuss crustal deformation. Here, I introduce one of the earliest of such studies, an ambitious geodetic campaign conducted in 1920s–1930s to detect the movement of a tiny island, Tobishima, in the Sea of Japan relative to Honshu.

Torahiko Terada (1878–1935), a professor of physics (also a member of the Earthquake Research Institute) in the University of Tokyo, imagined that the Islands of Japan came apart from the Eurasian continent and have been drifting away (Terada 1927) (Fig. 6), being inspired by the continental drift hypothesis by Alfred Wegener (1880–1930). Terada thought it an ongoing process, and that the small islands off the coast of the Sea of Japan, including Tobishima, are moving away from the mainland fast enough to be detected in a few years by astronomical positioning.

Astronomical latitudes were measured using optical zenith telescopes similar to those used in measuring the Earth’s polar motion. Astronomical longitudes were determined by measuring transit times of stars, whose accuracy depended on the clock synchronization errors. Their standard accuracy was 5–10 m (~0.4 arcseconds in longitude and ~0.2 arcsecond in latitude). We now know that this accuracy is insufficient for detecting secular crustal movements, usually slower than 10 cm/year.

In the fourth edition of “The Origin of Continents and Oceans,” Wegener (1929) wrote that Greenland is moving 36 m/year westward relative to Europe. This is based on

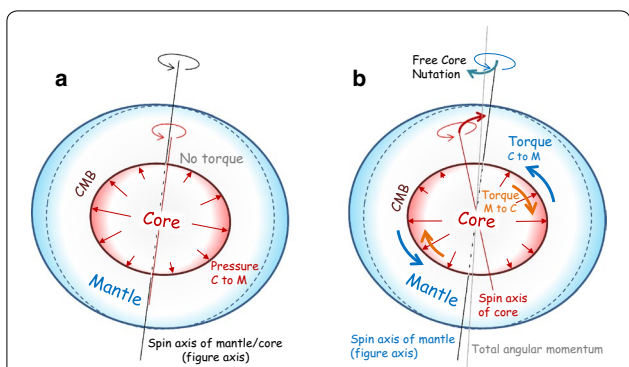


Fig. 4 Inertial core–mantle coupling and excitation of free core nutation (FCN). Pressure at the core–mantle boundary (CMB) (red arrows) does not exert a torque if the rotation axis of the mantle and the core are coincident (a). Deviation from this state let the pressure at CMB make opposite torques to the mantle (blue arrows) and to the core (orange arrows) (b). This causes FCN, i.e., rotational movements of the spin axes of the mantle and the core relative to stars in the opposite directions

the 1922–1927 astronomical longitude measurement in Greenland conducted using the radio link for clock synchronization, which enabled the most accurate longitude measurements at that time. We now know that such a fast velocity is unlikely, but people had little knowledge then to disprove it. Terada considered that astronomical positioning could detect continental drift within reasonable observing periods, and it is possible that he was inspired by such news about the “movement” of Greenland.

Terada’s idea moved the National Committee for Geodesy of Japan, and they conducted the first campaign in 1928 to detect the drift of Tobishima off the coast of the

Sea of Japan (Tobishima means “flying island”, see Fig. 7 for position) using astronomical latitude and longitude measurements. The second campaign took place in 1934. The comparison of the 1928 and 1934 measurements showed meters of “movements”, just like the Greenland case. However, the pattern was not suggestive of the opening of the Sea of Japan (Fig. 7a) (Miyaji 1935). Terada passed away in 1935 without seeing any positive data supporting his hypothesis.

In the second campaign in 1934, terrestrial triangulation was also done, which was repeated in 1954 by the Geographical Survey Institute (currently the Geospatial Information Authority of Japan, GSI). The comparison of the 1934 and 1954 results gave much smaller estimates of the velocity of Tobishima. Okuda et al. (1955) concluded that the triangulation did not yield any meaningful results for the movement of Tobishima. However, it is interesting to note that the triangulation result (Fig. 7b) is not much different from the modern global navigation satellite system (GNSS) measurements (Fig. 7c). This region is close to the convergent plate boundary along the eastern margin of the Sea of Japan (Fig. 7d), and east–west compressional strain prevails this region (Nakamura 1983).

A new piece of evidence for the opening of the Sea of Japan came from systematic difference of paleomagnetic declinations of Mesozoic rocks between NE Japan and SW Japan (e.g., Kawai et al. 1961). According to recent paleomagnetic studies, however, such an opening is considered to have completed 15 million years ago (e.g., Otofuji et al. 1994). This means that geodesy cannot detect the present-day opening of the Sea of Japan anyway. After all, this ambitious project to detect continental drift in Japan was not successful, but this surely was the first

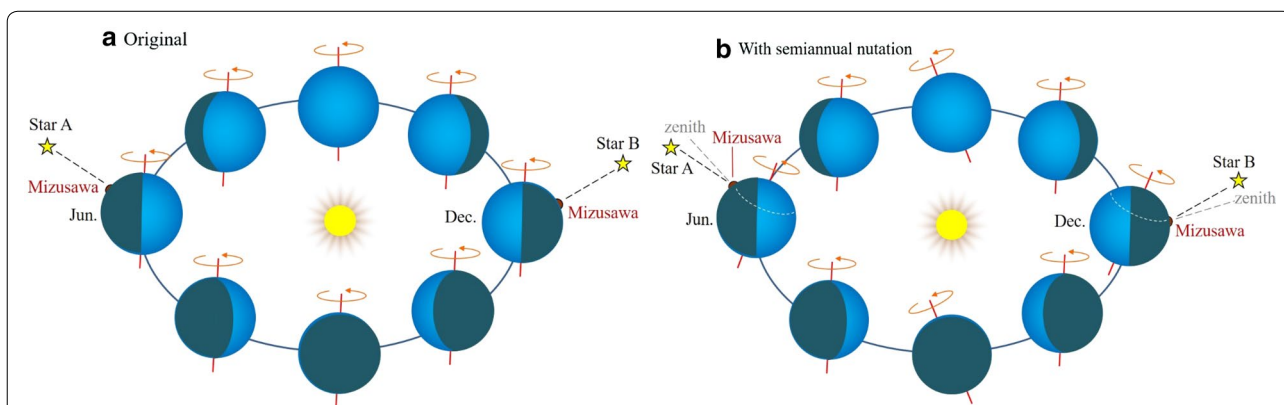


Fig. 5 Semiannual nutation and the Z-term. Here, we assume that, under the situation without nutation, Stars A and B are seen at the zenith from Mizusawa at midnight in June and December, respectively (a). With a significant amplitude of semiannual nutation (b), visible positions of Stars A and B from Mizusawa at midnight deviate in opposite directions from local zenith in June and December, causing annually varying bias (Z-term) to the astronomical latitude variation. Such biases appear as a common value for all observatories along the latitude 39° 08' N (white dotted circle). For the sake of simplicity, I excluded astrometric effects of the nutation terms other than the semiannual term, precession, and polar motion in this figure

study of the current crustal movements, the most prosperous field in Japanese geodesy 90 years later.

Post-WWII geodesy in Japan

Advance of geodesy after World War II in Japan and the world is rapid. Here, I just mention a few milestones. The launches of Sputnik 1 in 1957 by the Soviet Union and Vanguard 1 in 1958 by the United States marked the start of space-age geodesy. Yoshihide Kozai (1928–2018) formulated how the orbital elements of satellites change in time by spherically asymmetric mass distribution of the central body (e.g., Kozai 1959). A series of such theoretical studies paved the way for the accurate measurement of J_2 (equatorial bulge) and the discovery of J_3 (“pear” shape) of the Earth’s gravity field. Since the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite system in 2002, time-variable gravity became a major field in geodesy. Mass redistribution within the Earth system has long been studied by analyzing the Earth’s polar motion, but time-variable gravity replaced the polar motion as the principal sensor monitoring the Earth system.

In 1987, a long history of the Earth’s rotation observations with optical telescopes ended and space geodetic techniques took over. At the same time, the International Polar Motion Service (IPMS, the successor of ILS) was re-organized as the International Earth Rotation Service (IERS), which was renamed to the International Earth Rotation and Reference Systems Service in 2003. Space geodesy in Japan started in 1980s when the Simosato satellite laser ranging (SLR) station and the Kashima VLBI station started to take part in the observing campaigns conducted by NASA as Crustal Dynamics Project. Satellites launched in Japan, such as Ajisai (for SLR), ALOS-1&2 (Advanced Land Observing Satellite) (for synthetic

aperture radar, SAR), and the Quasi-Zenith Satellite System (QZSS) (for GNSS), play unique roles in space geodesy.

Deployment of the dense GNSS array in Japan during 1990s resulted in important discoveries such as slow fault slips, seasonal crustal movements, zones of strain concentration, and so on. Japanese researchers lead the development of the new technique for the ocean floor positioning known as the GNSS-Acoustic method, and recent observations off the Pacific coast of Japan have revealed inter-, co-, and postseismic seafloor movements near the Japan Trench and the Nankai Trough (e.g., Yokota et al. 2016).

Future role of geodesy in Japan

The last section of this article presents a perspective on the future of geodesy in Japan, emphasizing its role in transdisciplinary studies. Majority of the studies using the dense GNSS array in Japan have been done for crustal dynamics of tectonic origin. However, GNSS is a useful sensor also for meteorology, cryospheric science, aeronomy, oceanography, and hydrology. Here, I focus on the 2019 super-typhoon Hagibis [2019 Typhoon No. 19, named by the Japan Meteorological Agency (JMA)], one of the recent natural disasters in Japan, and discuss how geodesy helps us understand the whole event.

Since Bevis et al. (1992) showed the potential of GNSS receivers as a sensor of atmospheric water vapor, meteorological utilization of the Japanese dense GNSS network has been sought (e.g., Tsuda et al. 1998). In fact, precipitable water vapor data from GNSS have been assimilated in the meso-scale model of JMA to improve weather forecast accuracy since 2009 (e.g., Shoji 2015).

Figure 8 shows the distribution of zenith wet delay (ZWD) at three epochs on October 12, 2019, when the

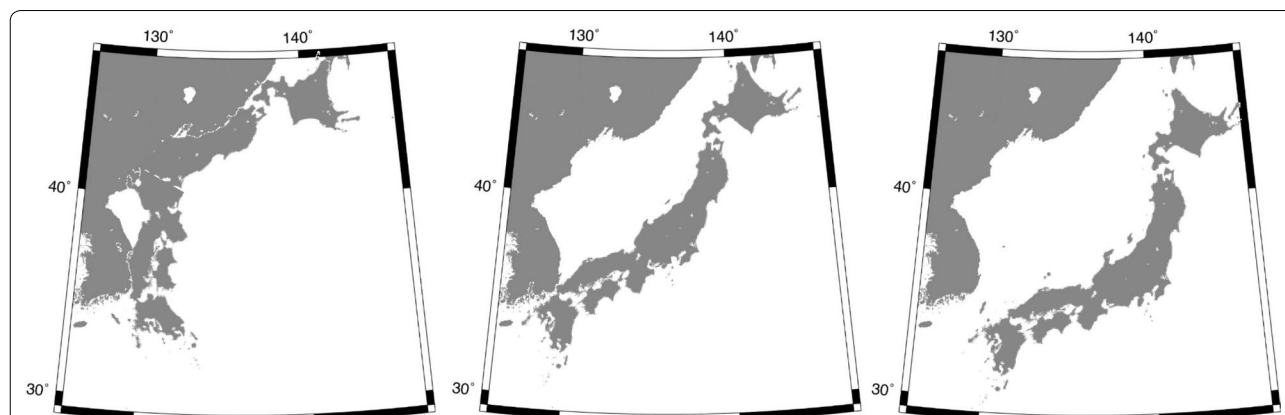
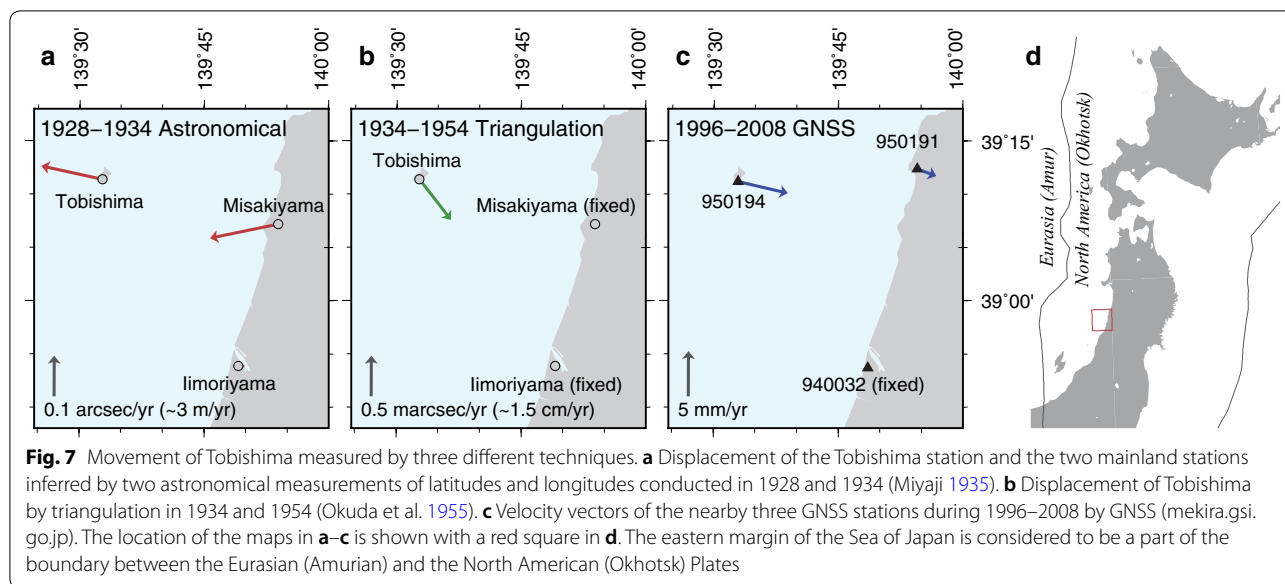


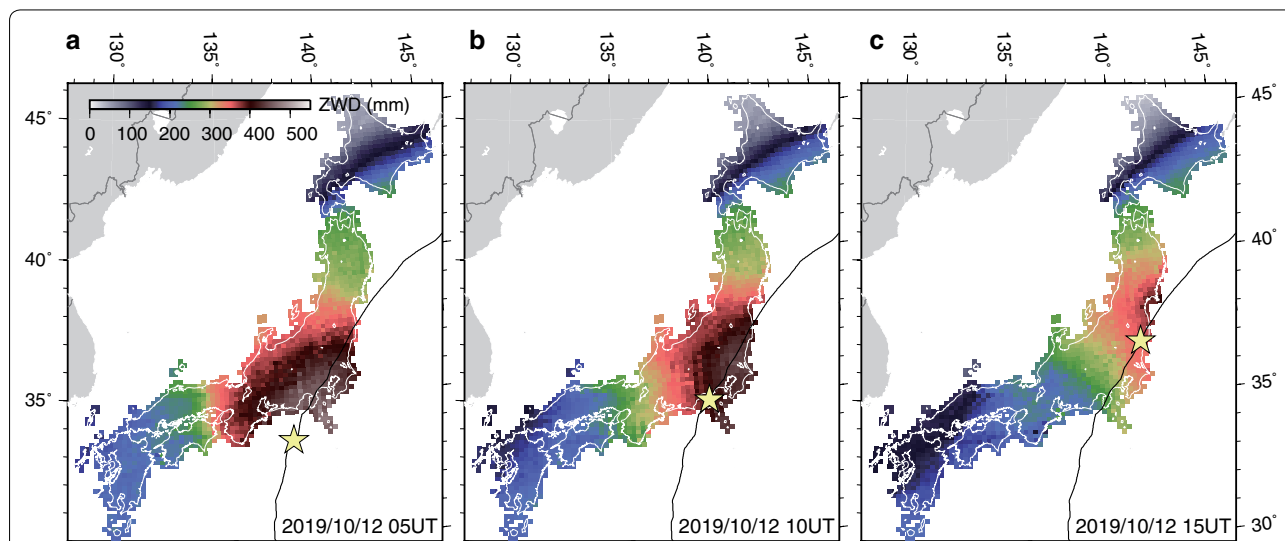
Fig. 6 The opening of the Sea of Japan has been verified later by paleomagnetic studies, which also revealed that the opening had completed long time ago. Terada (1927) considered that the opening still goes on and also that small islands off the coast of the Sea of Japan, such as Tobishima, are currently moving apart from the mainland fast enough to be detected by astronomical positioning



typhoon Hagibis made landfall in central Japan, derived from the dense GNSS network in Japan (downloaded from geodesy.unr.edu, Blewitt et al. 2018). We can see the region of high water vapor content, expanding northward from the center of the typhoon, moves along the typhoon path (ZWD can be converted to precipitable water, in mm, roughly by multiplying by 0.15). Such a detailed map can never be drawn with conventional meteorological instruments such as radiosondes, launched only twice a day at ~10 observatories in Japan.

Such a huge amount of water vapor resulted in heavy rains and floods. Although the former could be measured,

e.g., by rain gauges, it is difficult to infer the water depth distribution of a widespread flood with conventional sensors. Here, I show that a dense GNSS network can map the water depths by measuring crustal deformation. Stormwater acts as a surface load and depresses the crust to a detectable level. Figure 9a shows crustal subsidence in five regions flooded by this typhoon. I removed the common mode errors from the F3 solution (final daily coordinate solution) by GSI (Nakagawa et al. 2009), selected 7 stations from each region, and calculated their averages over days spanning ±15 days around the typhoon landfall day. The subsidence of the GNSS



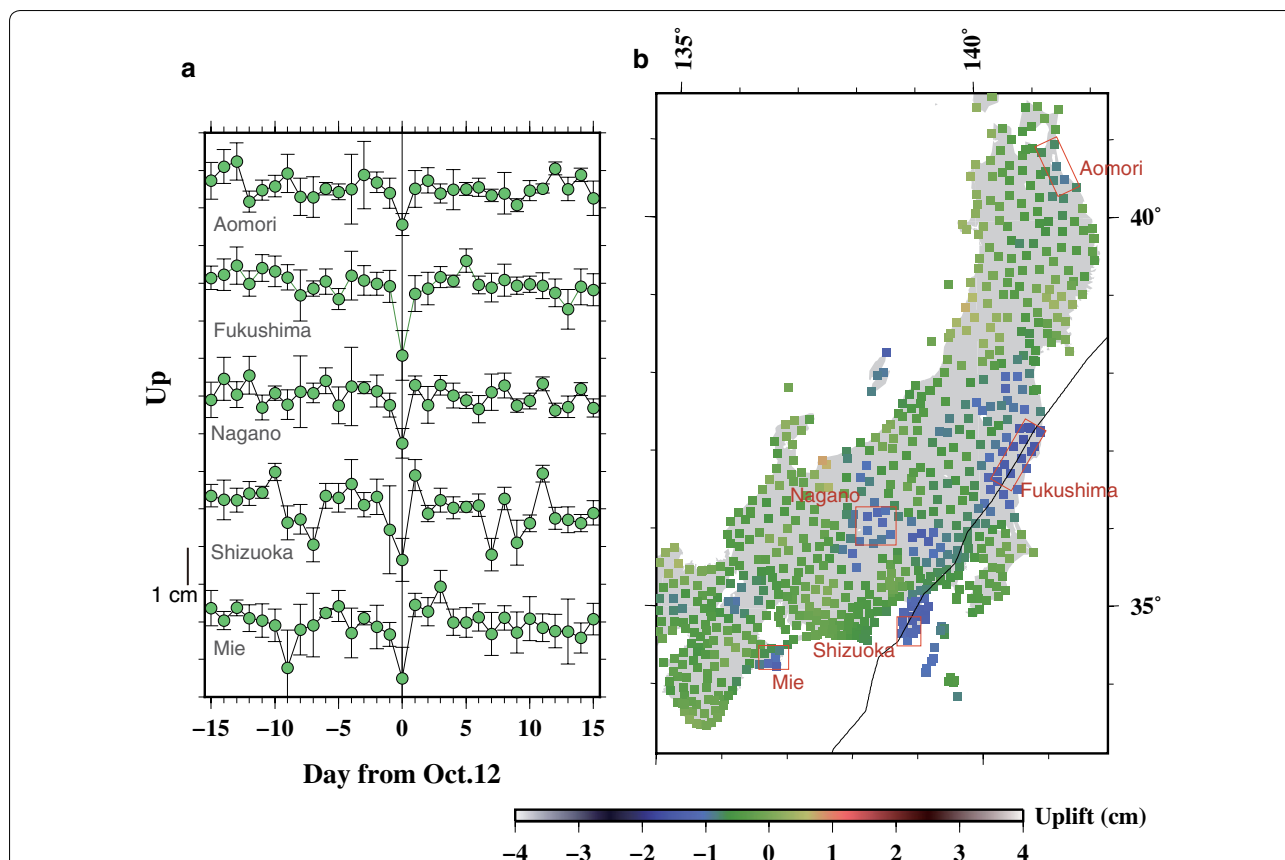


Fig. 9 Crustal subsidence by the stormwater load of the 2019 typhoon Hagibis. **a** Time series of vertical coordinates of the GNSS stations over a period around 2019 October 12, located in the five flooded areas given by red boxes in **b**. They are the averages of seven GNSS stations from each box, i.e., 0152, 0153, 0156, 0158, 0537, 0539, 0901 (Aomori), 0201, 0205, 0211, 0212, 0581, 0920, 0945 (Fukushima), 0263, 0271, 0272, 0273, 0610, 0613, 0979 (Nagano), 0297, 0620, 0814, 0838, 3049, 3053, 3086 (Shizuoka), 0065, 0314, 0636, 1104, 1105, 1139, 1149 (Mie). On the day of the typhoon landfall (October 12), average vertical positions show clear subsidence of 1–2 cm. **b** Subsidence of the GNSS stations relative to the median during the ± 15 days period. The data of the individual stations are spatially smoothed with an averaging radius of 20 km

stations is mapped as in Fig. 9b. Then, it is straightforward to map the surface water depth like Milliner et al. (2018) did for the Hurricane Harvey in the southern United States. Such a study will lead to the understanding of stormwater dynamics after extreme rainfall events and helps us forecast future floods in Japan.

An example shown here drops a hint about the future role to be played by geodesy in Japan, i.e., it must be transdisciplinary. Heki (2020) showed that a dense GNSS network will contribute to ionospheric studies, especially disturbances related to earthquakes. SAR satellites have become indispensable for monitoring volcanoes. Recently, usefulness of SAR as a two-dimensional sensor for atmospheric water vapor and ionospheric electrons has been recognized (Tsuda et al. 2018). A dense GNSS network will also complement GRACE in studying surface water redistribution in higher temporal and spatial resolutions. These research activities would yield next-generation legends of geodesy in Japan.

Abbreviations

ALOS: Advanced Land Observing Satellite; CMB: Core-mantle boundary; FCN: Free core nutation; FCR: Fluid core resonance; GNSS: Global navigation satellite system; GRACE: Gravity Recovery and Climate Experiment; GS: Geospatial Information Authority of Japan; IAG: International Association of Geodesy; IERS: International Earth Rotation and Reference Systems Service; ILS: International Latitude Service; ILOM: International Latitude Observatory of Mizusawa; IPMS: International Polar Motion Service; JMA: Japan Meteorological Agency; NE Japan: Northeast Japan; QZSS: Quasi-Zenith Satellite System; SAR: Synthetic aperture radar; SW Japan: Southwest Japan; SLR: Satellite laser ranging; VLBI: Very long baseline interferometry; ZWD: Zenith wet delay.

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Authors' contributions

KH did everything. The author read and approved the final manuscript.

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Availability of data and materials

GNSS data given in Fig. 7 can be downloaded from the webpage of Geospatial Information Authority of Japan (mekira.gsi.go.jp). The other data are given in the quoted papers.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

There are no financial or non-financial competing interests.

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References

- Bevis M, Businger S, Herring TA, Rocken C, Anthes RA, Ware RH (1992) GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system. *J Geophys Res* 97:15787–15801
- Blewitt GW, Hammond C, Kreemer C (2018) Harnessing the GPS data explosion for interdisciplinary science. *EOS* 99:1–2
- Chandler S (1891) On the variation of latitude II. *Astron J* 11:65–70
- Dong D, Dickey JO, Chao Y, Cheng MK (1997) Geocenter variations caused by atmosphere, ocean and surface ground water. *Geophys Res Lett* 24:1867–1870
- Gwinn CR, Herring TA, Shapiro II (1986) Geodesy by radio interferometry: studies of the forced nutations of the earth, 2. Interpretation. *J Geophys Res* 91:4755–4765
- Heki K (2020) Ionospheric disturbances related to earthquakes. In: Huang C, Lu G (eds) *Advances in ionospheric research: current understanding and challenges, space physics and aeronomy*, vol 3. Wiley, New York, p 320. ISBN 978-1-119-50755-0
- Herring TA, Gwinn CR, Shapiro II (1986) Geodesy by radio interferometry: studies of the forced nutations of the earth, 1. Data analysis. *J Geophys Res* 91:4745–4754
- Kawai N, Ito H, Kume S (1961) Deformation of the Japanese Islands as inferred from rock magnetism. *Geophys J R Astr Soc* 6:124–130
- Kazu T (2005) Shogunate astronomers and de Lalande's "Astronomia de Sterrekunde". *Astron Herald* 98:310–316 (in Japanese with English abstract)
- Kimura H (1902a) On the existence of a new annual term in the variation of latitude independent of the components of the pole's motion. *Astron Nachr* 158:233–240
- Kimura H (1902b) A new annual term in the variation of latitude independent of the components of the polar motion. *Astron J* 22:107–108
- Kozai Y (1959) The motion of a close earth satellite. *Astron J* 64:367–377
- Lalande JF (1771) *Astronomie*, vol 1-3. Chez la veuve Desaint, Paris
- Milliner C, Materna K, Burgmann R, Fu Y, Moore AW, Bekaert D, Adhikari S, Argus DF (2018) Tracking the weight of Hurricane Harvey's stormwater using GPS data. *Sci Adv* 4:eaa2477
- Miyaji M (1935) Continental drift and observations at Tobishima. *Astron Herald* 28:1–6 (in Japanese)
- Molodensky MS (1961) The theory of nutation and diurnal earth tides. *Commun Obs Roy Belgique* 188:25–56
- Nakagawa H, Toyofuku T, Kotani K, Miyahara B, Iwashita C, Kawamoto S, Hatanaka Y, Munekane H, Ishimoto M, Yutsudo T, Ishikura N, Sugawara Y (2009) Development and validation of GEONET new analysis strategy (Version 4). *J Geogr Surv Inst* 118:1–8 (in Japanese)
- Nakamura K (1983) Possible nascent trench along the eastern Japan Sea as the convergent boundary between Eurasian and North American plates. *Bull Earthq Res Inst Univ Tokyo* 58:711–722 (in Japanese with English abstract)
- National Astronomical Observatory (1999) North atmosphere of mind: latitude observations 100 years. *Earth Rotation Div, Nat Astr Obs Japan, Mizusawa* (in Japanese)
- Newcomb S (1891) On the periodic variation of latitude, and the observations with the Washington prime-vertical transit. *Astron J* 11:81–83
- Oda T (1974) History of map: Japan. *Kodansha-Gendai-Shinsho, Tokyo* (in Japanese)
- Okuda T, Dambara T, Otsuka Y (1955) Redetermination of the astronomical and geodetic positions of Tobishima Island. *J Geod Soc Japan* 1:42–44 (in Japanese)
- Otofuji Y, Kambara A, Matsuda T, Nohda S (1994) Counterclockwise rotation of Northeast Japan: paleomagnetic evidence for regional extent and timing of rotation. *Earth Planet Sci Lett* 121:503–518
- Sasao T, Okubo S, Saito M (1980) A simple theory on the dynamical effects of a stratified fluid core upon nutational motion of the earth. In: Fedorov EP, Smith ML, Bender PL (eds) *Nutation and the Earth's Rotation*. Int Astron Union, Paris, pp 165–183
- Shirai T, Fukushima T, Malkin Z (2005) Detection of phase disturbances of free core nutation of the Earth and their concurrence with geomagnetic jerks. *Earth Planets Space* 57:151–155. <https://doi.org/10.1186/BF03352559>
- Shoji Y (2015) Water vapor estimation using ground-based GNSS observation network and its application for meteorology. *Tenki* 62:3–19 (in Japanese)
- Terada T (1927) On a zone of islands fringing the Japan Sea Coast—with a discussion on its possible origin. *Bull Earthq Res Inst* 3:67–85
- Tsuda T, Heki K, Miyazaki S, Aonashi K, Hirahara K, Nakamura H, Tobita M, Kimata F, Tabei T, Matsushima T, Kimura F, Satomura M, Kato T, Naito I (1998) GPS meteorology project of Japan—exploring frontiers of geodesy. *Earth Planets Space* 50:1–5. <https://doi.org/10.1186/BF03352172>
- Tsuda T, Realini E, Shoji Y, Saito A, Yabuki M, Furuya M (2018) Special issue "GNSS and SAR technologies for atmospheric sensing". *Earth Planets Space* 70:123. <https://doi.org/10.1029/2002RS002767>
- Wahr J (1981) The forced nutations of an elliptical, rotating, elastic and oceanless earth. *Geophys J Roy Astron Soc* 64:705–727
- Wako Y (1970) Interpretation of Kimura's annual Z-term. *Publ Astron Soc Jpn* 22:525–544
- Wegener A (1929) *The origin of continents and oceans*, 4th edn. Friedrich Vieweg & Sohn Akt. Ges, Braunschweig
- Yokota Y, Ishikawa T, Watanabe S, Tashiro T, Asada A (2016) Seafloor geodetic constraints on interplate coupling of the Nankai Trough megathrust zone. *Nature* 534:374–377

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