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A review of the 19th International Symposium on geodynamics and earth tide, Wuhan 2021

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ABSTRACT

Modern geodetic technologies such as high-precision ground gravity measurements, satellite gravity measurements, the global navigation satellite system, remote sensing methods, etc. provide rich observation data for monitoring various geodynamic processes of the global Earth and its surface. The 19th International Symposium on Geodynamics and Earth Tides brought together scientific researchers from 26 countries around the world, shared the application of various measurements in different geoscience issues, covering Earth tidal deformation, oceanic and atmospheric loading effects, earthquake cycle, hydrology, Earth rotation changes, etc., and provided a precious exchange platform for global peers.

1. Introduction

During 23–26 June 2021, the 19th International Symposium on Geodynamics and Earth Tides (G-ET) was held at the Innovation Academy for Precision Measurement Science and Technology of the Chinese Academy of Sciences, located at the shore of the East Lake (Fig. 1), in Wuhan, China. Due to the COVID-19 pandemic, the symposium was organized in an onsite-online hybrid mode. About 200 participants attended the symposium in Wuhan, with the same number of attendees online. The participants came from 26 countries and regions. This symposium awarded the highest honor award in solid Earth tide research, the Paul MelchiorAward, to three scientists (David Crossley, Gerhard Jentzsch, and Walter Zürn) who have made outstanding contributions in this field. The invited report of Schuh, 2022 [1] introduced the research of space geodesy in geodynamics. Braitenberg, 2022 [2] gave a keynote speech on the geophysical requirements for future mass change research and gravity satellite missions. Sun, 2022 [3] introduced China's high-precision gravity observation network and the important progress in the field of Earth's tide and geodynamics. Rosat, 2022 [4] introduced the study of gravity signals generated by dynamic phenomena in the Earth's interior from the seismic cycle to decadal core fluctuations. The G-ET symposium was organized in six sessions, i.e., tides and non-tidal loading, geodynamics and the earthquake cycle, variations in Earth rotation, new technology and software development, time variable gravity and mass redistribution, and monitoring of subsurface fluids. Here a review of the topics during the symposium is given to document the research progress reported in the symposium.

2. Review of the topics presented at the symposium

2.1. Tides and non-tidal loading

Geophysical fluids (ocean, atmosphere, and land water), which produce tidal and non-tidal load effects over a large frequency band, are one of the most important sources of gravity changes. The International Geodynamics and Earth Tide Service (IGETS) supports the monitoring of temporal variations of the Earth gravity field through long-term records from more than worldwide 40 superconducting gravimeters (SGs) (Fig. 2). The IGETS data center, located at the Information System and Data Center (ISDC) of the German Research Centre for Geosciences (GFZ) in Potsdam

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Fig. 1. a) Venue and b) group photo of the 19th International Symposium on Geodynamics and Earth Tides.

Germany, provides the raw (Level 1) and processed data (Level 2 and Level 3). Boy, 2022 [5] compared atmospheric, non-tidal oceanic, and hydrological loading models from various sources to the gravity measurements of the IGETS network. The results show that the latest ECMWF reanalysis (ERA5 [6]) coupled with the TUGO-m [7] barotropic ocean model better explains gravity observations for periods between a few hours to several years. The Level-3 data could be improved by replacing the current atmospheric correction (MERRA2 with IB [8]) with the ERA5 + TUGO-m.

With various updates introduced in the program system ETERNA-x, a hypothesis-free estimation of parameters for different degrees of the tide generating potential becomes possible [9,10]. With the use of long observational time series from IGETS SG stations, Wzionteket al. [11] analyzed a specific set of wave groups (M1, 3MO2, 3MK2 and M3) originating from the third-degree coefficients of the spherical harmonic expansion of the tidal potential. The ocean load tide vectors relative to the body tide model (DDW) were compared with results from the purely-hydrodynamic, barotropic ocean tide model TiME. In comparison to the SG results, gravity effects computed from TiME(Tidal Model forced by Ephemerides [12]) with SPOTL (Some Programs for Ocean-Tide Loading [13]) and a global load Love number approach explain the observed parameters at levels of 80% and better. Riccardi et al. [14] used ET34-ANA-V80 to retrieve a set of frequency-dependent gravity factors for three-year gravity records from spring gravimeters installed in the area of Lake Nasser, Egypt. The residual gravity signal after tidal subtraction at Aswan station is in the range of ± 50 μGal. Further analyses of the instrumental contribution are needed before to be able to interpret this gravity signal in terms of surface loading (i.e. changes in the water level of Lake Nasser) or underground hydrology. Ducarme et al. [15] took advantage of the flexibility of ET34-ANA-V80 operated in conjunction with the preprocessing facilities of TSoft [16] to deal with sea level data, in which there are many data gaps, jumps and spikes in data sources as well as timing errors in the radio-transferred data. These datasets refer to a network of sea level monitoring stations progressively installed in French Polynesia since 2008.

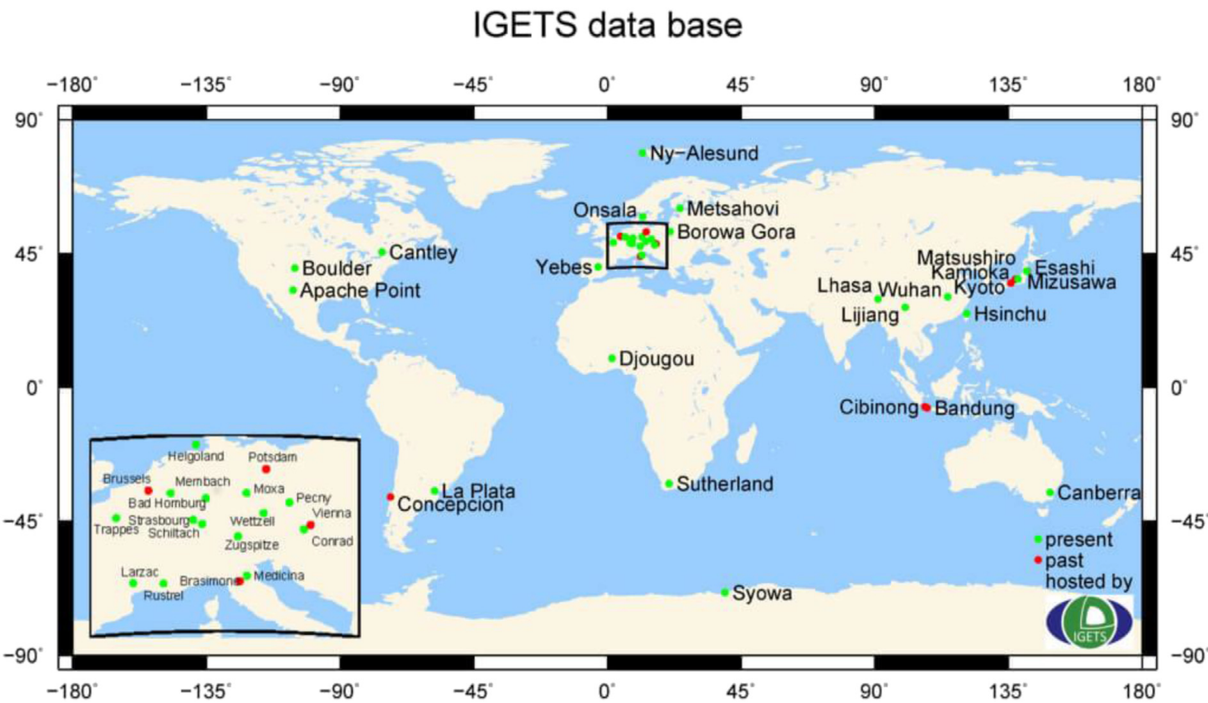

Fig. 2. Map of the stations contributing to the IGETS SG data base (https://ggos.org/item/igets/).

Observed gravity is usually corrected for atmospheric effects using the computed barometric admittance of the in situ measured pressure. However, this procedure is not giving satisfactory results for the wave S2 and other Solar heating pressure tides. Since the local pressure changes alone cannot account for the atmospheric mass attraction and loading, Ducarme, 2022 [17] improved the computation process of the total atmospheric effect at each station from the worldwide pressure field by adopting the “hybrid” pressure correction method, separating the“local” and the “global” pressure contributions. The “local” contribution of the model was replaced by the pressure measured at the station multiplied by an admittance. The validity of this method is verified by testing at 8 SG stations, especially at the three Central European stations Conrad, Pecny and Vienna.

In addition, when modelling atmospheric loading (Newtonian attraction and deformation) effects for terrestrial gravimetry, deformation effects are usually only computed over continents assuming the Inverse Barometer (IB) hypothesis to be valid over the oceans. Ocean-bottom pressure data products are used in non-tidal ocean loading corrections as a revised procedure. However, the Newtonian attraction contributions from the atmosphere may be accounted twice when combining these products with the modeling of atmospheric effects [18]. These effects can reach the μGal level, depending on the location of the station. Antokoletz et al. [18] proposed a new approach for the combination of atmospheric and non-tidal ocean loading effects, and verified the effectiveness based on tests at five superconducting gravity stations.

Accurate ocean tide models are the key to eliminating ocean tide loading effects in surface deformation observations.In the last twenty years, the accuracy of the global navigation satellite system (GNSS) technique and its great territorial coverage has favored its application in tidal studies. Navarro et al. [19] obtained ground displacements in the three coordinate components for the six main diurnal and semi-diurnal harmonic constituents in different sites in Argentina, using the PPP kinematic GNSS processing technique. The difference between GNSS observations and the results predicted by the non-hydrostatic, inelastic solid Earthmodel DDW-NHI [20] is negligible (less than a millimeter). The same is not true for ocean tidal load predictions, especially in coastal areas, reaching differences that far exceed the millimeter. Arana et al. [21]studied the methodologies for correcting ocean loading in different scenarios by choosing two typical stations (PPTE and NEIA) located respectively in the cities of Presidente Prudente - SP and Cananeia – SP. Ocean tide models showed difficulty in minimizing the effect, especially in the coastal region. It is advantageous to use empirical tidal models that include in each constituent the solid tide and loading effects. The results obtained in the temporal spectrum analysis show that it is possible to obtain the loading effects extracted from the gravity data by considering a theoretical elastic model [21].

Two SGs are closely located on the same vertical, with 520 m depth difference(iOSG24 is installed inside a tunnel and iGrav31 outside at the summit) at the underground research laboratory of Rustrel (LSBB), France, which offers a unique opportunity to study differential gravity of tidal origin. Hinderer et al. [22] tried to search for the difference between tidal gravity signals recorded on the ground and at a 520-m depth. Theoretical computations using an elastic non-rotating PREM Earth model show that this differential effect is very small. Thus, the observability of this difference will be strongly dependent on the calibration accuracy of the SGs. Both absolute and relative calibration were fulfilled in Hinderer et al. [22]. In the various tidal analyses done on 433-day-long records from the two SGs, the required calibration accuracy is still missing to be able to retrieve the elusive tidal differential signal. In addition, these two SGs provide a valuable opportunity to estimate water storage changes between both SGs. Kumar et al. [23] found that the gravity residuals can be explained well by large water fluxes and rapid runoff occurring in the LSBB catchment.

Earth's deformation under the tide-generating force will cause heat transport within it. Zhou et al. [24] present a semi-coupled theory to evaluate the temperature variation due to the tide-generating force. The results show that the magnitude of the tidal temperature variation can be more than 1 mK under both isothermal and adiabatic boundary conditions, which is detectable by the current precision thermometer.

Deformation monitoring technologies such as time-varying gravity and GNSS are widely used to study land hydrological changes. Many studies have combined the two independent geodetic technologies, GNSS and satellite gravity observations from the Gravity Recovery and Climate Experiment (GRACE) satellites, to study the water cycle or tectonic signals. However, whether the results obtained by GRACE and GNSS are comparable remains unclear. Zhang et al. [25] simulated the loading deformations in response to load masses with varying resolutions and distributions, and found obvious discrepancy in the spatial average between the accurate loading displacement and the truncated result due to a single load mass. The quantitative study of vadose zone water is of vital importance for understanding the groundwater flow mechanism, mass exchange, and circulation. Micro-gravity field observations have been proved useful as a constrain for the dynamic hydrologic model of the subsurface floods. Pivetta et al. [26] and [27] studied the Adriatic Sea tidal and non-tidal effects in continuous gravity observations with a gPhone to monitor the underground Karst hydrologic floods.It was found that FES2014b is adequate for the tidal mass and loading effect of the Adriatic Sea and the Mediterranean, but must be integrated through a local modeling of the Adriatic Sea if the gravimeter is located within 5 km from the coastline. Weather fronts stagnant above the southwestern (SW) Japan often bring disastrous heavy rains in early summer. Hekiet al. [28] studied four such episodes in 2017–2020 summer, and investigated transient lithospheric subsidence caused by rainwater loads using the daily coordinates of the dense network of continuous GNSS stations. Subsidence signals up to 1–2 cm were shown to have been measured in flooded regions. Such subsidence recovered in a day, as rainwater drained rapidly to the nearby ocean, promoted by large topographic slopes. High correlation is found between volumetric subsidence and total rain over the entire SW Japan.

2.2. Geodynamics and the earthquake cycle

Modern geodesy technology with high stability and sensitivity in a wide frequency band provides a very rich means for studying the law and mechanism of different stages of the earthquake cycle. For example, Eshkuvatov et al. [29] reported the ionospheric anomalies at six GNSS stations before the strong earthquakes during 2011–2015 in Uzbekistan and Pakistan. They found the ionospheric precursors appeared about 1–7 days before the occurrence of strong earthquakes. Abetov et al. [30] analyzed the seismic deformation processes under the influence of hydrocarbon production at the Karachaganak oil, gas, and condensate field (KOGCF), Kazakhstan based on repeated leveling, GNSS measurements, gravimetric and seismological monitoring.

Correlations between tidal stresses and seismicity have long been investigated by scientists over the world [31]. Statistical analyses have shown positive correlations between tides and seismicity in some geographical areas. Yan et al. [32] reviewed the tidal triggering of global earthquakes and found a positive contribution of tidal triggering to earthquake preparation with semidiurnal and diurnal periods. However, tidal effects are hardly connected with long-term seismicity. Tanaka et al. [33] indicated that a long-term change of seismicity in the Tokai region in Japan could be explained with a superposition of diurnal and semi-diurnal tides with decadal variations in the ocean bottom pressure (OBP) due to the Kuroshio Current, which could amplify the stress change on the plate interface non-linearly. In order to distinguish the local, regional and global variations corresponding to abnormal pre-seismic and co-seismic processes, Volkov et al. [34] investigated the seismic activity based on the analysis of non-tidal strain-baric and tilt–baric processes recorded by a system of ground-based laser interferometers-strainmeters within the Moscow Syneclise (Obninsk, Fryazino) together with synchronously operating tiltmeter instruments of deep underground installations in the Bohemian Massif (Skalna, Jezeri, Pribram). A high correlation between laser interferometers data and distant tiltmeters data was found before strong earthquakes in the time interval 2015–2020.

High-precision gravity observations have a very important application in detecting earthquake preparation and precursor information. Zhu et al. [35] analyzed the relationship between gravity variation near the epicenter region and 6 large earthquakes (the M_S8.0 Wenchuan and the M_S7.3 Yutian earthquake in 2008, the M_S7.1 Yushu earthquake in 2010, the M_S7.0 Lushan earthquake in 2013, the M_S7.3 Yutian earthquake in 2014, and the M_S7.0 Jiuzhaigou earthquake in 2017) in the Qinghai-Tibet Plateau using the absolute and relative gravity observations from the China Earthquake Administration (CEA). Obvious regional gravity anomalies and high-gradient zones were observed in the epicenter area prior to the earthquakes, which may be the gravity precursor information during the process of earthquake preparation. Pedapudi et al. [36] applied Detrended fluctuation Analysis (DFA) and Multifractal DetrendedFluctuation Analysis methods (MF-DFA) to data recorded with a SG at Badargadh, Gujarat, India, in order to study pre-seismic and co-seismic anomalies. During the monitoring period, the gravity field shows uneven scaling behaviour before the earthquake of June 20, 2012 (M5.1) which occurred about 20 km from Badargadh. The evolution of the scale instability index over time is also well correlated with this earthquake. The local variability estimated on June 19, 2012 at different scales allows to distinguish the anomalous pattern present in the gravity data, which in turn correlates with the occurrence of this earthquake on June 20, 2012.

The dislocation theory has been introduced into earthquake science for a long time as a valid verification of the observations. Both the flat-earth dislocation and spherical dislocation theory are well developed [37]. Ji et al. [38] proposed a new method for calculating the coseismic gravity gradient changes based on the spherical dislocation theory. The results obtained based on a spherical layered Earth model and those calculated using the flat-Earth model are in good agreement within the near field, while the differences in the far field show the advantages of the spherical model. The proposed method was applied to analyze the coseismic gravity gradient changes caused by the 2011 Tohoku-Oki earthquake. The theoretical gravity gradient changes agree well with the GRACE observations, indicating that the proposed dislocation theory is important and can be used to efficiently interpret seismic deformations.

On a long time scale, the viscoelastic properties of mantle media significantly affect post-seismic deformation. The stress field disturbance in a viscoelastic medium caused by fault slip gradually relaxes, and the relaxation process and its temporal–spatial characteristics are determined by the viscoelastic model. Tang and Sun [39] assumed that the mantle can be described by common linear rheological models, i.e., the Burgers body, the standard linear solid, and the Maxwell body, and calculated the dislocation Love number and Green function for a spherically symmetric, non-rotating, viscoelastic, and isotropic (SNRVEI) Earth model. The results show that on a time scale of less than one decade, the Burgers body and standard linear solid show similar deformations, while for time scales longer than one decade, the Burgers body and Maxwell body give similar deformations. It should be emphasized that the time scale mentioned here is highly dependent on the viscosity value of the Earth. The viscosity values they used are currently estimated from the post-seismic deformations. This suggests that the observations of post-seismic deformation on the surface have a great potential for the inversion of underground viscoelastic structures. However, the potential of using surface displacement to distinguish between different rheological models is limited when the observation period is less than one decade. Yang et al. [40] modeled the hydrologic response within 1.5 months following the 2015 M_W8.3 Illapel earthquake and removed its effects from the observed geodetic signals to constrain the poroelastic contributions to the early post-seismic deformation. Results demonstrate the post-seismic fluid-flow patterns from the co-seismic high-slip region to the north and south sides, and the northern poroelastic effects are remarkably stronger than those on the south side, verified by northern liquefaction phenomena. It reveals the importance of considering the poroelastic effects, when modelling the transient post-seismic deformation. Lin et al. [41] analyzed high-resolution borehole strainmeter signals to constrain the fault plane solutions and locations of the 2009 Fengpin-Hualien earthquakes, in eastern Taiwan, China. Significant positive static Coulomb stress changes (>+100 kPa) at shallow to moderate depths in the Longitudinal Valley (0–12 km) may have influenced the occurrence of large mainshocks in eastern Taiwan during the past decade.

For the low-order spherical modes of the Earth's free oscillations, SGs have higher signal-to-noise ratios than broadband seismometers, and play an important role in constructing long-period seismograms with frequencies below 1 mHz and exploring deep structures in the Earth. The normal spheroidal elastic mode $_2S_1$, the first overtone of the Slichter mode $_1S_1$, corresponds to the oscillations of the Earth's core as a whole. Milyukov and Vinogradov [42] detected the mode $_2S_1$ with the use of the records of 15 IGETS SG gravimeters with duration of 20.8 days after the Great Sumatra Andaman Earthquake on December 26, 2004. The averaged values of the degenerate frequency and the splitting parameter of the mode $_2S_1$ obtained for all gravimeters of the IGETS network are $f_d = 0.40406 \pm 0.00010$ mHz, $b = 0.0152 \pm 0.0013$. The corresponding frequencies of the triplet are 0.39885, 0.40491 and 0.41112 mHz. Pedapudi et al. [43] detected the free oscillations of the Earth after the large earthquakes in Chile (February 27, 2010, *M*8.8) and Japan (April 11, 2011, *M*9.1) using data from the SG (SG-055) installed in Badargadh, Gujarat, India. A total of 47modes for the earthquake in Japan and about 44modes for the earthquake in Chile were extracted. The lowest $_0S_2$ spheroidal mode and the $_0S_0$ radial mode were clearly observed for more than three weeks. The division of modes $_0S_3$ and $_0S_4$ due to the Coriolis effect is visible. Low-order toroidal modes of the Earth are not often detected at present. Zhang et al. [44] retrieved the low-order toroidal modes excited by the 2011 Tohoku Earthquake using observations of borehole tensor strainmeters from stations of the Plate Boundary Observatory network in America and stations in China. Results show that most of toroidal modes $_0T_2$—$_0T_{25}$ are detected with this kind of strainmeter. In addition, spectrum splitting of several multiplets is clearly observed.

The Tibetan Plateau (TP) experiences complex mass transfer and redistribution due to the effects of the internal Earth dynamics and external climate change, such as land water changes, crustal uplift, surface denudation, and Moho interface changes. These phenomena are accompanied by changes in the gravity field and can be observed by GRACE. Rao and Sun [45] uses GRACE data to estimate the mass changes expressed by the equivalent water height (EWH) anomaly of the TP. ICESat data and hydrological models were also used to estimate the effects of hydrological factors (lakes, glaciers, snow, soil moisture, and groundwater) and to separate them from the comprehensive mass field to obtain the tectonic information. A mean Moho interface uplift rate of 4.20 ± 5.13 mm/yr was estimated, and the distribution of Moho interface changes indicates that the northern TP's Moho interface is upwelling and the southern interface is deepening.

In addition to GNSS, the Doppler Orbitography and Radio-positioningIntegrated bySatellite (DORIS) system also provides precise ground station positioning for geodesy and geodynamics. Kong et al. [46] analyzed the time series of DORIS beacon stations and plate motion ofthe Eurasian plate by applying Singular Spectrum Analysis (SSA) and Fast Fourier Transform (FFT). The results show that the Eurasian plate moves eastward as a whole with an average velocity of 24.19 ± 0.11 mm/y in the horizontal direction, and the average velocity of it is 1.74 ± 0.07 mm/y in the vertical direction.

2.3. Variations in Earth rotations

One of the geodetic applications of the GRACE and GRACE Follow-On (GRACE-FO) data is interpretation of changes in polar motion (PM) excitation due to variations in the continental hydrosphere and cryosphere. Such impacts are described with time series of hydrological and cryospheric angular momentum (HAM/CAM). Śliwińska et al. [47] found that GRACE mascon solutions outperform spherical harmonic solutions in the HAM/CAM estimation especially in the seasonal spectral band. Furthermore, Satellite Laser Ranging (SLR) data can be used for determination of HAM/CAM to fill the data gap between GRACE and GRACE-FO particularly in the non-seasonal spectral band. Liu et al. [48] found that hydrological signals can explain the shift of Earth's PM in 2000s thanks to the launch of GRACE. Further investigation unveils that the accelerated ice melting over major glacial areas drives the polar drift toward 26°E for 3.28 mas/yr after the 1990s.

In theory, Fang et al. [49] studied the Eigen-mode excitation of linear oscillators and the Earth's PM. They found that the finite smoothness (i.e., the presence of jump in finite order derivatives) of the applied Newtonian forcing constitutes the sufficient and necessary condition for instantaneous excitation of free Eigen-modes. Eigen-modes can also be excited by an infinitely smooth forcing that has a finite domain of non-zero values. The Eigen-period serves as a macroscopic timescale to characterize the inertia of a linear oscillator.

Free Core Nutation (FCN) as the part of Earth rotation changes, is a normal model of rotation originating from the inconsistency of the rotation axis of the mantle and the liquid outer core, it is an important method to study the dynamic phenomena of core-mantle boundary (CMB) and physical parameters (viscosity near CMB, dynamic ellipticity of the liquid core, etc.). Yang et al. [50] estimated the eigen period and quality factor of FCN based on the resonance phenomenon of gravity and nutation by using SG data from 18 stations in the IGETS and VLBI Celestial Pole Offset (CPO) sequence provided by 10 institutions. The influence of three weight schemes on the FCN parameters calculated by VLBI and SG data and the influence of the ocean tide model on the calculation of FCN parameters by SG data were investigated. First-order ellipticity on the CMB represents a special kind of topography, which is also of importance for FCN. Zhang et al. [51]studied the effect of various single spherical harmonics models of Earth's topography of the core-mantle boundary on FCN, and computed the effect of several CMB topography models from seismology and equilibrium figure theory.

In addition, Earth's rotation rate defined by length-of-day (LOD) can be used to infer Earth's core oscillations and magnetic field inside the liquid outer core. However, the fine time-varying characteristics as well as relevant mechanisms of the intra-decadal variations, are still unclear. Duan and Huang [52] found a significant 8.6-year harmonic component with an increasing amplitude, which can be explained by the fast equatorial waves with sub-decadal period propagating at Earth's core surface. In addition, Zhou et al. [53] investigated the Mars' LOD change and polar motion and found the correlation with the dust cycles during the Martian Years 24–33.

2.4. New technology and software development

The presentations in this session introduced the developments of software, methods, and technology in tidal data processing, theoretical computation, and instrument development.

A new version of tidal analysis softwareATLANTIDA3.1_2019 was presented by Spiridonov and Vinogradova [54]. This software allows to calculate time series of tides in the Earth without the ocean, the oceanic gravimetric effect (load effect and Newtonian attraction of water masses) and their sum in the frequency range specified by the user, and allows to calculate the atmospheric gravimetric effect (loading plus attraction) as well as atmospheric displacements, tilts and deformations. In the traditional harmonic tidal analysis, gravimetric parameters for wave groups are estimated with the method of least-squares. Nevertheless, if any additional information from different harmonics within the assumed groups is present in the data, it cannot be resolved. Ciesielski and Forbriger [55]developed the new open-source software, RATA, by abandoning the concept of groups. The resulting ill-posedness of the problem is reduced by applying Tikhonov regularization in the Least Squaresobjective function. The model parameters are constrained to reference values or the condition that admittance shall be a smooth function of frequency.

With the changing tidal heights and current intensity each day, it is important to have computational mechanisms to detect and assess the differences in a multitemporal fashion. Chen, 2022 [56] introduces a novel machine learning-based approach by which supervised convolutional neural networks (CNNs) trained on bitemporal high-resolution satellite imagery was used to understand these tidal changes that have key ramifications for climate change and oceanic ecology.

Greens functions (GFs) are fundamental in computing deformation induced by earthquake which is represented by point dislocations. GFs are infinite sums of the product of Legendre functions and the coefficients called dislocation Love numbers (DLNs). If the field point at which the deformation is modeled is close to the source, a large number of DLNs are needed in the summation to ensure the convergence of the GFs. The conventional integral method, such as the Runge-Kutta method is not capable of producing the correct results for large harmonic degrees because of the correlation between the six variables for the spheroidal solution, for example. Zhou et al. [57,58] derive analytical expressions for the dislocation Love numbers (DLNs) for a layered, spherical, transversely isotropic and self-gravitating Earth. The DLNs can be obtained with high accuracy to an arbitrarily high degree, thereby allowing a wide range of applications based on high-resolution Earth models. Compared to the traditional numerical integration approach, the analytical solution is at least 3 orders of magnitude faster.

Due to limited observation methods, there is still much uncertainty on the lunar internal structure, and there is still no widely recognized internal structure model. Liao et al. [59] used the lunar solid tide Love number, average density, and average moment of inertia obtained from the Gravity Recovery and Interior Laboratory (GRAIL) mission as observation constraints to invert the lunar internal structure based on the mixture density network method. An optimal lunar internal structure model and the range of model parameters that satisfies the 1-σ criterion were provided.

Current developments in quantum physics and the application of general relativity open up enhanced prospects for satellite geodesy, gravimetric Earth observation, and reference systems. The new IAG project “Novel Sensors and Quantum Technology for Geodesy (QuGe)” exploits the high potential of quantum technology and novel measurement concepts for various innovative applications in geodesy. Müller, 2022 [60] presented the basic idea and general structure of QuGe and briefly illustrated those novel techniques and the beneficial application of the new methods for gravimetric Earth observation on ground and in space.

Calibration of SGs is mostly determined by using simultaneous observations of absolute gravimeters. This technique, implemented 25 years ago has a precision limited to 0.1%. The limitation comes from the amplitude of the tidal signal and from the precision of the absolute gravimeter. Francis, 2022 [61] proposed a procedure involving three types of gravimeters: a SG, a Scintrex CG6 and an absolute gravimeter by which the precision of the calibration factor can be improved by a factor 10. Calibration of SGs can also be done by comparing co-located two SGs.Elsaka et al. [62] estimated the calibration factor of the iGrav-043 based on the tidal analysis with co-located SG observations from OSG-CT040 in the Walferdange Underground Laboratory for Geodynamics (WULG) in the Grand Duchy of Luxembourg. The instrumental drift of the iGrav-43 shows the expected behavior: for the first and a half months, a fast exponential decrease of 171 nm s^{-2} followed by a linear drift with a rate of 66 nm $s^{-2} \pm 10$ nm s^{-2} per year.

Peng and Hwang [63] developed a tool to deal with large noises, including spikes, in the records from two SGs installed in Hsinchu and Taipei, Taiwan, China. The theory of the tool is based on mathematical morphology. The tool forms the basis for a filter that can remove spikes and smooth the original records to achieve an optimal time series of gravity changes from the SG records. The effectiveness of this filter was assessed by examining the power spectral densities of the SG-recorded gravity changes under different scenarios.

Jahr et al. [64] reported the scientific experience and a reanimation of SG CD-034 at Moxa Observatory of the Friedrich Schiller University Jena, Germany, e.g., the detection of polar motion, the influence of river loads, the gravimetric effect of North Sea storm surges and the study of hydro-gravimetric signals. Based on the experience of severe interference in the gravimeter electronics in 2012/2013 and 2022/2021, Jahr et al. [64] suggested to check the entire detection and control electronics after a period of about 10–15 years of continuous operation.

Pálinkáš et al. [65] developed a new measurement system with independent photodiode for FG5/FG5X gravimeters which could run also in parallel with the original system of the gravimeter. The new system could determine hidden systematic errors of the original system due to the signal distortion, impedance mismatch and electric dispersion and estimate corrections due to the verticality misalignment and the Coriolis effect. Besides, the measurement model of FG5/FG5X gravimeters has been improved by more precise description of the demodulation of the interferometric signal and by the extension of the model by 2 parameters related to the newly discovered spatial parasitic wave caused by the dropping mechanism of FG5/FG5X gravimeters [66]. The gravity effect generated from this parasitic wave could get in-phase or out-of-phase conditions with the tidal signal and therefore affecting the calibration factors of SGs.

2.5. Time variable gravity and mass redistribution

The large-scale mass distribution in the Earth system is continuously changing [67]. Since the launch of the gravity satellite,time-resolved satellite gravimetry has revolutionized our understanding of mass transport in the Earth system. Global observations of water and ice mass redistribution in the Earth system at monthly to decadal time scales are essential for understanding the climate system and studying its changes. Together with other observations, they provide information on the Earth's energy storage, ocean heat content, land surface water storage, and ice-sheet response to global warming. The interactions between the different climate system components involve changes in the mass of the continental surface and groundwater storages(rivers, lakes, groundwater, snow, polar ice sheets, and mountain glaciers), as well as mass redistribution within and between the oceans and the atmosphere. These mass movements are inherent to the evolution of droughts, floods, large-scale ocean currents, ice-sheet and glacier changes, and sea-level rise [68].

The GRACE and GRACE-FO missions have been providing monthly time-variable gravity field estimates since 2002. This has provided unique and valuable information on large-scale mass redistribution within the Earth system. This has led to a better understanding of mass fluxes within Earth's near-surface fluid envelopes and the relationship with global climate change and variability [69]. In addition, GRACE/GRACE-FO is expected to make significant advances in knowledge of time variable gravity fields and mass redistribution in combination with satellite altimetry (e.g., ICESat, CryoSat-2, and ICESat-2), other remote sensing techniques, and ground-based gravity observations. With appropriate data-fusion procedures, these datasets are valuable inputs to investigate time variable gravity fields.

Space gravity measurements have been mainly used to study temporal mass variations at the Earth's surface and within the mantle. Nevertheless, recent studies indicate that mass variations due to the Earth's core might be observable in the variations of the gravity field, as measured by GRACE and GRACE-FO satellites. Moreover, a possible correlation between the variable gravity and magnetic fields has been pointed out to exist at decadal time scales. To access these gravity variations, other known surficial effects must be corrected, such as hydrological, oceanic, or atmospheric loadings. However, these corrections also add errors to the final product. Earth's core dynamical processes inferred from geomagnetic field measurements are characterized by large-scale patterns. Studying them via gravity field observations involves using low-degree spherical harmonic coefficients, saying up to degree and order 8. Lecomte et al. [70] compare the corrections of several glacial isostatic adjustments, hydrological, oceanic, and atmospheric loading models for these large scales. These comparisons provide an estimate of the uncertainty associated with each correction. With the benefit of nearly two decades of space gravity data, a time-varying gravity field product was finally obtained, which considered the multiple corrections indicated above. This offered the possibility to revisit the correlation analyses between the gravity and magnetic fields.

As the oceans and atmosphere have warmed over the past decades, ice sheets and glaciers have experienced increased melting [71]. Mascon products derived from GRACE satellite gravimetry data are widely used to study the Greenland ice sheet (GrIS) mass balance. However, the products released by different research groups – JPL, CSR, and GSFC – show noticeable discrepancies. To understand them, Ranet al. [72] compared those mascon products with mascon solutions computed in-house using a varying regularization parameter. The results suggested that the observed discrepancies are likely dominated by differences in the applied regularization. Furthermore, they demonstrated that the quality of mascon-based estimates could be increased by a proper modification of the applied regularization: no correlation between masconsis assumed when they belong to different drainage systems. Yue et al. [73] retrieved the surface elevation change (SEC) over Antarctic from ICESat, CryoSat-2, and ICESat-2 data. They found a large SEC decline on the Antarctic Peninsula and the coastal regions of the East Antarctic. The Amundsen Sea Embayment suffers the largest mass loss of the Antarctic ice sheet, and the maximum annual variation rate was larger than −10 m/yr; the SEC time series revealed that this decline accelerated significantly around 2006. Meanwhile, the satellite gravimetry product (GRACE and GRACE-FO) also indicated that the Antarctic ice sheet increased mass loss after 2006 and acceleration after 2010. Wang et al. [74] determined the recent status of High Mountain of Asia (HMA) glaciers based on the first analysis of Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) data. They found a good agreement between ICESat-1/2 and GRACE/GRACE-FO data, which demonstrates the high reliability of the results. Based on their results, the continuous glacier mass change from 2003 to 2019 is -28 ± 6 Gt yr^{-1}, which is more negative than studies based on stereo images. The regional variability of glaciers ranges from -1.07 ± 0.10 m/yr in southeastern Nyaingentanglha to $+0.16 \pm 0.10$ m/yr in West Kunlun. ICESat-2 data provide new insights into the elevation change of continuously measured HMA glaciers.

Regarding the application of SG to geodetic measurements of time-variable gravity fields, starting in 2009, an SG began operating at Apache Point Observatory (APO) in New Mexico. The purpose of the project was to provide geodetic information to assist the modelling of Lunar Laser Ranging measurements in an attempt to reduce the error in the Earth-Moon distance to less than 1 cm. The Observatory-type instrument, SG046, operated in two time periods, 2009–2012 and 2013–2018, between which improvements to the sensor were undertaken at the GWR facility in San Diego. APO is at an altitude of 2799 m, perched on the edge of an escarpment that falls some 1600 m east of the SG. Consequently, two traditional corrections to the observed gravity, the local atmospheric pressure admittance, and the local hydrology admittance, have to be computed explicitly from high-resolution local topography, a situation faced by other SG sites in mountainous areas. It was found that the pressure admittance was not significantly affected by the topography, but there is an altitude effect to be considered [75]. On the other hand, the hydrology admittance is significantly enhanced (by almost a factor of 2) over the Bouguer plate value (0.042 mGal/mm water) normally assumed in hydrology modelling. This is due to precipitation significantly below the SG. This enhanced admittance is an important parameter for the correct performance of the hydrology models. Mou et al. [76] reported the important contribution of using SG simultaneous measurements during the 10th International Comparison of Absolute Gravimeters (ICAG-2017). Sixty-four consecutive days of observations were made with GWR-iGrav#012K SG at the Changping Campus of the National Institute of Metrology (NIM), China. The gravity variations observations from GWR-iGrav#012K SG gave an important correction to all the participating absolute gravimeters and influenced the comparison reference values. Hwang and Lien [77] measured gravity changes at the superconducting gravity station SG49 and several groundwater-sensitive gravity sites to examine how groundwater altered the gravity values in Tatun Volcanic Group (TVG). The results indicated incoherent variations between groundwater and gravity changes in eastern TVG, suggesting highly heterogeneous subsurface formations with fractures and barriers. The porous media can provide conduits for fluid migrations to great depths in the hydrothermal reservoirs of TVG. Luan et al. [78] analyzed iGrav-007 SG measurements in Kunming, China. After removing the Earth tides, atmospheric loading, non-tidal oceanic loading, polar motion effects, and linear drift, they found a good agreement between the SG residual gravity variations and the groundwater level variation.

In addition, hybrid gravimetry using both absolute and relative gravimeters is an efficient tool for monitoring mass redistribution. Chen et al. [79] applied Bayesian gravity adjustment to the hybrid gravity network in southeastern Tibet, and found that the crustal mass redistributions in this region are possibly controlled by active block boundaries and fluids distributed in the deep crust.

2.6. Monitoring of subsurface fluids

Networks of ground-based receivers of the GNSS technique constitute an incredible source of information about global, regional, and local geophysical phenomena, including postglacial rebound effects, plate tectonics, or environmental loading of Earth's crust induced by redistribution of masses within the Earth system. The latter corresponds to, e.g., changes in the terrestrial hydrosphere, named total water storage (TWS). Those studies are based on the position time series of permanent GNSS stations, which are also referred to as displacement time series. Plurality of geophysical effects seen within GNSS displacement time series cause problems with assessing the exact GNSS sensitivity. It was proven that GNSS is sensitive to geophysical effects of large magnitudes, but its sensitiveness to geophysical effects of small magnitudes remained unanswered. GNSS displacement time series enable monitoring of Earth's crust displacements induced by local and regional hydrological changes; both have been proven in terms of long-term trends and annual oscillation. However, the sensitiveness of GNSS to certain hydrological components, as groundwater changes, is still an open question. Boguszet al. [80] studied 14 regions using 140 GNSS permanent stations and GRACE/GRACE-FO observations. To estimate groundwater-induced displacements, both GNSS and GRACE-determined displacement time series were reduced by other TWS compartments using two hydrological models, namely GLDAS (Global Land Data Assimilation System) and WGHM(WaterGAP Global Hydrology Model); finally, TWS values were converted to displacement time series. The study showed that the largest vertical displacements were observed for areas of Africa and Jordan which were caused by decreasing groundwater level. For both areas, the largest positive trends were obtained for both GNSS and GRACE/GRACE-FO displacement time series. For the GNSS displacement time series, estimates of annual amplitudes were larger than those estimated for GRACE/GRACE-FO and the WGHM model, which are 71% and 96% of the GNSSvalues, respectively. For all tested areas, the groundwater-induced displacements estimated from GNSS and GRACE-GRACE-FO are characterized by mean correlation coefficient of 0.44.

The Earth's mass distribution is continuously changing due to physical processes taking place either beneath the subsurface or on the surface. Some of the primary sources for these mass variations are tides in the ocean and solid Earth, atmospheric disturbances and seasonal climate changes. SGs are suitable instruments to characterize and monitor such mass variations on wide time scales at the pico-g precision (where g is the Earth's mean gravity field value of 9.81 m/s^2). Since May 2019, two SGs (iOSG-24 and iGrav-31) have been continuously recording the time-varying gravity field in the multidisciplinary underground research laboratory of Rustrel (LSBB), in the south of France. The unique configuration of these two SGs located 520 m depth apart has provided several new insights into the understanding of hydrological processes occurring in the LSBB karst aquifer of the Fontaine de Vaucluse catchment. Kumar et al. [81] compared differential and residual gravity time-series together with the recent ECMWF Reanalysis (ERA5) global hydrological loading model. They found that most water-storage changes occur in the unsaturated karst zone between both SGs. The misfit between the residual gravity time-series and the local hydro-gravity effect computed from the ERA5 model showed large lateral fluxes and rapid runoff occurring in the LSBB.

He et al. [82] validated a new method for implementing the quantitative separation of the groundwater storage changes in the vadose zone based on a single SG (GWR-C032)and groundwater level observation data at the Wuhan National Geodetic Station (Wuhan Station), China. The calculation results showed that the change in the groundwater storage in the vadose zone obtained using the superconducting gravity technique is in good agreement with that obtained using the local hydrological modeling method, indicating that the quantitative separation of the change in the groundwater storage in the local vadose zone can be achieved using superconducting gravimeterand groundwater level observations.

Gravity observations made at the Metsähovi Geodetic Research Station, Finland, with two co-located very sensitive SGs show the underlying mass changes. To improve the understanding and modelling of the local hydrological changes in Metsähovi, Raja-Halliet al. [83] have made an extensive setup of hydrological sensors to monitor the rapid water table and soil moisture changes in the soil above the crystalline bedrock as well as the slower changes within the underlying fractures of the bedrock, from where the household water of the station is pumped. To understand the wider area water balance, they used the water reservoir estimates of the Finnish Environmental Institute for the whole runoff area around Metsähovi as well as for the entire Finland.

Zhang et al. [84] calculated the regional gravity changes and 3-D crustal deformations based on geodetic datasets, such as campaign gravity, GNSS, and leveling observations in the northeastern TP. The gravity changes show obvious negative–positive patterns across the Qilian thrust belt, which suggests that the northeastern TP thrust towards the North China Craton block beneath the Qilian thrust belt. Combined with GNSS and leveling observations, this study indicates a mid-lower crustal flow occurring beneath the northeastern TP.

3. Conclusions

The Geodynamics and Earth Tides Symposium offered a discussion platform to scientists involved in the interpretation of high precision geodetic and gravity field observations, both with terrestrial and on-satellite instrumentation. The Earth processes that are monitored with the observations cover the time scales from seismic waves to quasi-static earth deformations and involve mass changes in the atmosphere, hydro- and cryosphere, and in all earth layers, from the inner core to the upper crust. Inherently the problem of modelling the observations requires the interaction of an interdisciplinary community of scientists, reflecting the broad range of topics that must be known and modelled to fully exploit the high precision data series and push the knowledge to novel findings. With the development in the multidisciplinary approaches, the geodynamics research has been progressing fast, as well as the range of temporal and spatial scales on which geodynamic phenomena can be observed by modern instrumentation and monitoring systems. The high precision and continuous geodetic measurements from ground to space have advanced our knowledge of geodynamic phenomena, e.g., earthquakes, Earth rotation, mass redistribution, and climate change. The 19th G-ET symposium attracted ~400 international attendees and provided a platform for discussing a wide array of theoretical aspects and applications of geodetic and geophysical observations. A selection from the presentations is published in the Geodesy and Geodynamics Journal and Pure and Applied Geophysics.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geog.2022.11.003.

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