French National Report on the

GEODETIC ACTIVITIES

In the years 2019 to 2022

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In addition to the bibliography at the end of each section, we recommend the following web sites:

Form@Ter : www.poleterresolide.fr

EOST : https://eost.unistra.fr

CNES : https://sciences-techniques.cnes.fr/fr/web/CNES-fr/7352-sciences-de-la-terre.php

CNAM : www.esgt.cnam.fr/recherche (laboratoire-geomatique-et-foncier-gef)

IGN : https://geodesie.ign.fr

SHOM : www.shom.fr/fr/nos-activites/recherche-et-innovation

UPF : http://gepasud.upf.pf

PREFACE

For the compilation of the national report covering the scientific activities of the past 4 years it was decided to follow the structure of previous national reports and divide it into 4 commissions according to the structure of the International Association of Geodesy (IAG):

Commission 1: Reference Frames
Commission 2: Gravity Field
Commission 3: Geodynamics and Earth Rotation
Commission 4: Positioning and Applications
and
International Scientific Services

In addition, due to the significant investments of France in altimetry missions and ocean research and services (physical sciences of the oceans promoted by the International Association for the Physical Sciences of the Oceans, IAPSO), it was decided to add a section dedicated to that domain which includes numerous developments in space geodesy.

On behalf of the French Geodetic section of CNFGG, February 2023

Secretary	President
P. Exertier	S. Rosat / M.F. Lalancette

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1. Reference Frames

Our planet Earth is constantly deforming under the effects of geophysical and environmental processes that cause linear and nonlinear displacements of the geodetic stations upon which the International Terrestrial Reference Frame (ITRF) is established. The ITRF has traditionally been defined as a secular (linear) frame in which station coordinates are described by piecewise linear functions of time.

Nowadays, some particularly demanding applications require more elaborate reference frame representations that can accommodate non-linear displacements of the reference stations. Two such types of reference frame representations have been studied already: the usual linear frame enhanced with additional parametric functions such as seasonal sine waves, and non-parametric time series of quasi-instantaneous reference frames.

ITRF 2020

More than 30 years of space geodetic data have been reprocessed by the International Association of Geodesy technique Services and submitted to compute the new realization of the International Terrestrial Reference System (ITRS).

The new realization, ITRF2020, intends to replace ITRF2014. It is provided in the form of an augmented reference frame so that in addition to station positions and velocities, parametric functions for both post-seismic deformation and seasonal signals (expressed in the Center of Mass frame derived from Satellite Laser Ranging data) will also be delivered to the users. The main results of ITRF2020 analysis have been presented largely into the community and the solution has been evaluated from internal consistency via some key performance indicators. In particular, the level of the scale agreement between the four techniques, its linear and nonlinear time evolution, and the strategy adopted for the ITRF2020 scale definition. In addition, the performance of the parametric functions for both seasonal and post-seismic deformation signals have been evaluated, in addition to the level of consistency between the four techniques (DORIS, GNSS, SLR, VLBI) at colocation sites.

Future GENESIS mission

Improving and homogenizing time and space reference systems on Earth and, more specifically, realizing the Terrestrial Reference Frame (TRF) with an accuracy of 1 mm and a long-term stability of 0.1 mm/year are relevant for many scientific and societal endeavors. The knowledge of the TRF is fundamental for Earth and navigation sciences. For instance, quantifying sea level changes strongly depends on an accurate determination of the geocenter motion but also of the positions of continental and island reference stations, such as those located at tide gauges, as well as the ground stations of tracking networks. Also, numerous applications in geophysics require absolute millimeter precision from the reference frame, as for example monitoring tectonic motion or crustal deformation, contributing to a better understanding of natural hazards. The TRF accuracy to be achieved represents the consensus of various authorities, including the International Association of Geodesy (IAG), which has enunciated geodesy requirements for Earth sciences.

Moreover, the United Nations resolution 69/266 states that the full societal benefits in developing satellite missions for positioning and Remote Sensing of the Earth are realized only if they are referenced to a common global geodetic reference frame at the regional, national, and global levels. Today we are still far from these ambitious accuracy and stability goals for the realization of the TRF. However, a combination and co-location of all four space geodetic techniques on one satellite platform can significantly contribute to achieving these goals. This is the purpose of the GENESIS mission, a component of the ‘‘Future NAV’’ program of the European Space Agency.

The GENESIS platform will be a dynamic space geodetic observatory carrying all the geodetic instruments referenced to one another through carefully calibrated space ties. The co-location of the techniques in space will solve the inconsistencies and biases between the different geodetic techniques in order to reach the TRF accuracy and stability goals endorsed by the various international authorities and the scientific community.

Interest of ITRF solutions for Geosciences

Questions about the accuracy of the origin of the different versions of International Terrestrial Reference Frame (ITRF), have been regularly raised. In particular the origin drift between ITRF2000 and ITRF2005 (and subsequent solutions) is well-known to be problematic.

Geophysical signals provide an independent evaluation of ITRF solutions. The GNSS vertical velocity field provided by the last four ITRF solutions (ITRF2000 to ITRF2014) has been compared with different Global Isostatic Adjustment (GIA) model predictions (e.g., Métivier et al.). As a result, each new ITRF solution appears to be more and more consistent with all GIA predictions, except ITRF2014 whose consistency with the GIA models depends on the date of observation. Indeed, GNSS observations and GIA predictions appear consistent at global scale at a level of ~4 mm/yr using ITRF2000 data, ~2.5–3 mm/yr using ITRF2005 data, and ~2 mm/yr using ITRF2008 data (global weighted root mean squares).

As for ITRF2014, the consistency between GNSS observations and GIA predictions is extremely high in 2000 (~1.5 mm/yr) but seems then to decrease with time (~2 mm/yr in 2013). This discrepancy is very probably due to the recent ice melting effect that is not accounted for in GIA models, but clearly evidenced by ITRF2014 vertical velocities during the last years of observations, in particular in Greenland.

The Calern Geodetic Observatory at OCA (Grasse, France)

In addition to SLR and LLR, GNSS and DORIS space techniques, the French Calern geodetic Observatory (Observatoire de la Côte d'Azur, OCA) is developing a multi-technique approach. Recently a new artificial corner reflector (CR) has been designed and deployed in conjunction with InSAR instruments and satellites as Sentinel-1A/-1B. Although still few in number, such reflectors are an integral part of the Global Geodetic Observing System (GGOS) infrastructure. They can be used as a stable radar target in SAR images to connect local InSAR deformation maps to the global Terrestrial Reference Frame and for SAR absolute determination.

During a test phase, the orientation of the CR was changed in order to be aligned toward all possible orbits of Sentinel-1A/1B satellites. On the different SAR images, the CR exhibits a high backscattering signal, and provides a Signal-to-Clutter Ratio larger than 26 dB. Since December 2018, the CR is specifically oriented toward the relative orbit 88. It is clearly detected as a PS in the InSAR analyses and as expected, the standard deviation of displacement measured on the CR is lower than on surrounding PS. A first local survey was performed to locate precisely this CR with respect to the existing geodetic instruments and annual campaigns have been carried out since then to insure its stability over time.

Tahiti Geodetic Observatory

The Tahiti Geodesic Observatory (OGT), founded in 1998, is part of a network of twenty of similar observatories on the Earth's surface, and through its data participates in modelling and climate prediction. It contributes to this objective on several levels:

1. The long-term maintenance of a stable reference mark (ITRF) in relation to stars, Earth's surface mass transfers and reliable modelling of the orbits of artificial satellites, by acquiring the data mentioned in points 2/ and 3/ which follow. This model, is regularly computed with new data and then is distributed.

2. Ultra-precise remote observations by laser tracking of artificial geodetic satellites, navigation satellites (known as GNSS), and radar altimetry satellites that allow level tracking from space. The OGT is the only observatory that allows laser tracking within a 4000 km.

3. Radio-electric observations of navigation satellites (GNSS), with data modelling of atmospheric water vapor by the delays it causes on the radio wave propagation

4. Surface observations of sea level variations by a five geodetic tide gauge system, which allow to have a truth-terrain for spatial data and coastal data inaccessible to satellites.

J.P. Barriot

Since few years, a group of French Agencies for space, geodesy, geophysics and oceanography is working to find ways for a new development of this Observatory, taking into account its geographical situation in the South Pacific Ocean.

One of the main goals is to develop a new (k-Hz) laser ranging station (on the French side) which should be automated, and to deploy a new generation VLBI antenna which should be provided by NASA (Space Geodesy Program).

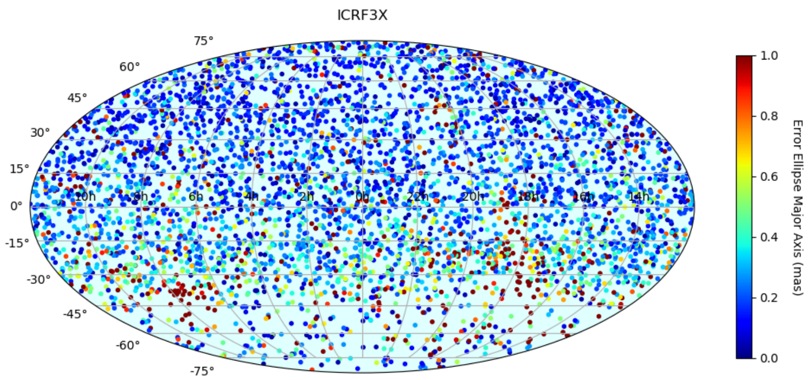
Celestial Reference Frame, Astrometry

As of January 1, 2019, ICRF-3 (Charlot et al. 2020) has become the fundamental celestial reference frame replacing ICRF2. Established by the analysis of almost 40 years of VLBI measurements, this benchmark is more accurate than its predecessor by a factor of 3 (median accuracy), contains more sources (4535 vs 3414) and, above all, corrects two major systematic effects compared to ICRF2, thus improving the accuracy of the marker. First, the drift (slow but clearly perceptible thanks to the precision of the data) of the positions caused by the Galactic aberration - detected for the first time in 2013 by the Syrte laboratory (Observatoire de Paris) and modelled upstream (MacMillan et al. 2019).

Secondly, the comparison with Gaia's DR2 allowed to remove the doubt as to the existence of zonal errors: these decreased considerably between ICRF2 and ICRF3, thanks to an increased number of data and a denser network in the southern hemisphere.

Finally, for the first time, the ICRF3 is a multi-wavelength frame, the coordinates of certain sources being given at 8 GHz, 22 GHz and 32 GHz. Let us also recall that ICRF is now the union of the radio part (VLBI, ICRF3) and the optical part (Gaia-CRF3, Gaia Collaboration, Klioner et al. 2022) to which we contributed via the Gaia consortium and the validation group (Fabricius et al. 2021). We have also developed methodologies for assessing the stability and accuracy of frames, based on comparisons with independent solutions or on AGN's astrometric position time series (Liu et al. 2022; Lambert and Malkin 2023).

In recent years, the French astrogeodetic team (OP/Syrte) has increasingly focused its work on an astrometric approach to AGN physics in order to better identify radio and optical emission mechanisms and isolate sub-parts of populations aligned or not with the most classical spectral classes determined by the morphology, color or dynamics of the jets. These studies are both a strong enhancement of the VLBI and Gaia astrophysical data (astrophysics of high energies) and will in turn guide the choices to build future celestial reference frames.



ICRF3: color is like astrometric precision (Charlot et al. 2020)

In Lambert et al. (2021), the comparison of the absolute positions of hundreds of four-frequency (radio and optical) AGNs with parsec-scale radio structures demonstrated the systematic shift of high frequencies within the jet (towards the central black hole) while the optics are more outward from the jet and often coincident with a highly polarized radio component (synchrotron emission). This study is currently continuing with the identification of very high energy emission zones (gamma rays) and the signature of light discs in some AGN populations.

Other studies complementary to the previous ones have been devoted to 'abnormal' behaviors detected by VLBI and/or GAIA. Souchay et al. (2022) used the Large Quasar Astrometric Catalog (a compilation of quasars catalogues established at OP/Syrte and, by construction, broader than the current set of surveys) as a statistical basis to isolate the abnormal own movements of Gaia EDR3 (> 10 mas/year) and separate those potentially due to halos or companions from those requiring specific monitoring in the coming years to determine the causes.

GAIA early data release 3

Gaia-CRF3 is the celestial reference frame for positions and proper motions in the third release of data from the *Gaia* mission, *Gaia* DR3 (and for the early third release, *Gaia* EDR3, which contains identical astrometric results). The reference frame is defined by the positions and proper motions at epoch 2016.0 for a specific set of extragalactic sources in the (E)DR3 catalogue. The construction of *Gaia*-CRF3 is described and its properties in terms of the distributions in magnitude, colour, and astrometric quality.

Methods. Compact extragalactic sources in *Gaia* DR3 were identified by positional cross-matching with 17 external catalogues of quasi-stellar objects (QSO) and active galactic nuclei (AGN), followed by astrometric filtering designed to remove stellar contaminants. Selecting a clean sample was favored over including a higher number of extragalactic sources. For the final sample, the random and systematic errors in the proper motions are analyzed, as well as the radio-optical offsets in position for sources in the third realization of the International Celestial Reference Frame (ICRF3).

Results. *Gaia*-CRF3 comprises about 1.6 million QSO-like sources, of which 1.2 million have five-parameter astrometric solutions in *Gaia* DR3 and 0.4 million have six-parameter solutions. The sources span the magnitude range $G = 13–21$ with a peak density at 20.6 mag, at which the typical positional uncertainty is about 1 mas. The proper motions show systematic errors on the level of 12 µas yr^{-1} on angular scales greater than 15 deg. For the 3142 optical counterparts of ICRF3 sources in the S/X frequency bands, the median offset from the radio positions is about 0.5 mas, but it exceeds 4 mas in either coordinate for 127 sources. We outline the future of *Gaia*-CRF in the next *Gaia* data releases. Appendices give further details on the external catalogues used, how to extract information about the *Gaia*-CRF3 sources, potential (Galactic) confusion sources, and the estimation of the spin and orientation of an astrometric solution.

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2. Gravity Field

For more than fifteen years, the Gravity Recovery And Climate Experiment (GRACE) mission and its Follow-on (GRACE-FO) mission has measured the time variations of the Earth's gravity field with an unprecedented precision of 2–3 cm on the geoid height at the spatial resolution of about 300 km. Several French teams are involved in the data treatment (CNES/GRGS 10-day gravity field models) and applications of GRACE products.

On the one hand, GRACE intersatellite accelerations are used to monitor Earth's mass variations in different components of the climate system, including regional to global scale terrestrial water storage (TWS) change, flood and drought detection, groundwater depletion, water storage change in snow and surface reservoirs, polar ice sheets and mountain glacier ice-mass change, global sea level change, and others.

On the other hand, GRACE satellite gravimetry provides a global tool for studying solid Earth deformation due to large earthquakes and Glacial Isostatic Adjustment (GIA). Thus, a comprehensive review of GRACE/GRACE-FO satellite gravimetry was carried out describing: time-variable gravity fields, data processing methods, and major applications in several different fields, including terrestrial water storage change, global ocean mass variation, ice sheets and glaciers mass balance, and deformation of the solid Earth. In addition, there are several major challenges related to the potential of satellite gravimetry in detecting gravitational changes that are believed to originating from the deep Earth's interior.

Detecting pre-seismic signals in GRACE gravity solutions

Retrieving pre-seismic signals before the occurrence of great subduction earthquakes is a major goal for seismic hazard mitigation. It requires a continuous monitoring of the deformations within the entire subduction system, from surface to depth along the descending slab and in the region surrounding the subduction zone. Space geodesy and seismicity provide monitoring of seismic events and shallower aseismic motions, but the full spectrum of transient deformations of the pulling slab at depth remains mostly unknown. Their detection is crucial, as they might precede shallower deformations and foreshocks that would result from their upward propagation.

Time-varying satellite gravity can overcome this observational limit, thanks to a unique sensitivity to mass redistributions at all depths and a global coverage. A method has been developed to identify solid Earth signals along plate boundaries in the time series of GRACE geoid models. The results underline the unique nature of the pre-seismic signals of the 2011 Tohoku earthquake with respect to water cycle contributions and noise (e.g., Panet et al.). The potential of space gravimetry to detect pre-seismic mass redistribution has been confirmed in the case of the 2010 Maule-Chile earthquake by Bouih and co-authors.

Simulations and new design for future gravity missions

From 2002 to 2017, the GRACE mission provided unparalleled information on the variable component of the Earth's gravity field. In May 2018, GRACE-FO was launched to pursue GRACE measures. These two missions are based on the principle of very accurate measurement of the distance between two co-orbiting satellites in a quasi-polar orbit at 450 km altitude. The separation between the two satellites is around 200 km. The accuracy of the distance measurement between the two satellites is 1 micrometer for GRACE (K-band radio system). It reaches 50 nanometers for GRACE-FO thanks to a probationary laser interferometer.

These two missions measure gravitational disturbances on the Earth's surface with an ultimate spatial resolution of 200 km. At this resolution the measurement uncertainty is about 3 cm in Equivalent Water Height (EWH), but it reaches around 1 cm at 1000 km. The temporal resolution is monthly, even 10 days. However, some limitations appeared so far: *i)* because of the near-polar orbits and the north-south orientation of the measurement, zonal perturbations are much better than sectoral ones, *ii)* simulations have shown that, due to the "along-track" character of the measurement, even in the case of perfect simulations (without instrumental noise or model noise) the precision of the gravity field restitution was limited to ~1 cm EWH, and *iii)* the new GRACE-FO mission unfortunately suffers from a deficiency of the accelerometer onboard one of the two satellites. Thus, it seems to be difficult, despite an inter-satellite measurement accuracy 20 times greater for GRACE-FO, that it will reach the performance of the former.

These various considerations make it urgent to study a new, innovative space gravimetry mission and versatile, which provides the Earth's gravimetric measurement with the continuity needed for its scientific and societal applications. This is the MARVEL (Mass And Reference Variations for Earth Lookout) project.

MARVEL

A new project of gravity mission has been studied during 2019-2020, by CNES (French National space agency) and collaborators with same goals as for GRACE (& -FO) but with an increased sensitivity. The target in terms of mass transfer observation is to reach an accuracy of the monthly solutions at least 5 times better than GRACE missions, i.e. 5 mm EWH at degree 50, and 100 mm at degree 100. The target in terms of reference frame accuracy and stability is 1 mm / 0.1 mm/y (as defined by the GGOS requirements). The scientific benefits from such a mission are multiple in many areas of science (hydrology, oceans, cryosphere, GIA, earthquakes, deep mass transport and its near-surface component via crustal deformations, internal response to surface water loads, etc.).

The principle is to develop both a high and low constellation: above 7000km (of min. 2 satellites, with a micro-accelerometer) and below 450 km (min. 1 satellite equipped with laser beam (one or two-way technique, a micro-accelerometer, a GNSS receiver). That could provide:

- a measure not just "along-track", and with a strong radial component,
- a constellation of satellites providing better temporal coverage,
- the possibility of later adding satellites to the original constellation in the future,
- an innovative inter-satellite measurement (two-way Laser measurement at the micron),
- multi-purpose scientific objectives (Earth Reference System and Earth Gravimetric Measurement)
- the possibility of considering nano-satellites for the upper part of the constellation.

Three scenarios have been defined with different costs and with different scientific ambitions: a nominal configuration, a ''Nanosat'' version, and a GNSS version. In this context, and following the recommendations of the 2019 CNES scientific prospective seminar, a pre-Phase-A study was launched in January 2020 at CNES on the concept of the MARVEL mission.

Water mass changes from GRACE data

A new approach to recover water mass changes from GRACE satellite data at a daily temporal resolution has been developed. Such a product can be beneficial in monitoring extreme weather events that last a few days and are missing by conventional monthly GRACE data (e.g., Ramilien et al.).

The determination of the distribution of these water mass sources over networks of juxtaposed triangular tiles was made using Kalman Filtering (KF) of daily GRACE geopotential difference observations that were reduced for isolating the continental hydrology contribution of the measured gravity field. Geopotential differences were obtained from the along-track K-Band Range Rate (KBRR) measurements according to the method of energy integral. The recovery approach was validated by inverting synthetic GRACE geopotential differences simulated using GLDAS/WGHM global hydrology model outputs. Series of daily regional and global KF solutions were estimated from real GRACE KBRR data for the period 2003–2012. They provide a realistic description of hydrological fluxes at monthly time scales, which are consistent with classical spherical harmonics and ''mascons'' solutions provided by the GRACE official centers but also give an intra-month/daily continuity of these variations.

Seafloor Topography from Marine Gravity data

Accurate knowledge of the Earth's topography remains fundamental to understand surface processes. Detailed mapping of the sea floor topography (bathymetry) is essential for studies in oceanography, biology, marine geology, natural disasters, airline crashes over ocean habitat loss and marine resources. In oceanography, currents and tides physical characteristics are controlled by the shape of the seafloor as well as smaller-scale topographic features like seamounts.

An iterative Extended Kalman Filter (EKF) approach has been proposed to recover a regional set of topographic heights composing an undersea volcanic mount by the successive combination of large numbers of gravity measurements at sea surface using altimetry satellite-derived grids and taking the error uncertainties into account.

The integration of the non-linear Newtonian operators versus the radial and angular distances (and its first derivatives) enables the estimation process to accelerate and requires only few iterations, instead of summing Legendre polynomial series or using noise-degraded 2D-FFT decomposition. To show the effectiveness of the EKF approach, we apply it to the real case of the bathymetry around the Great Meteor seamount in the Atlantic Ocean by combining only geoid height/free-air anomaly datasets and using ship-track soundings as reference for validation. Topography of the Great Meteor seamounts structures are well-reconstructed, especially when regional compensation is considered. Best solution gives a RMS equal to 400 m with respect to the single beam depth observations and it is comparable to RMS obtained for ETOPO1 of about 365 m. Larger discrepancies are located in the seamount flanks due to missing high-resolution information for gradients.

Underwater Mobile Gravimetry

Today, the study of the structure of the seafloor at tens to a few kilometers largely rely on high-resolution bathymetry and magnetism, particularly when conducted close to the seafloor onboard Autonomous Underwater Vehicles (AUVs). Meanwhile, sea surface gravity surveys carried out onboard oceanographic vessels have revolutionized our vision of the structure of the oceanic crust revealing a high spatial and temporal variability. The development of a new type of gravimetric sensor with a small footprint and low energy consumption, suitable for installation onboard AUV appears essential to meet the problem posed by the measurement of the Earth's gravity field near seafloor with unprecedent accuracy and spatial resolution.

Therefore, a new gravimetric system named GraviMob (Mobile Gravimetry System) has been developed. This system is inspired by the LIMO-g system (Light Mobile Gravimetry System) whose development was initiated in 1999 by the French National Institute of Geographic and Forest Information (IGN), Compared to competing systems, GraviMob is the only one that can measure the gravity vector by determining its east, north and vertical components. The performance of Gravimob has been tested during two marine campaigns in the Mediterranean in 2021. The internal accuracy of the system in terms of repeatability and its external accuracy in comparison with reference surface gravity data were estimated at less than 4 mGal for a spatial resolution of 3 km.

Temporal variations of low degrees

Although the GRACE data have been largely used to determine the temporal variations of the gravity field, spectral signatures showed that the phenomena at the global scale, that correspond to the very low degrees of spherical harmonic modelling, were less well determined. The low degrees are representative of fundamental characteristics of the Earth, namely: i) the mass of the Earth for degree 0, ii) its center of mass for degree 1, iii) its inertia tensor for degree 2.

These terms are directly related to the scale of the Earth's landmark, its centering and rotation. Their variations or trends are all clues to the global evolution of the Earth, either directly or through applications especially in oceanography. The purpose of the works established in 2019 (e.g., Couhert et al.) was to study and exploit in synergy the various sources of spatial geodesy data: observations (DORIS, GNSS, SLR, GRACE), earth rotation parameters, and geophysical models (of winds and currents, surface masses and loads); these constrain the low degrees of gravity (zero, one and two) the goal being to improve their determination.

The study by Couhert et al. (2020) presents a self-consistent determination of these three properties of the Earth. The main objective is to deal with the remaining sources of altimetry satellite orbit uncertainties affecting the fundamental record of sea surface height measurements. The analysis identifies the modeling errors, which should be mitigated when estimating the geocenter coordinates from SLR observations. Uncertainties in the value of *GM* could be inferred. Overall, the influence of the orbit characteristics, SLR station ranging/position biases and satellite signature effects, measurement modeling errors (tropospheric corrections, non-tidal deformations) are also discussed. The long-term behavior of the degree-0 and -2 spherical harmonics over the 34-year period 1984–2017 finally put constraints on the Earth's rheology. Consistently improved determination of the low degree gravity coefficients remains a challenge for future space gravity missions.

Detecting core signals in space gravity solutions

The determination of the low degree gravity field variations requires a better consistency between the geodetic techniques and a more precise modeling in the surface mass redistribution models. The goal is to reach the precision required to detect core processes (e.g., Rosat et al. 2021). Currently, degree-2 SLR determined gravity coefficients from different analysis centers are beyond the equivalent mm accuracy targeted by GGOS making the detection of deep Earth's mass redistribution challenging.

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3. Earth Rotation and Geodynamics

Earth's rotation and Core Dynamics

The rotational motions of the internal Earth core layers induce resonances in the Earth nutation and tidal gravimetric responses to external luni-solar gravitational forcing. The characterization of these resonances is a mean of investigating the deep Earth properties since their amplitudes and frequencies depend on a few fundamental geophysical parameters.

In their work, Ziegler et al. (2020) have determined the free core nutation and free inner core nutation periods and quality factors using a Bayesian inversion of VLBI and Superconducting

Gravimeter data. A joint inversion of data from both techniques shows that, even if the results are only slightly different from the inversion of VLBI data alone (Huda et al., 2020), such approach may be valuable in the future if the accuracy of gravimetric data increases. The overall estimates of the FCN period and quality factor $T_{\mathrm{FCN}} = (-430.2, -429.8)$ solar days and $Q_{\mathrm{FCN}} = (15\,700, 16\,700)$, respectively, are in good agreement with other studies, albeit slightly different for unclear reasons. Despite some concerns about the detection and characterization of the FICN, it seems that we could also successfully estimate its period, $T_{\mathrm{FICN}} = (+600, +1300)$ solar days, and give a loose estimate of the upper bound on its quality factor.

Earth's polar motion and Length of day

The Earth's rotational response under surficial layers forcing exhibit a resonance in the diurnal frequency band related to the Chandler Wobble (e.g., Bizouard et al.). In addition, the response to zonal tide components can be described by admittance coefficients. Same authors have shown that removing the atmospheric-oceanic excitation from length-of-day (LOD) allows to better constrain the admittance complex coefficients than applying the atmospheric correction only. They have also noted the role of land water and associated sea level variation at the semi-annual period.

The polar motion and the axial rotation (associated with LOD) of the Earth have also been determined from the degree-2 gravity field space measurements by Zotov et al. (2022).

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4. Positioning and Applications

Vertical land motion at tide gauges for sea level Science

A reanalysis of Global Navigation Satellite System (GNSS) data at or near tide gauges worldwide was produced by the University of La Rochelle (ULR) group within the third International GNSS Service (IGS) reprocessing campaign (repro3). The new solution, called ULR-repro3, complies with the IGS standards, implementing advances in data modelling and corrections since the previous reanalysis campaign and extending the average record length by about 7 years.

The results focus mainly on the products of interest for sea level science: the station position time series and associated velocities on the vertical component at tide gauges. These products are useful to estimate accurate vertical land motion at the coast and supplement data from satellite altimetry or tide gauges for an improved understanding of sea level changes and their impacts along coastal areas. To provide realistic velocity uncertainty estimates, the impact of non-tidal atmospheric loading in the position time series was investigated. Overall, the ULR-repro3 position time series show reduced white noise and power-law amplitudes and lower station velocity uncertainties compared with the previous repro2 analysis. The products are available via the SONEL website (see section below about ‘‘International Scientific Services’’).

Multi-GNSS solution from GPS and Galileo

Two main evolutions in the geodetic positioning community have been: the arrival of Galileo data and products in view of the new solution ITRF2020 (IGS20), and the PPP-AR method. The Working Group on PPP-AR methodology from IGS has demonstrated that IGS products are now inter-operable.

Precise point positioning (PPP) has been used for decades not only for general positioning needs but also for geodetic and other scientific applications. The CNES-CLS Analysis Centre (AC) of the International GNSS Service (IGS) is performing PPP with phase ambiguity resolution (PPP-AR) using the zero-difference ambiguity fixing approach also known as “Integer PPP” (IPPP). This paper examines the post-processed kinematic PPP and PPP-AR using Galileo-only, GPS-only and Multi-GNSS (GPS + Galileo) constellations. The interest is to examine the accuracy for each GNSS system individually but also of their combination to measure the current benefits of using Galileo within a multi-GNSS PPP and PPP-AR. Results show that Galileo-only positioning is nearly at the same level as GPS-only; around 2–4 mm horizontal and around 10 mm vertical repeatability (example station of BRUX). In addition, the use of Galileo system -even uncompleted- improves the performance of the positioning when combined with GPS giving mm level repeatability (improvement of around 30% in East, North and Up components). Repeatability observed for multi-GNSS (GPS + GAL) PPP-AR, taking into account the global network statistics, are a little larger, with 8 mm in horizontal and 17 mm in vertical directions. This result shows that including Galileo ameliorates the best positioning accuracy achieved until today with GPS PPP-AR.

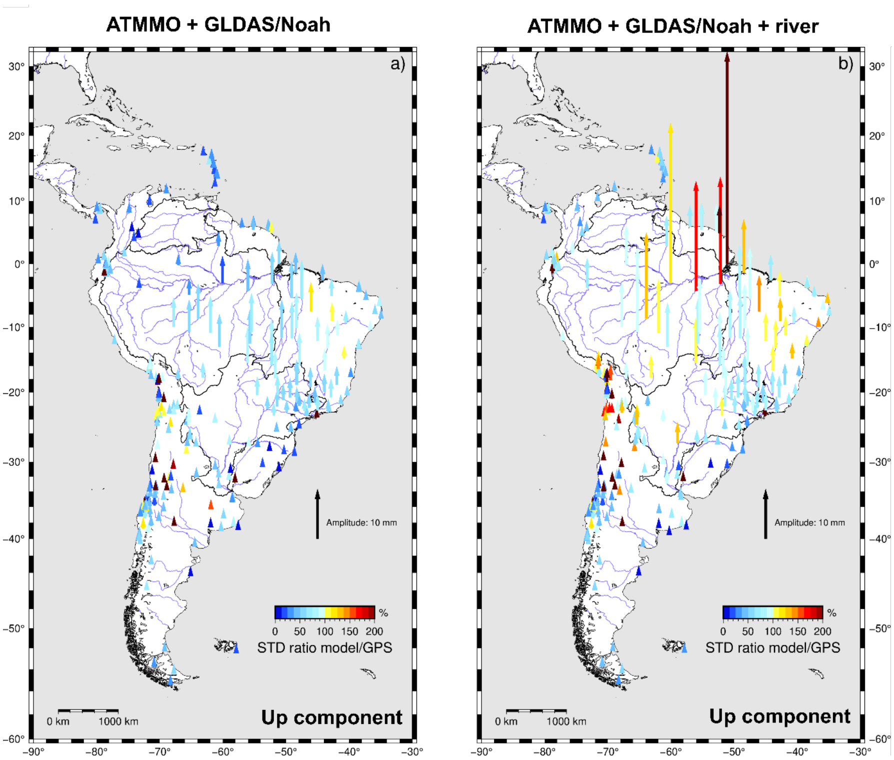
GNSS-R: new applications

Recent Global Navigation Satellite System Reflectometry (GNSS-R) studies take advantage of continuously emitted navigation signals by the GNSS constellations. In addition, it presents the advantage of sensing a whole surface around a reference GNSS antenna.

A first application of the GNSS-R technique consists to derive the local sea level variations by using the Signal-to-Noise Ratio (SNR) of the GNSS reflected signals. Four GNSS sites representing various ocean conditions (waves, tides, storm surges, …), tides estimate by SNR are highly consistent to tide gauges records as highlighted by tidal harmonic analysis, with a Root-Sum-Square (RSS) ranging from few cm in micro-tidal environment to near a decimeter in macro-tidal environment (Gravalon et al., 2022).

A second application of GNSS-R has been developed for monitoring the soil moisture dynamics in some areas where the signal is ambiguous. The study focused on sandy SM monitoring in the driest condition observed in the area of Dahra, (Senegal). It consists of 95% sand and in situ volumetric soil moisture (VSM) range from ~3% to ~5% during the dry to the rainy season (Ha et al., 2022).

A third application (GNSS-R) has been conducted in order to retrieve the water heights during asymmetric tides on a narrow river. A new process was developed to filter out the noise introduced by the environmental conditions on the reflected signal due to the narrowness of the river compared to the size of the Fresnel areas, the presence of vegetation, boats etc. Evaluation of the results showed that the quality of the retrieved heights was consistent, whatever the vertical velocity of the reflecting surface, and was highly dependent on the number of satellites visible (Zeiger et al., 2021).



Annual vertical observed GPS signal and loading model a) without and b) with the river contribution in South America. The length of arrows represents the annual term amplitude (in mm). The color represents the standard deviation ratio of the model with respect to GPS. ATMMO corresponds to atmosphere (ECMWF) and barotropic ocean loading (TUGO-m). Figure from (Nicolas et al., 2021).

Improved Hydrological Loading models in South America

The comparison of long GNSS positioning time series with loading signals computed from global models and those deduced from GRACE and GRACE-Follow On observations has been performed (Nicolas et al., 2021). The main achievements are the development and validation of the M-SSA (Multichannel Singular Spectrum Analysis) analysis method for 3D seasonal signal extraction and time series comparisons for many permanent GNSS sites as well as the validation of new hydrological loading models (not included in models such as GLDAS, MERRA…). Therefore, huge discrepancies exist between geodetic observations (GNSS, GRACE) and models around large rivers such as the Amazon, where nearly half of the vertical signal observed cannot be explained by the combination of loading models. The surface water contribution was obtained using river flow velocity adjusted from radar altimetry virtual stations and MODIS imagery. In the Amazon basin, the river contribution (ATMMO +GLDAS +river) explains most of the missing signal in the models (see Figure).

GNSS tropospheric delay and gradients

The computation of GNSS tropospheric parameters was conducted from 2013 to 2018 in the frame of the project COST Action GNSS4SWEC for meteorological and climate monitoring (Morel et al., 2021). The authors demonstrated that the gradient orientates towards the larger slopes when GNSS stations are close to mountains. They developed a dense tropospheric tomographic network around Le Mans (France) and optimized the PPP processing strategy considering tropospheric and ionospheric errors. The improved methodology was applied to the permanent GNSS stations on the Réunion island in the Indian Ocean (France), showing the impact on tropospheric delays of topography, of the Piton de la Fournaise volcano eruptions, and of hurricanes. The produced ionospheric delays can then be used for ionospheric modelling in different applications. The hence modelled GNSS tropospheric delays are used to improve InSAR deformation computation applied for geophysical and geotechnical applications.

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5. Space Techniques and Tools

Benefit of a second Calibration phase between Jason-3 and Sentinel-6a

The originality of this study is to propose a new calibration method based on two calibration phases between Jason-3 and Sentinel-6A (S6A) to better estimate the relative global and regional mean sea level drifts between the two missions.

A first calibration phase of approximately 12 months was planned from January 15, 2021, to December 31, 2021, when both satellites were on the same orbit spaced out by approximately 30 seconds. This calibration allowed for a very accurate assessment of the Global Mean Sea Level (GMSL) bias between Jason-3 and S6A (less than 0.5 mm).

A second calibration phase after a few years (1.5-2 yrs) would reduce the uncertainty levels of the GMSL drift estimate. The uncertainty would be low enough to detect any drift detrimental to the stability of the current GMSL record. It would indeed be possible to evaluate the stability between the two satellites with an accuracy at least 3 times better at the global scale (0.15 mm/yr) than with the most accurate method to date.

Laser Ranging for Geodesy, Telecom and Planetary missions

In December 2020, synchronous two-way laser ranging in deep space was successful for the first time over distances up to 6.46 million km. A laser altimeter aboard spacecraft Hayabusa2 was used as an optical transponder, detecting laser pulses emitted from the ground stations on Earth and retransmitting the pulses from the spacecraft to the ground. These retransmitted pulses were successfully detected at the ground station. The experiment was conducted as a demonstration of the deep-space laser ranging. The repetition frequency of the onboard instrument was limited to 0.5 Hz, and there was a lot of background noise because the experiments were carried out in daytime on the ground. Nevertheless, laser detection on the ground was still possible due to the high time-correlation between the detected and the predicted pulses in the presence of random noise.

Procedures similar to satellite laser ranging were applied to create residuals by subtracting the orbit predictions of the spacecraft from the observed round-trip time. Furthermore, some of the transponder return pulses were uniquely identified, where the time coherence of the measurements had been recovered from the telemetry data of the laser altimeter.

DORIS: Ultra-stable Oscillator; the frequency behavior under radiation

The DORIS on-board clock frequency stability is degraded by the increased radiation found in the region of the South Atlantic Anomaly (SAA) and has been shown to degrade station position estimation.

A new model correction to the DORIS data for the frequency of the Jason-2 Ultra Stable Oscillator (USO) was derived from the Time Transfer by Laser Link (T2L2) experiment (Belli and Exertier, 2018). It has been shown that a multi-satellite DORIS solution including this T2L2-corrected data applied to the frequency modelling improves the estimation of station coordinates. As a result, the tie residuals with respect to collocated GPS stations are improved by several millimeters. The 117-day (Jason-2) draconitic signal in the geophysical parameters is also reduced, implying that the origin of this signal is not just solar radiation pressure mis-modeling, but also radiation-induced clock perturbations on the Jason-2 DORIS Ultra-Stable-Oscillator (USO). Finally, comparisons with the International Earth Rotation and Reference Systems Service (IERS) C04 series for Earth Orientation Parameters (EOP), have shown an improvement in both a Jason-2 DORIS-only and a multi-satellite DORIS solution for EOP.

SARI: a tool for GNSS series analysis

GNSS position time series contain signals induced by earth deformation, but also by systematic errors, at different time scales, from sub-daily tidal deformation to inter-annual surface-loading deformation and secular tectonic plate rotation.

The SARI software (Santamaria-Gomez) allows users to visualize GNSS position time series, but also any other series, and interactively remove outliers and discontinuities, fit models and save the results. A comprehensive list of features is included to help the user extracting relevant information from the series, including spectral analysis with the ‘‘Lomb–Scargle’’ periodogram and wavelet transform, signal filtering with the Kalman filter and the ‘‘Vondrák’’ smoother, and estimation of the time-correlated stochastic noise of the residuals.

The software can be run on a local machine if all the package dependencies are satisfied or remotely via a public web server (https://alvarosg.shinyapps.io/sari/) with no requirement other than having an internet connection.

GPS-based LEO orbits referenced to the Earth’s center of mass

Global Navigation Satellite System satellite clock solutions of the International Global Navigation Satellite System Service (IGS) are aligned to the International Terrestrial Reference Frame origin. This strategy is not sufficient to model correctly the Low Earth Orbit (LEO) Global Positioning System (GPS) measurements, because the geocenter motion is not taken into account for the ground station positions in these solutions.

In order to be consistent with the dynamic motion of a LEO satellite, and also with the other measurement systems where the geocenter motion can be modeled (e.g., SLR and DORIS), it is necessary to take into account or mitigate the mis centering effect of the constellation solution. Along this study (see Couhert et al.), is used a parametric model representing the reference network translations; this model can be adjusted in the OSTM/Jason-2 and Jason-3 LEO satellites orbit determination.

Measurements with cold-atom sensors

The research on cold-atom interferometers gathers a large community of about 50 groups worldwide both in the academic and now in the industrial sectors. The interest in this sub-field of quantum sensing and metrology lies in the large panel of possible applications of cold-atom sensors for measuring inertial and gravitational signals with a high level of stability and accuracy.

A review by Geiger and co-authors presents the evolution of the field over the last 30 years and focuses on the acceleration of the research effort in the last 10 years. The article describes the physics principle of cold-atom gravito-inertial sensors as well as the main parts of hardware and the expertise required when starting the design of such sensors. The author then reviews the progress in the development of instruments measuring gravitational and inertial signals, with a highlight on the limitations to the performances of the sensors, on their applications and on the latest directions of research.

Superconducting Gravimeter time-varying Gravity Field

The International Geodynamics and Erath Tide Service (IGETS) as an IAG service established in 2015, is providing support to geodetic and geophysical research activities around an international network of superconducting gravimeter (SG) data.

Four different French institutions (EOST Strasbourg, ‘‘Observatoire de Paris’’, OREME Montpellier, and LSBB Rustrel) are operating five different sites contributing to the IGETS. All products (levels 1, 2, and 3) are primarily available at the IGETS database located in GFZ Potsdam, Germany (http://isdc.gfz-potsdam.de/igets-data-base/).

Detailed description of the stations as well as access to the data can be found on the dedicated site http://igets.u-strasbg.fr/.

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6. Geodesy and fundamental physics

At the present level of accuracy, signals from space-geodetic techniques like VLBI (Very Long Baseline Interferometry), GPS (Global Positioning System) and SLR/LLR (Satellite/Lunar Laser Ranging) have to be modelled and analyzed in the context of a post-Newtonian formalism within the General Relativity frame.

Quantum metrology enables new applications in geodesy, including relativistic geodesy. The recent progress in optical atomic clocks and in long-distance frequency transfer by optical fiber together pave the way for using measurements of the gravitational frequency redshift for geodesy. The remote comparison of frequencies generated by calibrated clocks will allow for a purely relativistic determination of differences in gravitational potential and height between stations on Earth surface (chronometric leveling).

The long-term perspective is to tie potential and height differences to atomic standards in order to overcome the weaknesses and inhomogeneity of height systems determined by classical spirit leveling. Complementarily, gravity measurements with atom interferometric setups, and satellite gravimetry with space borne laser interferometers allow for new sensitivities in the measurement of the Earth's gravity field.

The MicroscoPE mission

The weak equivalence principle (WEP), stating that two bodies of different compositions and/or mass fall at the same rate in a gravitational field (universality of free fall), is at the very foundation of general relativity. The MICROSCOPE mission aims to test its validity to a precision of 10e-15, two orders of magnitude better than current on-ground tests, by using two masses of different compositions (titanium and platinum alloys) on a quasi-circular trajectory around the Earth.

This is realized by measuring the accelerations inferred from the forces required to maintain the two masses exactly in the same orbit. Any significant difference between the measured accelerations, occurring at a defined frequency, would correspond to the detection of a violation of the WEP, or to the discovery of a tiny new type of force added to gravity. MICROSCOPE's first results show no hint for such a difference, expressed in terms of Eötvös parameter (both 1-sigma uncertainties) for a titanium and platinum pair of materials. This result was obtained on a session with 120 orbital revolutions representing 7% of the current available data acquired during the whole mission. The quadratic combination of 1-sigma uncertainty leads to a current limit of about [-1.5 ±2.3 (stat) ±1.5 (syst).10e-15].

Chronometric Geodesy

The gravitational redshift effect discovered by Einstein must be taken into account when comparing the frequencies of distant clocks. However, instead of using our knowledge of the Earth’s gravitational field to predict frequency shifts between distant clocks, one can revert the problem and ask if the measurement of frequency shifts between distant clocks can improve our knowledge of the gravitational field. This is known as chronometric geodesy (Delva et al., 2019).

Since the beginning of the atomic time era in 1955, the accuracy and stability of atomic clocks were constantly ameliorated, with around one order of magnitude gained every ten years. Now that the atomic clock accuracy reaches the low 10e-18 in fractional frequency, and can be compared to this level over continental distances with optical fibers, the accuracy of chronometric geodesy reaches the cm level and begins to be competitive with classical geodetic techniques such as geometric levelling and GNSS/geoid levelling. Moreover, the building of global timescales requires now to take into account these effects to the best possible accuracy. In the work of Delva, Lion and collaborators, is explained how atomic clock comparisons and the building of timescales can benefit from the latest developments in physical geodesy for the modelling and realization of the geoid, as well as how classical geodesy could benefit from this new type of observable, which are clock comparisons that are directly linked to gravity potential differences.

The Lunar Laser Ranging experiment

The Lunar Laser Ranging (LLR) experiment has accumulated 50 years of range data of improving accuracy from ground stations to the laser retroreflector arrays (LRAs) on the lunar surface. The upcoming decade offers several opportunities to break new ground in data precision through the deployment of the next generation of single corner-cube lunar retroreflectors and active laser transponders. This is likely to expand the LLR station network. Lunar dynamical models and analysis tools have the potential to improve and fully exploit the long temporal baseline and precision allowed by millimetric LLR data. Some of the model limitations are outlined for future efforts. Differential observation techniques will help mitigate some of the primary limiting factors and reach unprecedented accuracy. Such observations and techniques may enable the detection of several subtle signatures required to understand the dynamics of the Earth-Moon system and the deep lunar interior. LLR model improvements would impact multidisciplinary fields that include lunar and planetary science, Earth science, fundamental physics, celestial mechanics and ephemerides.

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7. Geodesy for Climate Research

This section is dedicated to the use of geodetic measuring techniques for innovative climate and Earth system studies. Modern geodetic observing systems document a wide range of changes in the Earth's solid and fluid layers at very different spatial and temporal scales related to processes as, e.g., the terrestrial and atmospheric water cycle, ocean and atmosphere dynamics, sea level, ice-mass balance, and glacial isostatic adjustment. Different time spans of observations need to be cross-compared and combined to resolve a wide spectrum of climate-related signals.

Geodetic observables are also often compared with geophysical models and climate models, which helps to explain observations, test theories, evaluate simulations, and finally merge measurements and numerical models via data assimilation. Contributions utilizing data from diverse geodetic observation techniques including altimetry and gravimetry satellites, navigation satellite systems, satellite radio occultation and reflectometry, InSAR, tide gauges are under development; for example studies that cover a wide variety of applications of geodetic measurements and their combination to observe and model Earth system signals in hydrological, ocean, atmospheric, climate and cryospheric sciences. All these contributions are working towards any of the goals of the Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) of the International Association of Geodesy (IAG).

The development of the ocean mass balance solution using GRACE data and the characterization of sources of error, has enabled the development of a method for combining spatial geodesy data, namely spatial altimetry and spatial gravimetry (Blazquez et al., 2018). This work led to determine the ocean's heat content and the planetary energy imbalance (Marti et al., 2022). This product made possible the first estimation of equilibrium climatic sensitivity with spatial geodesy data (Chenal, 2022). Moreover, the extension to the past of the principle of calculating the heat content of the ocean from a reconstruction of the sea level by tide gauge and the ocean mass balance made possible the first observational estimation of a time series of the parameter of climate feedback (Meyssignac and collaborators)

Satellite characterization of Water mass exchange

Blazquez et al. revisit the treatment of GRACE satellite data to obtain GRACE-based estimates of the water mass exchange between ocean and continents at interannual to decadal timescales paying a special attention to the different sources of errors and uncertainties. They consider all state-of-the-art data processing of GRACE data, from which he developed an ensemble of consistent solutions to estimate the mass changes in Greenland, Antarctica, the ocean and the rest of the emerged lands including glaciers.

With this ensemble, the nature of water mass exchange between ocean and continents was documented and the associated uncertainties were estimated. The range of the uncertainty explain the spread in previous GRACE-based estimates of the components of the global water budget. This approach enables also the exploration of the sources of the uncertainties in GRACE based estimates of the components of the global water budget. As a result, post-processing is responsible for 79% of the uncertainty in the global water budget estimates and only 21% is due to the differences in the GRACE data inversion process. The main sources of uncertainties in the GRACE-based global water budget at annual to interannual time scales are the spread in the geocenter corrections and the uncertainty in the so-called GIA correction that are applied to GRACE data. This is particularly true for the ocean mass and glacier and Total Water Storage (TWS) mass change estimates for which the uncertainty in trends for the period from 2005 to 2015 is ±0.33 mm SLE /yr.

Regarding the glacier and TWS mass change at basin scale, glacier leakage was identified as the main source of uncertainty at local scale in regions close to glaciers. A method using non-GRACE-based mass estimates has been proposed to reduce the leakage uncertainty on the GRACE-based local water mass estimate. Accounting for glacier mass changes derived from satellite imagery leads to improved estimates of other hydrological processes affecting the local water cycle.

Regarding the ocean mass, a method was explored in order to improve the estimates of the ocean mass by working in a reference frame centered in the center of mass of the Earth in order to remove the geocenter correction and the associated uncertainty. Thus, the consistency between GRACE-based ocean mass, altimetry-based sea-level, and ARGO-based steric sea level has been analyzed to improve the estimates of the ocean mass changes. It further leads to a better closure of the sea level budget and a more accurate estimate of the Earth Energy Imbalance (EEI).

Climate sensitivity

The work by Chenal et al. explores the observational estimate of the equilibrium climate sensitivity (ECS) derived from historical recent instrumental data, particularly space data. The ECS is the equilibrium global mean surface temperature of the Earth reached after an instantaneous doubling of atmospheric carbon dioxide concentration relatively to preindustrial concentration. The ECS is the fundamental metric of contemporary climate change amplitude, because the actual and future evolution of many climate variables, such as surface temperature or ocean thermal expansion, are strongly correlated with it.

However, the ECS is poorly known. From the Charney report in 1979 to the International Panel of experts on Climate Change (IPCC) Fifth Assessment Report, the likely rang of ECS has remained remarkably large with values between 1.5 and 4.5 K, and a marked bias between instrumental estimates, which are on low end of the range, and numerical climate models estimates, which are on the high end. The main cause of this dispersion is that climate sensitivity varies with time, in link with the radiative effect of surface warming pattern, which can change over time due to the climate internal variability or to historical time variations of forcing agents

Recent observational time series of ocean heat content and surface temperature, have been used in addition to a recent reconstruction of radiative forcing, in order to estimate the climate feedback parameter, and the ECS, by linear regression of the planetary energy budget equation (e.g., Chenal et al.). In this process, the author takes into account all uncertainty sources and he propagate them in the regression in order to get a comprehensive description of observational uncertainty associated to the ECS. Moreover, he used the time variations of the climate feedback parameter simulated by climate models to evaluate biases and uncertainties associated to this parameter and due to the surface warming pattern. On the basis of the 1971-2017 energy budget, the author demonstrated that it is very unlikely ($p<0.05$) that the ECS is lower than 2.4 K. This result is 0.4 K above last estimates of the IPCC. He showed that the IPCC estimate is probably biased low because of an underestimated cooling of the ocean in 1860 in response to the Little Ice Age.

Satellite altimetry: an essential contribution to climate modeling

In 2018 we celebrated 25 years of development of radar altimetry, and the progress achieved by this methodology in the fields of global and coastal oceanography, hydrology, geodesy and cryospheric sciences. Many symbolic major events have celebrated these developments, e.g., in Venice, Italy, the 15th (2006) and 20th (2012) years of progress and more recently, in 2018, in Ponta Delgada, Portugal, 25 Years of Progress in Radar Altimetry.

On this latter occasion it was decided to collect contributions of scientists, engineers and managers involved in the worldwide altimetry community to depict the state of altimetry and propose recommendations for the altimetry of the future. The work summarizes contributions and recommendations that were collected and provides guidance for future mission design, research activities, and sustainable operational radar altimetry data exploitation (International Altimetry Team, 2021).

Recommendations provided are fundamental for optimizing further scientific and operational advances of oceanographic observations by altimetry, including requirements for spatial and temporal resolution of altimetric measurements, their accuracy and continuity. There are also new challenges and new openings mentioned in the paper that are particularly crucial for observations at higher latitudes, for coastal oceanography, for cryospheric studies and for hydrology.

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8. International Scientific Services

DORIS Service (IDS)

The Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is a tracking technique based on a one-way ground to space Doppler link. For Low Earth Orbit (LEO) satellites, DORIS shows a robust capability in terms of data coverage and availability, due to a wide and well-distributed ground network, where data are made available by the International Doris Service (IDS). However, systematic errors remain in the DORIS data, such as instabilities of the on-board clock due to radiation encountered in space, which limit the accurate determination of station positions.

During the period 2019-2023, the DORIS community worked for improving the system (technology, models, data analysis) : antenna, performance of Precise Orbits determination (POE-F), updating of HY-2A SRP model, hybrid DORIS+GPS measurements processing using the REGINA and DORIS networks for Sentinel-3A (ground beacon and on-board clock corrections), North-South mis-centering of the Jason-3 orbit.

CNES and collaborators, who are in charge of the operational use of tracking data for the precise orbit determination of altimetry missions (around 10 satellites in 2022), worked on the quality analysis of the overall products in the framework of a Copernicus WG.

GNSS Service (IGS)

The International GNSS Service (IGS) recently finalized its third reprocessing campaign (repro3). Ten Analysis Centers (ACs) reanalyzed the history of GPS, GLONASS and Galileo data collected by a global tracking network over the period 1994-2020. Combinations of the daily repro3 AC terrestrial frame solutions constitute the IGS contribution to the next release of the International Terrestrial Reference Frame, ITRF2020.

Compared to the previous IGS reprocessing campaign (repro2), a number of new models and strategies have been implemented in repro3, including the new IERS linear pole model, the new IERS-recommended sub-daily EOP tide model, and rotations of phase center corrections for tracking antennas not oriented North. Besides, a new set of satellite antenna phase center offsets was adopted in repro3, based on the published pre-flight calibrations of the Galileo satellite antennas.

As a consequence, the IGS contribution to ITRF2020 provides for the first time an independent Galileo-based realization of the terrestrial scale, instead of being conventionally aligned in scale to the previous ITRF. Quality metrics from the daily repro3 terrestrial frame combinations are first introduced and compared to those from repro2. The impacts of the newly adopted models are then assessed and discussed. The terrestrial scale realized by the IGS repro3 solutions is in particular confronted to independent estimates from SLR and VLBI. The precision of the IGS repro3 station position time series is finally compared to that of the IGS repro2 series as well as of station position time series from independent groups.

Laser Ranging Service (ILRS)

The primary task of the Laser Ranging service in France is double. On the one hand, the SLR-LLR geodetic station located in the South of France (plateau de Calern, OCA) is participating in the tracking of several targets (especially of high altitude, like MEO) following the recommendations and priorities emitted by ILRS. On the other, Analysis Centers are regularly computing the solutions of station coordinates, geodetic satellites and Moon orbits, and Earth Orientation Parameters (EOP).

The Analysis Center of LLR data on the Moon and with an expertise in Solar System dynamics, including some research in fundamental physics, is located at the ‘‘Observatoire de Paris’’ : see the group POLAC on http://polac.obspm.fr

The Analysis Center of SLR data, during the period 2019-2022 has been suspended. However, in 2023, the service will resume, in particular with the participation and help of CNES/CLS.

Very Long Baseline Interferometry (VLBI) Service

The IVS analysis center in Paris analyses the VLBI observations (24h sessions and intensive sessions) in order to form a series of EOPs, station positions and radio-source positions. SINEX files are provided to the International Service to contribute to the intra-technical operational combination. Once a year, a complete reanalysis of the data since 1979 makes it possible to generate a celestial frame, a series of more precise EOPs and, according to an adapted analysis configuration, more precise time series of radio transmitter positions than those generated in operation.

More punctually, the Paris Analysis Centre contributes to specific analytical campaigns such as the generation of ICRF3 prototype catalogues that were used for internal comparisons within the working group or the generation of pre-processed data for ITRF2020.

International Gravity field Services (IGFS)

The International Gravity Field Service (IGFS) promotes the interaction, cooperation and synergy between the Gravity Services, namely the Bureau Gravimétrique International (BGI, France), the International Service for the Geoid (ISG, Italy), the International Geodynamics and Earth Tides Service (IGETS, France), the International Center for Global Earth Models (ICGEM, Germany) and the International Digital Elevation Model Service (IDEMS, United-States of America). Furthermore, through its product center, namely the International Combination Service for Time-variable Gravity Fields (COST-G, Switzerland), IGFS provides consolidated monthly global gravity models in terms of spherical harmonic coefficients and thereof derived grids by combining solutions from individual Analysis Centers.

ILICO (with SONEL): French Research Infrastructure

ILICO, a French Research Infrastructure (RI) for Coastal Ocean and Nearshore Observations is a notable example of national and pan-institutional efforts to expand knowledge of the complex processes at work within the critical coastal zone in line with the European Ocean Observing System perspective. Providing a forum for its community to work together on priority issues is a challenge, and ILICO's organizational structure and governance are designed accordingly.

Future challenges for this RI include the question of whether France's original model of combining both land and nearshore in its study of the coastal domain is transferable to the pan-European context and how far we can go in integrating overseas and ultramarine issues.

A future Fundamental Geodetic Observatory in French Polynesia

The evolution of the current ''Observatoire Géodésique de Tahiti'' (OGT) towards an observatory of Earth and environmental sciences is a goal likely to develop sustainable research and teaching activities in this region of the South Pacific and to consolidate the attractiveness of the University of French Polynesia (UPF) with national and international actors. CNRS/Insu and CNES (French space agency) are involved in this project since years.

The identification of a field away from urban areas where to install all the equipment of the new observatory with the VLBI station proposed by NASA seems particularly urgent to accompany the project. Different viable scenarios are being explored. Another challenge for Tahiti is to develop a new generation of laser ranging telescope, as it is the case with NASA Geodetic Project notably (see ILRS recommendations).

A systematic approach to integrating the different types of data generated by the observatory into national and international (IAG) observation services and research infrastructures adapted to the solid Earth – astronomy–astrophysics – ocean atmosphere domains obviously is one of the main goals.

The 'Bureau Gravimétrique International' (BGI)

The International Gravimetric Bureau (BGI) is the service of IAG aimed at ensuring the data inventory and availability for the scientific community of the gravity measurements acquired at the Earth's surface (see Terms of Reference in the IAG Geodesist's Handbook 2020). For this purpose, BGI maintains and gives access to 4 global gravity databases of relative measurements from land and marine surveys, of absolute gravity measurements and of reference gravity stations related to the former IGSN71 networks. These database support scientific studies and modeling of the Earth's gravity field at regional or global scales. BGI also provides derived products and services such as: global or regional gravity grids & models (anomalies, geoid), regional gravity compilations, processing software, documentation and contributes to the definition of standards and networks in gravimetry for the international community. Most of the databases and services provided by BGI are available from the BGI website (http://bgi.obs-mip.fr).

During 2019-2022, BGI and its partners has maintained their activities related to data collection, validation and distribution of relative and absolute gravity measurements in France and all over the world and has modernized its web services to data users. Systematic DOI referencing has been implemented to all gravity dataset from recent or old land and marine surveys.

In the same period, BGI also co-chaired the IAG Joint Working Group for the realization of the International Terrestrial Gravity Reference System and Frame (ITGRS/ITGRF) that will provide the first precise and absolute gravity frame for referencing and monitoring the Earth's gravity field.

In addition, BGI has also contributed to several international projects dedicated to the realization of high-resolution geoid or gravity regional models based on the combination of surface and satellite gravity data. These projects led to the realization of published digital grids of geoid and gravity anomalies in Europe (ALP-ARRAY gravity database, Pyrenees, Bay of Biscay, Mediterranean Sea) and Asia (first high-resolution geoid model for Vietnam and surrounding areas).

Finally, BGI has also supported the evaluation of innovative gravity instrumentations based on cold-atom interferometry in collaboration with French labs and companies (MUQUANS/EXAIL, ONERA and LNE/SYRTE). This includes the qualification of the first commercial Quantum gravity meter (AQG form MUQUANS/EXAIL) and the realization of a first airborne absolute gravity survey in 2019 with the GIRAFE Quantum dynamic gravity meter developer by ONERA/SHOM.

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