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Session 1

Global Reference Frame Theory, Concepts and Computations

ITRF2020: An overview of its features and results

Zuheir Altamimi (IGN-IPGP-France), Paul Rebiscung (IGN-IPGP-France), Xavier Collilieux (IGN-IPGP-France), Laurent Métivier (IGN-IPGP-France) and Kristel Chanard (IGN-IPGP-France)

Abstract. The ITRF2020 was the occasion to better describe the shape of the deforming Earth's surface by an accurate and consistent modelling of nonlinear station motions induced by various geophysical processes. The ITRF2020 is an augmented reference frame where the temporal station positions are modelled by a linear part, and parametric functions describing annual and semi-annual deformation caused mainly by loading effects, as well as Post-Seismic Deformation (PSD) for stations subject to major earthquakes. The paper discusses the ITRF2020 new analysis strategy that integrates time series of station positions and Earth Orientation Parameters provided by the IAG technique services of the four space geodesy techniques (DORIS, GNSS, SLR, VLBI). It evaluates the performance of the main ITRF2020 features, namely the seasonal signals embedded in the station position time series, the corresponding geocenter motion, that is the motion of the Center of Mass with respect to the Center of Figure of the solid Earth surface, as well as the PSD parametric functions.

ITRF2020 seasonal geocenter motion model

Paul Rebischung (IGN / IPGP), Zuheir Altamimi (IGN / IPGP), Xavier Collilieux (IGN / IPGP), Laurent Métivier (IGN / IPGP) and Kristel Chanard (IGN / IPGP)

Abstract. The computation of the latest release of the International Terrestrial Reference Frame, ITRF2020, involved not only the combination of long-term, piece-wise linear coordinates from the four space geodetic techniques, but also, for the first time, of annual and semi-annual terms describing the seasonal displacements of the geodetic stations. The origin of these seasonal terms was defined in such way that there is no seasonal translation between them and the input Satellite Laser Ranging (SLR) solutions. The seasonal terms stemming from the ITRF2020 combination are thus expressed with respect to the Earth's center of mass (CM), as sensed by SLR.

If integrated over the Earth's surface, the field of seasonal surface deformation with respect to CM gives access to seasonal geocenter motion, i.e., the seasonal motion of the Earth's center of figure (CF) with respect to CM. Taking advantage of the dense network of GNSS stations in ITRF2020, it was thus possible to estimate seasonal geocenter motion from the field of ITRF2020 seasonal terms. This presentation describes the procedure which was followed to obtain the final ITRF2020 seasonal geocenter motion model. This model is then compared with other recent estimates of seasonal geocenter motion.

The ILRS Analysis Standing Committee Contribution to ITRF2020

Erricos C Pavlis (GESTAR II / UMBC and NASA Goddard 61A), Vincenza Luceri (e-GEOS SpA & ASI/CGS-Matera), Antonio Basoni (e-GEOS SpA & ASI/CGS-Matera), David Sarrocco (e-GEOS SpA & ASI/CGS-Matera), Magda Kuzmicz-Cieslak (GESTAR II / UMBC), Keith Evans (GESTAR II / UMBC) and Giuseppe Bianco (ASI/CGS-Matera)

Abstract. The ILRS contribution to ITRF2020 is a time series of weekly/bi-weekly SINEXs with station position estimates and EOP, from 7-day arcs (1993.0 – 2021.0) and 15-day arcs over 1983.0-1993.0. Each solution was obtained as the combination of loosely constrained individual solutions from the seven ILRS Analysis Centers: ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF. Everyone followed strict standards agreed within the ILRS Analysis Standing Committee (ASC) and used SLR data from LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2, (LAGEOS-only from 1983 to 1992). The ILRS ASC devised an innovative approach in handling systematic errors in the network, never before utilized. After a 5-year pilot-project documented in Luceri et al., (2019). The Station Systematic Error Monitoring PP (SSEM), delivered a series of long-term mean bias estimates for each station, the time intervals of applicability and their statistics. They were derived from freely adjusted station position and EOP solutions for the period 1993.0 to 2020.5, using the latest satellite CoG model. The simultaneous estimation of the station heights and measurement biases resulted in a self-consistent set of weekly bias estimates for each site. Breaks and “jumps” were used to define the periods of applicability and to calculate the mean bias and its standard deviation. The mean biases were pre-applied in the re-analysis, limiting the remaining jitter of the bias to negligible level. This approach strengthened the estimation process without a compromise of the final results’ accuracy. As a result, the ILRS contribution to ITRF2020 minimized the scale difference between SLR and VLBI to below 2 mm (ITRF2014 ~9 mm). We present an overview of the procedures, models, and the improvement over previous ILRS products, focusing especially on the Core ILRS sites.

Evaluation of common-mode errors in global multi-year frames: A case study in the ITRF solution series

Christopher Kotsakis (Aristotle University of Thessaloniki) and Miltiadis Chatzinikos (Aristotle University of Thessaloniki)

Abstract. The quality assessment of global multi-year frames is essential for verifying their compliance with stringent accuracy standards imposed by scientific user needs for Earth science applications. This task is usually engaged in a relative framework through comparisons with other independently (or semi-independently) derived frame solutions from the same and/or different space geodetic techniques. However, in order to acquire a complete view of the quality of global multi-year frames, it is also important to assess their internal accuracy at coordinate system level (origin, orientation, scale, and their time evolution) which is reflected in the estimated solution and its full covariance matrix for the frame positions and their predicted secular/non-secular changes. This is essentially an inverse "error mapping" problem without a single straightforward solution, aiming to infer, in a statistical sense, the common-mode errors of translational, rotational and scaling type that commonly occur in multi-year frame solutions. Such errors are always hidden in the correlated part of the total estimation error of any frame solution, and they dictate the intrinsic accuracy of the coordinate system which is inherited to users by the respective solution. The aim of this paper is to expose the key aspects of the aforesaid evaluation scheme for quantifying the (internal) common-mode errors in global multi-year frames, and to present the results from its implementation in the historical series of ITRF solutions, including the latest release of ITRF2020.

Noise evolution in IDS contributions: from ITRF2014 to ITRF2020

Janusz Bogusz (Military University of Technology), Anna Klos (Military University of Technology) and Guilhem Moreaux (Collecte Localisation Satellites)

Abstract. We examine DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) position time series processed by the IDS (International DORIS Service) within “ids21wd02” reprocessing, serving as an official input into the newest International Terrestrial Reference Frame, namely ITRF2020 as well as “idswd09” series aligned to ITRF2014. The North, East and Up coordinate time series are carefully pre-processed by means of removing outliers and offsets with the use of IDS database supported by manual inspection. To reliably describe the DORIS position time series, we use a time series model of long-term non-linear signal, linear trend, seasonal oscillations and a stochastic part. Both deterministic and stochastic components are determined using Maximum Likelihood Estimation (MLE). Firstly, we search for a preferred noise model and then demonstrate, that there is an ongoing improvements of noise parameters over years in station-to-station comparison. They may be caused by implementation of new mean pole and HF tidal EOP model as recommended by IERS, the use of quaternions for the attitude of the Jason and Cryosat-2 satellites, addition of the new missions: Jason-3 and Sentinel-3A/B, the use of a new Alcatel phase center model, an implementation of Jason-2 SAA mitigation strategies or new data editing.

DTRF2020: the ITRS 2020 realization of DGFI-TUM

Manuela Seitz (DGFI-TUM), Mathis Bloßfeld (DGFI-TUM), Matthias Glomsda (DGFI-TUM), Detlef Angermann (DGFI-TUM), Sergei Rudenko (DGFI-TUM) and Julian Zeitlhöfler (DGFI-TUM)

Abstract. As one of the ITRS Combination Centers of the IERS, DGFI-TUM contributes with the computation of the DTRF2020 to the ITRS 2020 realization. In this presentation, we show the strategy for the computation of the DTRF2020 and address the new developments since the DTRF2014. We present the DTRF2020 solution and the content of the DTRF2020 release and show results of internal comparisons, as well as comparisons with ITRF2020, JTRF2020 and external EOP series. We also discuss the particular challenges that arose in the computation of DTRF2020, also with regard to future realizations.

Sequentially Estimating and Updating Terrestrial Reference Frames

Richard Gross (Jet Propulsion Laboratory), Claudio Abbondanza (Jet Propulsion Laboratory), T. Mike Chin (Jet Propulsion Laboratory), Mike Heflin (Jet Propulsion Laboratory) and Jay Parker (Jet Propulsion Laboratory)

Abstract. The terrestrial reference frame (TRF) is the foundation for virtually all space-based and ground-based Earth observations. Positions of objects are determined within an underlying TRF and the accuracy with which objects can be positioned ultimately depends on the accuracy of the TRF.

Requirements for TRFs have increased dramatically since the 1980s. Today, the most stringent requirement comes from critical sea level programs: a global accuracy of 1.0 mm and stability of 0.1 mm/yr is required. Future Earth observing satellites will have ever-increasing measurement capability and should lead to increasingly sophisticated models of the processes they are observing. The accuracy and stability of the TRF needs to dramatically improve in order to fully realize the measurement potential of the future Earth observing satellites.

Recent ITRFs have been produced at intervals of 3-6 years (ITRF2000, ITRF2005, ITRF2008, ITRF2014, ITRF2020). Between these realizations, users must rely on predictions of the motions of the reference stations. However, these predictions degrade with time leading to errors in products that depend on the ITRF. Updating the TRF more frequently would eliminate the need for multi-year predictions and hence eliminate this source of error in the TRFs.

JPL is developing a sequential estimation approach to realizing TRFs. This approach, which was used at JPL to produce JTRF2014 and which is being used to produce JTRF2020, is particularly well-suited to the task of updating the TRF in a timely manner. It is straightforward to save the state vector and its full covariance matrix at the end of a TRF solution. As more recent data become available, the filter can be re-started from the saved state and run forward in time, assimilating the new data until it ends, thereby updating the TRF. This process can then be repeated at regular intervals. JPL is currently planning on using this approach to update JTRF2020 at monthly intervals.

VLBI-based assessment of the consistency of the conventional EOP series and the terrestrial reference frames

Mariana Moreira (Atlantic International Research Centre | Associação RAEGE Açores), Esther Azcue (National Geographic Institute of Spain), Maria Karbon (UAVAC, Applied Mathematics Dept., University of Alicante), Santiago Belda (UAVAC, Applied Mathematics Dept., University of Alicante), Víctor Puente (National Geographic Institute of Spain), Robert Heinkelmann (GFZ German Research Centre for Geosciences), David Gordon (NVI, Inc./NASA Goddard Space Flight Center) and José Ferrándiz (UAVAC, Applied Mathematics Dept., University of Alicante)

Abstract. The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) envisages stringent accuracy goals for the International Terrestrial Reference Frame (ITRF) realization in terms of position (1 mm) and velocity (0.1 mm/year). These requirements entail that the Earth Orientation Parameters (EOP) should be estimated with similar accuracy.

The ITRF is based on the combination of solutions from the four space geodetic techniques, with each new release incorporating updated data and models. Likewise, the current conventional EOP series, IERS 14 C04, is produced in a separate process following a different strategy, based on a monthly combination of the EOP estimates obtained by the analysis centers of each space geodetic technique. Using independent processes might cause slow degradation of the consistency among EOP and the reference frames or a misalignment of the current conventional EOP series. The recent release of the ITRF2020 brings an exciting opportunity to investigate this topic.

In this work, we empirically assess the consistency among the conventional terrestrial reference frames and EOP through the analysis of Very Long Baseline Interferometry (VLBI) data, taking different terrestrial frames as alternative settings in the analysis. ITRF2020, ITRF2014, and the terrestrial frame used to produce the ICRF3 are considered in this work. This study allows evaluating if the selection of the terrestrial frame has a significant impact on the consistency of the estimated EOP and assesses its agreement with the conventional EOP series.

The contributions by BKG to the realization of the global geodetic reference frame

Daniela Thaller (BKG), Claudia Flohrer (BKG), Gerald Engelhardt (BKG), Anastasiia Girdiuk (BKG), Hendrik Hellmers (BKG), Daniel König (BKG), Sadegh Modiri (BKG), Sabine Bachmann (BKG), Wolfgang Dick (BKG), Sonja Geist (BKG), Markus Goltz (BKG), Lisa Lengert (BKG), Sandra Schneider-Leck (BKG) and Dieter Ullrich (BKG)

Abstract. The United Nations (UN) underlined the importance of the Global Geodetic Reference Frame (GGRF) by their resolution in 2015. Since many years, the activities in the context of the GGRF are coordinated by the IAG and its different services. Several institutions and individuals are the stakeholders of the IAG services and they ensure on a best-effort basis that the GGRF is realized so that the necessary products are generated and available for the uses.

BKG is one of these institutions contributing to the IAG services by operating observing stations, performing data analysis, generating combined products, and provide data and products publicly to the broad user community. This presentation will focus on BKG's activities within the three IAG services IVS, ILRS and IERS, and therein we will summarize the contributions by our analysis, combination and data centers.

We will show the operational activities for generating GGRF-related products on a daily and weekly basis using the most recent observing data as well as the re-processing activities using the data available since the beginning of VLBI and SLR observations, e.g., for the recently finalized ITRF2020. The most important products resulting from our data analyses and combination are Earth Orientation Parameters (EOPs) and station positions, but also satellite orbits, troposphere parameters and quasar coordinates are provided. We will summarize how the product generation is organized, where the diverse products can be accessed, which methods we support for accessing the data and products, and we will show the quality level of our products.

Advances in the determination of a global unified reference frame for physical heights

L. Sanchez (DGFI-TUM), J. Huang (NRCan), R. Barzaghi (Polimi) and G. Vergos (AUTH)

Abstract. Measuring, studying, and understanding global change effects demand unified geodetic reference frames with (i) an order of accuracy higher than the magnitude of the effects to be observed, (ii) consistency and reliability worldwide, and (iii) long-term stability. The development of the International Terrestrial Reference System (ITRS) and its realisation, the International Terrestrial Reference Frame (ITRF), enable the precise description of the Earth's geometry by means of geocentric Cartesian coordinates with an accuracy at the cm-level and with global consistency. An equivalent high-precise global height reference system that provides the basis for the consistent determination of gravity field-related coordinates worldwide, in particular geopotential differences or physical heights, is missing. Without a conventional global height system, most countries are using local ones, which have been implemented individually, applying in general non-standardised and non-uniform procedures. It is proven that their combination in a global frame presents discrepancies at the metre level. Therefore, a core objective of the international geodetic community is to establish an international standard for the precise determination of physical heights. This standard is known as the International Height Reference System (IHRS). Its realisation has been a main topic of research during the last years. Recent achievements concentrate on (1) compiling detailed standards, conventions, and guidelines for the IHRS realisation, (2) evaluating computational approaches for the consistent determination of potential differences, and (3) designing an operational infrastructure that ensures the maintenance and long-term stability of the IHRS and its realization. This contribution summarises advances and current challenges in the establishment, realization and sustainability of the IHRS.

The GeoMetre project: a comprehensive study to advance local tie metrology

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Abstract. Local tie vectors are essential to spatially correlate the observations of different space-geodetic techniques at space-geodetic co-location sites. They play an important role for data fusion and the subsequent reference frame computation. Reducing their uncertainty further is hence frequently considered a way to reduce the uncertainty of reference frame coordinates in general. The European GeoMetre project has tackled this problem in a joint effort of 15 institutions from geodesy and metrology from multiple angles. Key studies were performed at the co-location sites of Metsähovi, Finland (METS) and Wettzell, Germany (WTZ).Local reference networks at co-location sites secure traceability of the local tie vector scale to the SI definition of the metre. The surveying networks at METS and WTZ were expanded and updated, e.g., by enabling seamless measurements performed with global navigation satellite system (GNSS) and terrestrial measurements. Furthermore, the project developed several novel instruments capable to measure distances in air with low uncertainty, based on high-frequency amplitude modulation or even absolute interferometry. They were used to measure the longer distances in the METS and WTZ networks. Another issue is the transformation of the local tie vectors measured in a local horizontal system into the geocentric reference frame in which the space-geodetic techniques report their data. Thereby, deviations of the local gravity field from the model geoid can lead to systematic deviations in the height and the deflection of the vertical. Due to the significant orientation error of GNSS-based solutions on short baselines, the high accuracy of terrestrial measurements can also be substantially degraded during the transformation. To assess this problem, the project determined the local gravitational field at METS and WTZ and considered this information in the data analysis.

Consistency evaluation of seasonal signals in ITRF2020

Xavier Collilieux (IPGP / IGN / ENSG), Altamimi Zuheir (IPGP / IGN / ENSG), Paul Rebischung (IPGP / IGN / ENSG), Laurent Métivier (IPGP / IGN / ENSG), Kristel Chanard (IPGP / IGN / ENSG) and Maylis de la Serve (IPGP / IGN / ENSG)

Abstract. The new release of the International Terrestrial Reference Frame, ITRF2020, differs from ITRF2014 by the addition of parametric functions describing annual and semi-annual displacements for every station. ITRF2020 coordinates are now described with piece-wise linear functions, occasional exponential and logarithmic functions modelling post-seismic displacements and the newly provided seasonal parameters.

Firstly, the paper presents the seasonal parameters that are provided either in the Center of Mass (CM) or in the Center of Figure (CF) frame. Users are free to use one or the other set as a function of their applications. Secondly, the seasonal displacements determined by the four space geodesy techniques (DORIS, GNSS, SLR, VLBI) are recomputed in the same reference frame on the basis of ITRF2020 results. The level of consistency of those signals at co-location sites with sufficient observations will be discussed.

The impact of non-tidal surface loading deformation on GNSS coordinate time series

Benjamin Männel (GFZ German Research Centre for Geosciences), Susanne Glaser (GFZ German Research Centre for Geosciences), Andre Brandt (GFZ German Research Centre for Geosciences) and Harald Schuh (GFZ German Research Centre for Geosciences)

Abstract. Time-dependent mass variations of near-surface geophysical fluids in the atmosphere, the oceans, and the continental hydrosphere lead to significant and systematic load-induced deformations of the Earth's crust. These deformations impact the space geodetic techniques, and thus, uncorrected deformations can be seen in the estimated parameters such as station positions and the terrestrial reference frame, mainly as periodic signals. Based on station coordinate time series it is possible to assess the impact of time-dependent mass variations on the Earth's surface geometry and, thus, to assess the impact of uncorrected deformations on station positions and terrestrial reference frame parameters. While these corrections were not applied in the recent third reprocessing campaign (IGS repro3) of the International GNSS Service, the subsequently derived ITRF2020 presents seasonal signals estimated for each time series. These signals cover therefore non-tidal loading effects but also other periodic coordinate variations.

To assess the seasonal signals given in the ITRF2020 release we compare them for each individual GNSS station in the IGS repro3 against the model-based surface deformation products provided by GFZ (ESMGFZ). These products contain deformations due to non-tidal atmospheric and hydrospheric loading. The comparison is done in terms of stations-wise amplitude differences and correlations, but also with respect to regional variations and patterns. In the second part of the contribution, we will present the differences between the official GFZ contribution to repro3 and a second solution derived by applying the ESMGFZ models at the observation level. While previous studies indicate improvements for around 80% of the considered stations, both investigations will help to further understand periodic components in station coordinate time series.

Comparison of ITRF2020 residual displacements with environmental loading models

Jean-Paul Boy (EOST/ITES), Paul Rebischung (IGN/IPGP) and Zuheir Altamimi (IGN/IPGP)

Abstract. All geodetic techniques have been reprocessed since the 1980s for SLR and VLBI and the 1990s for DORIS and GNSS in order to compute the latest realization of the International Terrestrial Reference Frame ITRF2020 (https://itrf.ign.fr/en/solutions/ITRF2020). Besides ocean tide loading, no environmental loading corrections have been applied, following the IERS conventions.

The IERS Global Geophysical Fluid Center has provided atmospheric, induced oceanic and hydrological loading estimates for all permanent stations based on the latest ECWMF reanalysis (ERA5) and the barotropic ocean model TUGO-m (http://loading.u-strasbg.fr/ITRF2020/).

In this paper, we present a comparison of the ITRF2020 residual displacements to environmental loading estimates, and in particular for GNSS because of their higher sampling rate (daily instead of weekly). In more details, we show that ERA5 is slightly better than MERRA2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) reanalysis. We also show that a dynamic ocean response to pressure and wind is more suitable to model high frequency ocean non-tidal loading effects than the classical inverted barometer (IB) approximation.

Effects of non-tidal loading applied in VLBI reference frames

Matthias Glomsda (DGFI-TUM), Manuela Seitz (DGFI-TUM), Mathis Bloßfeld (DGFI-TUM) and Detlef Angermann (DGFI-TUM)

Abstract. Up to the latest (2020) realization of the International Terrestrial Reference System (ITRS), the contributions by the geodetic space techniques have not been corrected for non-tidal loading (NTL) effects on the observation sites or the satellite orbits. Although such corrections are not yet part of the Conventions of the International Earth Rotation and Reference Systems Service (IERS) either, many studies have nevertheless shown their benefit for the estimation of geodetic parameters by the distinct techniques. Hence, the two latest ITRS realizations by DGFI-TUM, DTRF2014 and DTRF2020, have been corrected for site displacements generated by NTL at the normal equation level, i.e., the single techniques‘ normal equations have been modified before they were combined. Furthermore, with the Very Long Baseline Interferometry (VLBI) technique, the operational analyses for the International VLBI Service for Geodesy and Astrometry (IVS) at least contain antenna site corrections w.r.t. the atmospheric component of NTL. In this presentation, we discuss the application of site displacements driven by all three common NTL components (atmospheric, oceanic, hydrological) at the observation level in the realization of a VLBI-only reference frame. We make use of the same NTL data as applied for the DTRF2020, but the observation and normal equations with and without NTL corrections are based on our own VLBI solutions rather than the IVS combined solution for the ITRS 2020 realization. Next to the impact on station position offsets and velocities, we will also focus on periodic signals in jointly estimated Earth orientation and Helmert transformation parameters.

Assessment of geodetic products from 24 h VGOS sessions using ITRF2020

Periklis-Konstantinos Diamantidis (Chalmers University of Technology) and Rüdiger Haas (Chalmers University of Technology)

Abstract. The VLBI Global Observing System (VGOS) is a new network of antennas that are deployed for use in geodetic Very Long Baseline Interferometry (VLBI). It utilizes broadband receivers in the 2-14 GHz frequency range, and modern antennas that enable short integration times, and rapid and precise pointing. The result is that more observations with a diverse geometric coverage are obtained for the same time-window compared to legacy S/X systems.

Until recently the evaluation of geodetic products from sessions that are carried out using VGOS was challenging due to the fact that these new stations were not part of combined solutions for the determination of a reference frame. Their a priori coordinates had to be extracted either by short-baseline measurements to legacy S/X telescopes (Varenius et al., 2021), or by unconstrained estimation of their coordinates using known stations to fix the geodetic datum (Mikschi et al., 2021). The new iteration of the International Terrestrial Reference Frame (ITRF), the ITRF2020, was recently published in April 2022, and it is the first combined catalogue of well-defined stations that includes VGOS. The International Earth Rotation and Reference Systems Service (IERS) has also aligned its IERS-C04 earth orientation parameter (EOP) series to ITRF2020.

We assess the geodetic products of VGOS using 24 hr long observation sessions, spanning 2019 to 2021 by utilizing ITRF2020, and the corresponding EOP a priori series. A kalman filter and a least-squares estimator are deployed and we evaluate the accuracy and precision of station positions and EOP that are obtained. The tropospheric parameters are compared to those obtained from Water Vapor Radiometers (WVR) at co-location sites. The differences between the two estimators are also discussed.

Automatic determination of the SLR reference point at Côte d’Azur multi-technique geodetic Observatory

Julien Barneoud (Institut National de l'information Géographique et forestière (IGN), Institut de physique du globe de Paris (IPGP)), Clément Courde (Observatoire de la Côte d'Azur), Jacques Beilin (IGN, ENSG Géomatique), Madec Germerie-Guizouarn (IGN), Damien Pesce (IGN), Maurin Vidal (Observatoire de la Côte d'Azur), Xavier Collilieux (IGN, ENSG Géomatique) and Nicolas Maurice (Observatoire de la Côte d'Azur)

Abstract. The “Observatoire de la Côte d’Azur” (OCA) hosts several space geodesy techniques in Nice area (Caussols, France). The relative positions (local tie vectors) between the measuring reference points of these instruments are essential for the International Terrestrial Reference Frame (ITRF) construction and should be known at one millimeter accuracy.

The satellite laser ranging (SLR) station known as GRSM-7845 in the International Laser Ranging Service (ILRS) performs daily distance measurements. It is one of the four telescopes in the world capable of laser ranging on the Moon (Lunar Laser Ranging). Its reference point is the intersection of the telescope axes, which is supposed to be static. Currently, the coordinates are determined once a year during a multi-technique local survey. However, this is a time-consuming operation during which the telescope cannot perform its satellite measurements. It also requires specific metrology accessories and trained surveyors.

To improve this protocol, measuring devices and a data-processing chain were set up to automatically determine the reference point of the SLR station.

In order to use an indirect approach (circular fitting), circular and motorized prisms were fixed on the station to be always visible during the telescope rotation. A software package was developed to control the telescope, the dome and the total station motions for fully automatic measurements.

In addition to providing an easy determination of the cross-axis for local ties, this system will allow to study the potential motion of the telescope’s axes intersection throughout the year.

The Vienna VLBI contribution to the ITRF2020

David Mayer (BEV), Johannes Böhm (TU Wien), Sigrid Böhm (TU Wien) and Hana Krásná (TU Wien)

Abstract. In the course of the preparation of the ITRF2020, the Federal Office of Metrology and Surveying (BEV) has created together with the TU Wien one of the VLBI solutions combined by the BKG.

VLBI analysis centres usually model the Earth orientation parameters (EOP) as offsets and rates. However, the Vienna solution uses piecewise linear offsets (PWLO) to model the EOP and is the only analysis centre that has also submitted these for combination. After some initial problems the solutions could be combined successfully.

This poster will discuss the creation of this solution. Specifically, the parameterization of the EOP will be described in more detail. Furthermore, the finished Vienna VLBI TRF will be presented.

Session 2

Space Geodetic Measurement Techniques

Upgrading the Metsähovi Geodetic Research Station

Markku Poutanen (Finnish Geospatial Research Institute FGI), Mirjam Bilker-Koivula (Finnish Geospatial Research Institute FGI), Joona Eskelinen (Finnish Geospatial Research Institute FGI), Ulla Kallio (Finnish Geospatial Research Institute FGI), Niko Kareinen (Finnish Geospatial Research Institute FGI), Hannu Koivula (Finnish Geospatial Research Institute FGI), Sonja Lahtinen (Finnish Geospatial Research Institute FGI), Jyri Näränen (Finnish Geospatial Research Institute FGI), Jouni Peltoniemi (Finnish Geospatial Research Institute FGI), Arttu Raja-Halli (Finnish Geospatial Research Institute FGI) and Nataliya Zubko (Finnish Geospatial Research Institute FGI)

Abstract. Metsähovi Geodetic Research Station (MGRS) of the National Land Survey of Finland, has been undergoing a major upgrade. First SLR observations were started in 1978, and later GPS, DORIS, superconducting and absolute gravimeters. During decades the equipment and facilities. became outdated. A decade-long reform began in 2012, during which all major equipment was renewed. This included a new SLR system and geodetic radio telescope, and the area's infrastructure has been completely refurbished. When completed, MGRS will be one of the northernmost stations in the global geodetic core network of the International Association of Geodesy (IAG) with a full suite of co-located space geodetic instrumentation, including Global Navigation Satellite Systems (GNSS) receivers, Satellite Laser Ranging (SLR), Very Long Baseline Interferometer (VLBI) radio telescope, The Doppler Orbitography and Radio-positioning Integrated by Satellite instrument (DORIS), absolute and superconducting gravimeters, and local geodetic networks and facilities to connect various observing techniques. Together, the core stations form the solid backbone for maintaining the International Terrestrial Reference Frame (ITRF), monitoring the orientation of the Earth in space, global tectonic movements, and producing information for computing precise orbits of satellites, including GNSS. The stability of the stations and their long and stable series of observations is paramount both for global and regional networks. Since 1992 MGRS has been a part of the IGS network, currently a member of GGOS Space Geodetic Network, and it has produced data for EUREF Permanent GNSS Network (EPN) since the very beginning of EPN. We present recent developments at MGRS and introduce the instrumentation that already contributes and will contribute in the future to various IAG services.

NASA SLR Systematic Error Analysis

Van Husson (NASA/Peraton), Peter Dunn (NASA/Peraton), Jason Laing (NASA/Peraton), Tom Oldham (NASA/Peraton) and Troy Carpenter (NASA/Peraton)

Abstract. Not solving for SLR range biases in individual SLR stations resulted in small scale errors in the International Terrestrial Reference Frame 2014 (ITRF 2014) [Appleby et al, 2016]. In order to improve the scale of the next ITRF, we will present approaches for investigating known systematic errors in the NASA SLR MOBLAS and TLRS systems and their net results. This approach relies upon several data sources including the NASA SLR processing summary database; NASA SLR system characterization ground test results; raw NASA SLR fullrate data; NASA SLR Survey Reports; Vienna Mapping Function data; the NASA SLR LOR Timing database; the Time Transfer by Laser Link (T2L2) results [http://www.geoazur.fr/t2l2/en/data/v4/], and satellite center of mass corrections [Rodriguez, 2019]. Based on our analysis we will then compare our systematic errors to the ILRS Systematic Error file, a recent by-product of the SLR ITRF 2020 solution. Therefore, this report is different than a typical system characterization report, where Root Sum of the Squares (RSS) analysis of theoretical SLR error sources per sub-system are aggregated over different time scales [Pearlman, 1984], but will be more valuable to the end user. First, we will discuss the most common types of range biases and their signatures as a function of range and elevation. Then we will discuss the systematic errors for each station. We will conclude with recommendations on how to improve NASA SLR data accuracy.

Accuracy Improvement to SLR network stations from Reference Frame Analysis

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Abstract. The ITRF2020 Reference Frame Analysis includes estimates of non-geodetic signals in the SLR observations. Interpretation of these signals and the resulting data handling refinements yield improved orbit and station positioning. It has been established in recent work (Appleby, Rodriguez and Altamimi, JG 2016) that most stations in the ILRS network exhibit millimeter-level systematic errors. Each of the three types of SLR sites (Microchannel Plate (MCP), Single Photon (SP), and Compensated SP Avalanche Diode (C-SPAD)) exhibit different characteristics (Couhert et al., JG 2020). ILRS requirements to maintain high quality SLR data include the ability to perform extensive tests on-site (Otsubo and Genba, 13th. Int. Laser Ranging Workshop, 2002). Core ITRF SLR stations, including the NASA Mobile and Transportable MCP Systems, regularly monitor electronic characteristics for each satellite pass. Data features exceeding error specifications can be defined with close consideration of known engineering variables. This paper will discuss current accuracy for core stations and system development in the ILRS Network to maintain the millimeter requirement for geodynamic measurements.

Assessment of thermal deformation modelling for the geodetic VLBI telescopes at Onsala Space Observatory

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Abstract. Thermal and gravitational deformation are among the most important telescope-specific error sources to be considered in geodetic Very Long Baseline Interferometry (VLBI), for both the legacy S/X and the VLBI Global Observing System (VGOS) networks. Correcting for these effects is important in order to achieve mm- accuracy for station coordinates, in particular in the context of the International Terrestrial Reference Frame (ITRF). Thermal deformation concerns the expansion of the telescope mount as a function of environmental temperature.

We focus on the thermal deformation of the geodetic VLBI telescopes at the Onsala Space Observatory (OSO), namely ONSALA60 (On) and the Onsala twin telescopes (OTT), that are regularly involved in the observations coordinated by the International VLBI Service for Geodesy and Astrometry (IVS).

We assess the topic by using the geodetic VLBI software packages ASCoT (Artz et al., 2016) and c5++ (Hobiger et al., 2010) using different analysis approaches. These include using the IVS-recommended thermal deformation model by Nothnagel (2009), in-situ temperature sensor data, as well as using in-situ height measurements with an invar rod system (Johansson et al., 1996). The height measurements for On clearly show the presence of an annual signature and a trend. We also investigate the time lag between environmental temperature and in-situ temperature in the concrete telescope mounts.

For On, our study covers several years of IVS R1-sessions, and for the OTT weekly IVS-VGOS sessions since June 2021. Furthermore, we also investigate sessions referred to as ONTIE, which are usually 24 hours long and include only On and the OTT. The latter are specifically designed to determine local tie vectors between the legacy S/X antenna On and the new VGOS antennas.

Precise VLBI/GNSS ties with micro-VLBI

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Abstract. Precise measurement of ties between space geodesy techniques is critically important for a technique inter-comparison and for gaining benefits of collocation of several techniques at one site. It turned out challenging to provide such measurements with a millimeter level if accuracy using conventional surveys. To overcome these challenges, we propose an innovative technique. We opened the cover of a GNSS receiver and put a splitter in the signal chain from the antenna. While the antenna processes GNSS signal in a normal way, we digitize the copy of the raw antenna signal within 1 to 2 GHz bandwidth, reformat it, and then process the digitized signal from a GNSS antenna and a signal from a collocated radiotelescope using a conventional way of processing VLBI data. We are effectively transforming a GNSS receiver into a micro-VLBI site. We will discuss advantages of this approach for precise tie measurements and discuss early results of the observational field campaigns.

Understanding the change in the VLBI scale behaviour detected in the ITRF2020

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Abstract. The new realisation of the International Terrestrial Reference System, the ITRF2020, became available in April 2022. It shows a significant change, after 2013.75, in the behaviour of the scale defined by the Very Long Baseline Interferometry (VLBI) technique.

In a previous work, we identified various reasons for such a change by investigating the impact of geophysical mismodeling, observation network non-homogeneity, and the inclusion of data from stations with technical problems.

The latter aspect was investigated for only three specific stations of the IVS network. In this work, we study position residuals of all IVS stations with a focus on the period 2013.75 to 2020 in the goal of identifying significant changes or noisy structure that could impact the behaviour of the scale in VLBI global solutions.

Consistency of Galileo Satellite Antenna Phase Center Offsets

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Abstract. Knowledge of the satellite antenna phase center offsets (PCOs) is a prerequisite for precise applications of Global Navigation Satellite Systems (GNSSs). For all satellites of the European GNSS Galileo, satellite-specific pre-launch chamber calibrations of the PCOs were published by the European GNSS Service Center. They comprise frequency-specific values for the E1, E5a, E5b, E5, and E6 frequency bands. Galileo orbit and clock products of the analysis centers of the International GNSS Service (IGS) refer to the ionosphere-free linear combination of E1 and E5a. Whereas tracking of early Galileo receivers was limited to these two frequencies, an increasing number of IGS stations nowadays also provide E5b and E6 observations. In the frame of the 3rd IGS reprocessing campaign, multi-frequency receiver antenna calibrations including the E5b and E6 were made available allowing for a consistent processing of these observations.

Recent analysis of BeiDou-3 satellite antenna PCOs revealed inconsistencies of the B1C/B2a and B1/B3 antenna calibrations that are the motivation for the current study. To analyze the consistency of the ground-calibrated Galileo satellite antenna PCOs, PCO values are estimated from ionosphere-free linear combinations of E1/E5a, E1/E5b, and E1/E6 observations. The global network comprises about 140 stations supporting all four frequencies and equipped with fully calibrated receiver antennas. The stability of the estimated PCOs is evaluated and they are compared to the pre-flight chamber calibrations.

The scale of the ground network used for PCO estimation is fixed to the most recent release of the International Terrestrial Reference Frame (ITRF2020). The scale of ITRF2020 is defined by Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). Due to a significant offset of the Galileo-based scale, this technique did not contribute to the ITRF2020 scale realization. As a consequence, a systematic offset of 1-2 dm between the chamber-calibrated Galileo PCOs and the estimated ones is expected. Therefore, differences between individual frequency pairs are used for the consistency analysis. This consistency is in particular important for multi-frequency precise point positioning applications utilizing three or even four frequencies. Such applications are expected to grow in the near future in view of the provision of multi-frequency correction data by the Galileo high accuracy service.

Draconitic, tidal, and orbital aliasing signals in multi-GNSS solutions

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Abstract. The time series of geodetic parameters based on Global Navigation Satellite Systems (GNSS) are contaminated by various systematic errors emerging from: errors in the background tidal models, resonances between the revolution period of GNSS constellations and the Earth rotation, as well as orbit modeling errors, especially those related to the direct solar radiation pressure. We derive Earth rotation parameters with daily and sub-daily resolutions and station coordinates from network solutions and Precise Point Positioning (PPP) based on GPS-only, GLONASS-only, Galileo-only, as well as multi-GNSS data. We identify systematic errors in the station and pole coordinates and length-of-day time series with the distinction between orbital artifacts due to satellite revolution periods, tidal-related errors, aliasing between Earth rotation and tides, as well as orbit modeling errors with the occurrence of the draconitic year and its harmonics.

Most of the systematic errors in GNSS time series are different for GPS, GLONASS, and Galileo constellations due to different revolution periods of satellites, and thus, can be mitigated by generating a multi-GNSS combination. However, some effects, such as the aliasing of the errors in tidal models in daily solutions detected in the length-of-day series, are common for all GNSS constellations and cannot be handled by combining various GNSS systems. The lengths of the draconitic years are similar for GPS, GLONASS, and Galileo, however, their harmonics reveal different amplitudes because of different numbers of orbital planes for each constellation: 6, 3, and 3 (+1 eccentric), respectively. We found that the dominating errors in Galileo solutions repeat every 14.08 h, 34.20 h, 2.49 d, and ∼3.4 d, whereas the corresponding periods for GLONASS are 5.63 h, 10.64 h, 21.26 h, 3.99 d, and ∼8 d due to the resonances between Earth rotation and satellite revolution periods. GLONASS introduces large-scale noise into the sub-daily Earth rotation parameters and PPP solutions due to orbit modeling issues. For GPS, there are very strong orbital resonances at the periods close to a sidereal day, which are close to major tidal constituents, such as K1. Therefore, GPS does not allow for a separation of the tidal errors from orbit-related artifacts, whereas Galileo can successfully be employed for such a separation. Moreover, the accumulated length-of-day values based on GPS show a large secular drift, which is up to fourteen times smaller in Galileo-based solutions. Despite that Galileo has not reached yet the full operational capability, it can successfully be employed for the recovery of fundamental geodetic parameters.

Adjustment of orbital elements of Galileo satellite arcs with simulated VLBI observations

Helene Wolf (TU Wien), Johannes Böhm (TU Wien), Urs Hugentobler (TU München) and Axel Nothnagel (TU Wien)

Abstract. Over the last years, the installation of a Very Long Baseline Interferometry (VLBI) transmitter on satellites has been considered as a future research field with high potential for novel possibilities. With the Genesis-1 mission of ESA, once again, the idea of installing a VLBI transmitter next to GNSS and DORIS receivers and SLR reflectors on a satellite is proposed, realizing co-location in space. Observations to satellites with VLBI telescopes allow the combination of satellite and quasar frames through the unique opportunity of determining the absolute orientation of the satellite orbit in the International Celestial Reference Frame (ICRF).

In this contribution, we present the adjustment of Galileo satellite orbit arcs by estimating offsets for the orbital parameters, such as the right ascension of ascending node. For this purpose, the satellite orbit arc is sampled with observations from a VLBI network over several hours. The scheduling software VieSched++ is used to create a schedule including appropriate satellite observations covering the orbit arc and filling the remaining part of the schedule with quasar observations. The scheduled observations are simulated and further analyzed using the Vienna VLBI and Satellite Software (VieVS). In the analysis, offsets for the orbital elements from the a-priori values are determined based on the Monte Carlo simulations and further investigated in terms of their mean formal errors and repeatabilities.

Precise orbit and reference frame determination using multiple altimetry satellite missions with DORIS technique

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Abstract. The German Research Centre for Geosciences (GFZ) is one of the Associate Analysis Centers (AAC) of the International Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Service (IDS). As part of the future contribution to the DORIS part of the International Terrestrial Reference Frame a repertoire of well-known DORIS equipped satellite missions, in particular Topex, Envisat, Jason-1/2/3, Sentinel-3A/B, Sentinel-6A Michael Freilich, has been processed. Precise Orbit Determination (POD) is performed for these missions based on DORIS and Satellite Laser Raging (SLR) observations, either in a combined approach or DORIS stand-alone. To ensure the orbit quality, orbit comparisons with external orbit solutions are performed. For the Sentinel missions the combined orbit solutions of the Copernicus POD quality working group are used for this purpose and conduce as reference for the comparison. Combined orbit solutions are assumed to have superior absolute accuracy and minimal residual systematic errors. Eventually, starting from the DORIS-only solutions weekly local terrestrial reference frames (TRF) are computed for each of the satellites as well as a combined solution for the time span starting in the early 1990's. The so generated TRF solutions are evaluated in terms of the reference frame defining parameters, i.e. origin, scale, and orientation, in comparison to the apiori TRF.

On how multi-technique co-location in space can contribute to the Global Geodetic Observing System goals

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Abstract. Accurate global terrestrial reference frames (TRF) are the backbone of Earth system studies. Therefor requirements on the TRF accuracy have been defined by the Global Geodetic Observing System (GGOS), which have not yet been reached. This in view, the German Research Centre for Geosciences (GFZ) realized in collaboration with the Technische Universitaet Berlin (TUB) the project GGOS-SIM-2. One focus of this project is to investigate the potential of co-location of different observation techniques on dedicated satellites. These satellites are a frequently recurring concept, which has nevertheless not yet been realized, but currently been revived by f.i. ESA. Therefore, we performed simulations for the four main space geodetic techniques, namely DORIS, GNSS, SLR and VLBI towards co-location in space on a single satellite. For most realistic simulations firstly, Precise Orbit Determination (POD) to a range of prominent satellite missions launched and operated during the last thirty years was performed. The analysis of the real observations and the POD derived information provide the basis for the simulation environment in highest coincidence with reality. Adapting this simulation environment, we performed multi-technique simulations to existing satellites and quasars currently used for TRF determination and also to a future dedicated space-tie satellite in overall six different orbit scenarios. Following the simulations, single-technique and combined TRF solutions were generated based on existing infrastructure and in addition with the space-tie satellite. The effect on the TRF is quantified in terms of the reference frame defining parameters and the formal errors of adjusted parameters. Based on all the scenarios, we aspire to answer the question if and how TRFs can be improved by co-location in space towards the important GGOS goals.

Assessing the potential of VLBI transmitters on next generation GNSS satellites for geodetic products

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Abstract. There is an ongoing global effort to improve the Space geodetic techniques contributing to the Global terrestrial reference frames, which do not yet fulfill the Global Geodetic Observing System (GGOS) scientific requirements.

Next-generation Global Navigation Satellite Systems (NextGNSS) satellites are planned to be equipped with optical inter-satellite links and ultra-stable clocks. The motivation of the study is to assess the improvement in the reference frames and Earth orientation parameters (EOP) achieved by the NextGNSS. In addition, transmitters on NextGNSS satellites for Very Long Baseline Interferometry observations (VLBI) are envisaged that will result in co-location in Space in addition to co-location on the ground between the Space geodetic techniques.

The VLBI will observe the satellites along with the radio sources realizing the ICRF (International Celestial Reference Frame). This will empower the NextGNSS to directly determine the Earth's Rotation angle, which is otherwise impossible. Furthermore, it would allow for independent validation of satellite orbits. For this study, we will investigate multiple scenarios, such as having a NextGNSS satellite constellation with and without VLBI transmitters, and determine the improvement in the station positions and EOP.

Global reference frame realization onboard GNSS satellites

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Abstract. Modern satellites of the Global Navigation Satellite Systems (GNSS), such as Galileo, carry onboard laser retroreflector arrays (LRA) for the Satellite Laser Ranging (SLR). Colocation of two space geodetic techniques onboard GNSS allows for the realization of the global geodetic reference frames using integrated GNSS and SLR observations. Currently, the SLR-to-GNSS satellites are neglected for the realization of the terrestrial reference frames (TRF).

This study presents the results of the combination of the GNSS and SLR observations aiming at the realization of TRF. We test different approaches for the GNSS and SLR network constraining. The best results are obtained when No-Net-Translation (NNT) and No-Net-Rotation (NNR) minimum constraints are applied to GNSS and SLR networks. When NNT and NNR constraints are imposed on two networks the 3D station coordinates repeatability is at the level of 5.8 mm (40.7 mm) for GNSS (SLR) stations. In contrast, when the NNT constraint is neglected, the 3D repeatability is at the level of 9.8 mm (45.9 mm) for GNSS (SLR) sites. When the SLR network is freed from the minimum constraints, we obtained the strength value of the SLR-GNSS connection which is at the level of 40-50 mm for the 1-day solution.

The secondary product which is delivered as a colocation result is the so-called space ties. The space ties are the estimation linkage between co-located GNSS and SLR stations which constitutes an equivalent of the ground measured local ties. The agreement of single space ties with ground measurements is at the level of 2.4 mm for the station Wettzell, Germany, and 1 mm in terms of long-term mean values for the co-located station in Zimmerwald, Switzerland. The estimated values of local ties using integrated GNSS and SLR-to-GNSS observations might be used for validating the local ground measurements or may constitute additional data with full variance-covariance information as an input for the future releases of the International Terrestrial Reference Frames. All that makes the GNSS satellite the great probe for the realization of global TRFs in space.

Quality assessment of the BeiDou-3 phase center offset calibrations in terms of the realization of the terrestrial reference frame scale

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Abstract. Thanks to the release of the phase center offset (PCO) calibrations for both, the ground (receivers) and space (satellite antennas) segment, BeiDou-3 became a new potential contributor to the realization of the terrestrial reference frame (TRF) scale of future International Terrestrial Reference Frame releases. This study focuses on the evaluation of the potential usage of the BeiDou-3 Medium Earth Orbit (MEO) constellation to the definition of the TRF scale. Firstly, we assessed the quality of the manufacturer-released PCOs within the BDS-3 MEO constellation including 24 satellites. Secondly, we evaluated the differences between the TRF scale derived from the BDS PCOs released by the China Satellite Navigation Office and the scale of IGS14. Two linear combinations of signals, namely B1I/B3I, and B1C/B2a, have been investigated. Considering that proper modeling of the direct solar radiation pressure is a prerequisite for the accurate determination of PCOs, special attention was given to the selection of the best processing strategy regarding the latest BDS-3 orbit modeling advances. Differences between the z-components of the satellite PCO as given by manufacturer calibrations and those estimated based on the IGS14 scale amount to 6.55 ± 12.56 cm and -0.32 ± 10.99 cm for B1I/B3I and B1C/B2a frequency pairs, respectively. On the one hand, the substantial deviation from the mean reflects the disparities in the quality of calibrations for the individual spacecraft, especially those manufactured by the Shanghai Engineering Center for Microsatellites (SECM). On the other hand, the difference between the two frequency pairs arises to a great extent from the doubtful quality of the SECM PCO calibrations, which certainly do not reflect the frequency dependence of the PCOs. Eventually, the mean scale bias w.r.t. IGS14 equals +0.546 ± 0.085 ppb, and +0.026 ± 0.085 ppb, for B1I/B3I and B1C/B2a solutions, respectively.

GNSS-based scale realization by integrating LEOs

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Abstract. The phase center offsets (PCOs) of the transmitting antennas of GPS satellites in the z-direction are highly correlated with the terrestrial scale when they are estimated simultaneously. Due to the uncertain PCOs of the GPS satellites launched before Block-III, the GNSS technique was not involved in the realization of the scale. On the contrary, the GPS PCOs in the z-direction (z-PCO) are estimated by introducing the scale determined by other geodetic techniques. Two approaches to realizing a pure GNSS-based scale are raised by using low Earth orbiters (LEOs) and Galileo, respectively. In the LEOs-based approach, the scale is realized by integrating LEOs with the GPS in processing in which the z-PCO, orbits, station coordinates, and some other parameters are estimated jointly. Based on the well-calibrated transmitting and receiving antennas of Galileo, a Galileo-based scale was derived in the third re-processing of the International GNSS Service (IGS).

To study the LEOs-based approach, the GPS observations obtained by six LEOs and ground networks with different numbers of stations in 2019 and 2020 are used in the processing. The scale of the ground networks is not constrained. By adding six LEOs, the correlation coefficient between the z-PCO and the scale is reduced significantly (from about 0.85 to 0.30). For GPS satellites operated in 2019 and 2020, excluding GPS III, their estimated z-PCOs have an average difference of -231 mm compared to the IGS values and the corresponding scale to the IGS14 reference frame is +1.89 part per billion. The improvement due to different numbers of LEOs and the impact of the accuracy of LEO z-PCO on the estimation are studied. More LEOs decorrelate the GPS z-PCOs and the scale more efficiently. A one-millimeter accuracy of the z-PCOs of the LEOs is required to achieve a one-millimeter scale. For validation, a comparison and cross-check study of the LEOs- and Galileo-based approaches is done. Both approaches agree well with each other in the realized scale and the estimated z-PCO. Thanks to the long-term available data of LEOs, the LEO-based approach has an advantage in the real-data-based processing backward in time over the Galileo-based one. A twelve-year scale is realized by using the two satellites of the GRACE mission. We will discuss the scale and the impact of the z-PCO of GRACE in a dedicated way.

Overall, we will present the scale realized by using six LEOs and their subsets, the scale comparison between the LEO-based and the Galileo-based methods, and a long-term scale based on the real data of the GRACE mission in 12 years. The above-mentioned result and conclusions will be discussed in detail.

Assessment of parameters describing the signal delay in the neutral atmosphere derived from VGOS R&D sessions

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Abstract. VGOS is the next generation VLBI system for geodetic and astrometric VLBI. It is currently in its build-up phase and by 2022 the VGOS operational network has reached 10 stations. The main goal of the VGOS design is to improve the accuracy and precision of the estimated geodetic parameters by one order of magnitude compared to the so-called legacy S/X VLBI system. One important aspect in this context is the ability to correctly resolve small-scale and rapid variations in the signal propagation delay caused by the neutral atmosphere, which had been identified as one limiting factor in terms of accuracy of geodetic VLBI. VGOS addresses this topic by performing many observations per time unit that cover the local sky at the stations as uniformly as possible.

To achieve this, relatively small, 12-13 m diameter, fast-slewing radio telescopes with reasonably high sensitivity, backends with high sampling capability, and relatively large receiver bandwidths are employed in VGOS. Currently, at least a factor of two in the number of observations per station is achieved within operational VGOS sessions (VO) compared to legacy S/X VLBI. Dedicated VGOS Research and Development (R\&D) sessions achieve an even larger number of observations through minimizing the scan lengths. We analyse these VGOS R\&D sessions and assess the current ability of VGOS to sense small-scale, rapid variations in the signal propagation delay caused by the neutral atmosphere. We compare the VGOS-derived results to corresponding results from simultaneous observation with co-located instrumentation at VGOS sites. Among these is the Onsala Space Observatory which is operationally active with its VGOS twin telescopes since 2019. Onsala operates additionally to its VLBI stations a multitude of co-located GNSS stations, as well as a ground-based microwave radiometer.

On the Impact of Local- and Tropospheric Ties for the Rigorous Combination of GNSS and VLBI

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Abstract. Earth Orientation Parameters (EOPs) are heterogeneously determined in the current realisation of the International Terrestrial Reference Frame (ITRF). Polar motion (x-pole and y-pole) is estimated based on the combination of the four major space geodetic techniques, whereas their rates are only based on two techniques, namely Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI). Moreover, the Earth's phase of rotation (UT1-UTC) and Length of Day (LOD) are taken solely from the VLBI solution. In addition, the combination of troposphere parameters from VLBI and GNSS through the use of tropospheric ties at fundamental sites is not implemented in ITRF's combination strategy. Hence, a rigorous combination of all parameter types common to the various techniques, with consistent EOPs and with appropriate inter-technique tropospheric ties, is still an ongoing challenge.

In this contribution, we study the impact of the use of tropospheric ties between VLBI and GNSS observations at co-location sites during the CONT17 campaign. In our approach, we perform the rigorous estimation of all parameter types common to these techniques: station coordinates, troposphere zenith delays and gradients, and the full set of EOPs and their rates, including their full variance-covariance information. The core element of our processing scheme is the combination of observations via local- and tropospheric ties, which are essential especially for the height estimates. By using and evaluating different weighting schemes, to obtain a unique set of consistent parameters, we analyse station coordinate repeatabilities and the characteristics and behaviour of the EOPs, and discuss the impact of the accuracy and weighting of the local- and troposphere ties on the estimation of the different geodetic parameters. We discuss the challenges and results of this rigorous inter-technique combination of VLBI and GNSS observations, and provide evidence of the need of such an approach.

How Do Atmospheric Tidal Loading Displacements Differ Temporally as Well as between Models?

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Abstract. Mass redistribution within the Earth's fluid envelope including the atmosphere, the oceans, and the continental hydrosphere elastically deforms the crust hence inducing displacements of geodetic markers in excess of 1 cm at sub-daily to seasonal timescales. In this contribution we study high-frequency deformation induced by atmospheric tides. While the effect is responsible for crustal deformation at the mm-range, it is crucial to be considered during space geodetic data analysis to mitigate aliasing artefacts. Herein, we have identified the waves that are responsible for the largest mass anomalies in the sub-diurnal frequency band and calculated the associated displacements upon convolving them with globally 1D symmetric load Green's functions in the center of mass isomorphic reference frame. Mass anomalies are retrieved by three different global reanalyses: ECMWF's ERA5, NASA's MERRA2 and JMA's JRA55. At this point, atmospheric pressure loading over the oceans as the atmospheric contribution to ocean tides is not considered, but will be explicitly treated with a global ocean tide model (Sulzbach et al., 2021) for all relevant frequencies, thereby making any assumption about an inverse barometric response of the ocean superfluous. We assess the extent to which the predictions of atmospheric tides differ depending on the numerical weather model, as well as how much they differ as a function of time. While the inter-model differences are below 10% of the signal, we note significant annual and semi-annual modulations for the main spectral lines, the S1 and S2, as well as non-linear long-term amplitude and phase trends. Model results that are available globally will be finally contrasted against the 5-minute final solutions of selected GNSS station coordinate time-series from the Nevada Geodetic Laboratory.

New generation of NRCan's Final GNSS orbit and clock products: overview and validation

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Abstract. GNSS Precise Orbit Determination (POD) has a key role in geodetic and earth sciences. Natural Resources Canada (NRCan) has historically been contributing high quality POD products: satellite orbits and clocks to the International GNSS Service contributing to their Final products. However, a modernization of the processing strategy, including the software in use, was necessary to accommodate multi constellation POD among other updates. The previously used software for the Rapid and Ultra-Rapid products (Bernese version 5.2) and for the Final products (GIPSY-OASIS II version 6.4.1) have been replaced by GipsyX, which features combined estimation of geodetic and geophysical parameters using Kalman filter. This work presents NRCan's Final products' processing strategy and validates the new products against the IGS combined products as well as other ACs'. These results pave the way for the official transition to NRCan's new generation products.

VLBI and GNSS space-tie onboard Galileo satellites

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Abstract. Surveying with different space geodetic techniques results in technique-specific terrestrial frames and combining those individual techniques requires links between those frames such as tie vectors. Collocation of different geodetic techniques on Earth-orbiting satellites offers the unique opportunity of continuously measurable 'space-ties'.

A VLBI transmitter (VT) on future Galileo satellite(s) could realize such a link through the orbital parameters between the positions of the VLBI ground station network which are determined by quasar observations (VLBI frame) and Galileo ground station network which are determined by Galileo GNSS observations (GNSS frame). Comparing the orbit of the Galileo satellites in the two different frames allows it to estimate rotation parameters between them. In this study, we investigate the contribution of a VT to this by evaluating the formal precision of orientation parameters under different geometrical configurations and error sources.

Future SLR satellite constellations – a simulation study

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Abstract. Satellite laser ranging (SLR) is currently one of four space geodetic techniques that provide a relevant contribution to the International Terrestrial Reference Frame (ITRF) as well as to the determination of global geodetic parameters or low-degree harmonics of the Earth's gravity potential. ITRF realizations are mostly based on the observations to the two Laser GEOdynamics Satellite (LAGEOS) and two Etalon satellites, however, the impact of observations to Etalon satellites is marginal. Currently under consideration is an extension of the ITRF solution to include the LAser RElativity Satellite (LARES) and LARES-2 developed by the Italian Space Agency ASI and launched on July 13, 2022. The contribution of other satellites with retroreflectors is still being investigated.

This study aims at evaluating the contribution of the LARES-2 satellite to the realization of ITRF and deriving global geodetic parameters, such as geocenter motion, pole coordinates, length-of-day, as well as low-degree gravity field coefficients. Moreover, we consider adding subsequent satellites which supplement the existing constellation. Our research aims to investigate a positive or negative influence on the accuracy of global geodetic parameters and their correlations. We also examine various approaches to estimating geodetic parameters depending on the number of determined empirical once-per-revolution parameters of satellite orbits and different approaches of parametrization for the Earth rotation parameters, including piecewise linear and piecewise constant parametrization.

We simulate satellite orbits and SLR observations to LAGEOS-1/2 and LARES-1/2, as well as to possible pairs of LARES-3/4 and LARES-5/6. We check how the satellites at different inclination angles and heights contribute to deriving global geodetic parameters and compare the results to LAGEOS-1/2 solutions based on simulated data. We analyze the standard deviations of derived parameters, the sensitivity of particular orbits to gravity field spherical harmonics, as well as the correlations between length-of-day and Earth's oblateness term, and between the gravity field parameters of the same order and similar degree. Finally, we assess the potential improvement of estimating geocenter coordinates and Earth rotation parameters emerging from the combination of SLR observations to satellites at different inclination angles and altitudes for future geodetic missions. Having current constellations of LAGEOS and LARES satellites, we show that the highest improvements can be obtained by adding the next LARES satellite – with the same altitude as LAGEOS-2 but with a complementary inclination angle, i.e., 128 deg, thus orbiting the Earth in the opposite direction to the Earth rotation. In addition, we show that observations to the new LARES-2 satellite will especially improve determining the Z-geocenter component.

Designing a DORIS processing software for orbit determination and estimation of geodetic parameters

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Abstract. Dionysos Satellite Observatory (DSO) of the National Technical University of Athens, has long been involved in the DORIS community, hosting a system beacon since 1989 in its infrastructure, located at mountain Penteli, in Attika, Greece. Starting a year ago, the laboratory decided to take its involvement and contribution one step furhet, via the in-house design and development of a brand new DORIS processing software suite. Apart from precise orbit determination, the DORIS technique allows for accurate positioning as well as estimation of geodetic, earth orientation parameters. It is one of the four fundamental satellite techniques, contributing to the realization of the ITRF. The latest contribution of International DORIS Service (for ITRF2020), covered a data span starting in early 1993. In this study, we present first results from designing and implementing a state-of-the-art DORIS data processing software. We focus on methodology issues and and estimation techniques relevant to parameters of geodetic interest, that have a strong effect on the realization of global reference frames.

Impact of Tropospheric Ties in GNSS and VLBI Integrated Solution

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Abstract. International celestial and terrestrial reference frames (ICRF and ITRF) and Earth Orientation Parameters (EOP) are determined by the four space geodetic techniques, including Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI). An integrated processing strategy with proper handling of the ties could exploit the benefits of each technique and improve the solution. Currently, only global ties (EOP) and local ties (station positions) are commonly used in the combined solution. For the microwave-based techniques, such as GNSS and VLBI, the tropospheric ties at co-locations can also be adopted. We present the challenges and benefits in applying tropospheric ties in the GNSS and VLBI integrated solution, including the 24-hour continuous (CONT) campaigns (CONT05 – CONT17) and the 1-hour Intensive (INT) sessions. We demonstrate that the tropospheric zenith delays of GNSS and VLBI agree at the level of 4 mm in terms of standard deviation, whereas the systematic bias could reach up to 5 mm. By properly handling the tropospheric ties, the TRF, CRF, and EOP estimates in the integrated solutions could all be improved significantly. As for the INT sessions, the UT1-UTC estimates benefit from tropospheric gradient ties, especially the east component.

Session 3

Regional Reference Frames and their Applications

Advancing the geodetic infrastructure in Europe through EUREF

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Abstract. EUREF´s (IAG sub-commission 1.3a for Europe) primary mission is to define, realize and maintain the European Terrestrial Reference System 1989 (ETRS89) and the European Vertical Reference System (EVRS) for scientific and practical purposes in Europe.

This is primarily done through the EUREF Permanent GNSS Network (EPN) , while the physical height system EVRS is realized through common adjustment of the Unified European Levelling Network (UELN). All contributions to EUREF are provided on a voluntary "best effort" basis, with more than 100 European bodies (agencies/research institutes) involved.

EPN consists of more than 350 continuously operating GNSS stations, sup-ported by Data and Analysis Centers and a Central Bureau. The backbone EPN has been complemented with additional national CORS networks. The dense European network (EPND) incorporates ten times more stations as the core EPN

In the presentation we will discuss current and future challenges regarding continental scale geodetic infrastructure and the contribution from EUREF. Due to the availability of the ITRF2020 and reprocessed orbit and clock products, a consistent reprocessing of the entire EPN from 1996 to the present is imminent. Strategic options for this analysis (EPN-Repro3) will be briefly discussed. We will also metion the development of a European Height Reference Surface, models for crustal deformations, realization of the emerging International Height Reference System (IHRS) in Europe.

Current needs, like the proper application of the European Union's General Data Protection Regulation (GDPR), and future developments like the integra-tion of GNSS and InSAR will be touched, as well as the future role of EUREF in the emerging organizational landscape, where the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy, UN GGIM: Europe and the European Plate Observing System (EPOS) are important partners.

Status of the SIRGAS reference frame: recent developments and new challenges

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Abstract. In accordance with recent developments of the International Association of Geodesy and the policies promoted by the UN-GGIM Subcommittee on Geodesy, a main goal of SIRGAS is the procurement of an integrated regional reference frame that not only supports the precise determination of geocentric coordinates but also provides a unified physical reference frame for gravimetry, physical heights, and geoid. The geometric reference frame is given by a network of ~500 continuously operating GNSS stations, which are routinely processed by ten analysis centres to generate weekly station positions aligned to the International Terrestrial Reference Frame (ITRF) and multi-year (cumulative) reference frame solutions. This processing is also the basis for the generation of precise tropospheric zenith path delays with an hourly sampling rate over Latin America. The reference frame for the determination of physical heights is a regional densification of the International Height Reference Frame (IHRF). Current efforts focus on the estimation and evaluation of potential values obtained from high resolution gravity field modelling, an activity tightly coupled with the geoid determination. The gravity reference frame is aimed to be a regional densification of the International Terrestrial Gravity Reference Frame (ITGRF). SIRGAS activities in this regard are devoted to evaluate the quality of existing absolute gravity stations and to identify regional gaps where further absolute gravity stations are needed. Another main SIRGAS objective is to promote the use of its geodetic reference frame at the national level and to support capacity building activities in the region. This presentation summarises key milestones in the establishment and maintenance of the SIRGAS reference frame and discusses current efforts and future challenges.

Deformation Models - Progress with development of an OGC Standard

Richard Stanaway (Quickclose), Chris Crook (Land Information New Zealand), Kevin Kelly (ESRI) and Roger Lott (IOGP)

Abstract. IAG WG 1.3.1 (Time-dependent transformations between reference frames in deforming regions) has been working in close association with the Open Spatial Geospatial Consortium (OGC) CRS Domain Working Group since 2020. The aim has been to develop specifications for both a functional deformation model and an associated geodetic grid exchange format (GGXF). These will eventually be refined into an OGC standard for adoption in geodetic applications. In deforming zones, a globally recognised grid-based time-dependent transformation standard is essential to ensure precise alignment of positioning (especially GNSS-PPP) and spatial data on different temporal and spatial scales. Existing conformal transformation approaches are proving inadequate outside stable plate regions and a usable alternative approach and standard is required to take better advantage of the rapid improvements in modern positioning and spatial data technologies.

This paper summarises both WG efforts to date. Basic principles and requirements of deformation models in geodetic applications such as positioning, reference frame transformations and GIS are reviewed. Results of a global geodetic agency survey on the usage and requirements of deformation models are summarised and the final draft specification for deformation models will be presented with a brief summary of the GGXF development to date.

EuVeM2022: A 3D GNSS velocity field for Europe

Rebekka Steffen (Lantmäteriet), Ambrus Kenyeres (Kozmikus Geodéziai Obszervatórium), Holger Steffen (Lantmäteriet) and Martin Lidberg (Lantmäteriet)

Abstract. The increased availability of GNSS (Global Navigation Satellite System) station velocities makes it possible to obtain a complete picture of the horizontal and vertical deformation via an interpolation. However, most well-known interpolation techniques (e.g., triangulation, spline interpolation) have the disadvantage that the entire signal is used while every signal always includes noise due to unknown errors or local effects. Additionally, those interpolation techniques can only be applied to one component at a time. The least-square collocation solves both problems of dividing the dataset into a signal and noise component and applying different datasets simultaneously. In addition, a recent extension to the least-squares collocation allows the usage of the correlation between the horizontal velocity components.

Here, we will show results of applying a combined least-square collocation for the example of Europe using a velocity field solution by the EUREF Permanent Network Densification (EPND2150). This velocity field is obtained by the combination of weekly position SINEX solutions generated by 28 EPND Analysis Centres. More details on EPND can be found on the www.epnd.sgo-penc.hu website. The homogenized and quality-checked velocity field is then interpolated via a least-square collocation using a fixed scale length of 150 km for the east-west and north-south velocity components and 130 km for the vertical velocity component. In addition, the effect of known plate boundaries is considered during the interpolation to avoid a smoothing of nearby velocities on different tectonic plates. We also apply a moving variance approach to avoid effects of non-stationarity, which arise due to the variable station densities. The final dataset (vertical and horizontal velocities) will be freely available and provided in different formats and reference frames to ease application for users with different scientific background.

Validation of reference frame consistency of GNSS service products

Lennard Huisman (Kadaster - NSGI) and Huib de Ligt (Kadaster - NSGI)

Abstract. In GNSS point positioning the coordinate reference frame of the positioning results is determined by the reference frame of the used GNSS service product. Examples of GNSS service products are broadcast ephemeris (for SPP), precise orbits, clocks and biases (for PPP, PPP-RTK) or (virtual) reference station observations with coordinates (for RTK, PPK).

In earth science applications and geomatics, consistency between the reference frame of point positioning results is of importance in analysis of coordinate differences and velocities. To ensure consistency of the coordinate reference frame between GNSS service providers, national agencies compute coordinates for the GNSS reference stations used by these providers. This approach ensures consistency of the national reference frame on the input side of the process that generates GNSS RTK service products.

The approach of computing only station coordinates is not suitable for GNSS service providers that provide GNSS service products for multiple countries and can only select one coordinate for each station. This holds for some GNSS RTK service providers, but especially for other GNSS point positioning techniques (SPP, PPP, PPP-RTK) where a global network of reference stations is used to compute the GNSS service products. Also the approach has some drawbacks for both providers and users, especially as the consistency of the reference frame that is provided by the GNSS service product to the end user is not validated.

This contribution will introduce two new approaches for reference frame validation of GNSS service products and their relation with the EUREF densification guidelines, including results of a first prototype assessing the consistency of a cross-border GNSS RTK service with the EPN realization ETRF2000 and consistency of a GNSS PPP service with the IGS realization IGb14.

How Do Different Phase Center Correction Values Impact GNSS Reference Frame Stations?

Johannes Kröger (Leibniz Universität Hannover), Tobias Kersten (Leibniz Universität Hannover), Yannick Breva (Leibniz Universität Hannover) and Steffen Schön (Leibniz Universität Hannover)

Abstract. For highly precise positioning with Global Navigation Satellite Systems (GNSS), it is mandatory to take Phase Center Corrections (PCC) into account. This holds especially true for data processing at reference stations contributing to regional or global reference frames as well as Precise Point Positioning (PPP).

Currently, the International GNSS Service (IGS) is updating the PCC values for several geodetic antennas mounted at reference stations contributing to the IGS20. When analysing the variations at the pattern level, differences at the centimeter level occur for the GPS ionosphere-free linear combination L0. However, for users and network providers it is of most interest to investigate the effect of different sets of PCC (dPCC) on geodetic parameters. This includes topocentric coordinate deviations, receiver clock errors and tropospheric parameters.

In this contribution, we describe our developed standardized simulation approach, which allows to assess the impact of multi-GNSS dPCC on geodetic parameters with changing processing parameters. This includes the selection of the frequency or linear combination, the elevation cut-off angle, the observation weighting scheme and the weighting with respect to the satellite coverage as well as the geographic location.

Using the simulation approach, we illustrate the impact of the PCC updated by the IGS on geodetic parameters on a global map. We study the effect for longer time series of 10 years showing the impact of variations in the GNSS constellations. For selected stations contributing to the IGS20, we compare the simulation results with PPP results from real observations. Here, we also analyse the role of the reference point for code observations, i.e. applying phase center offsets or full sets of PCC on the code observations or not.

Versatile Processing Program for RINEX Files

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Abstract. In the field of geodesy, Receiver Independent Exchange Format (RINEX) is adata interchange format for raw satellite navigation system data. However, notall RINEX files can be used directly in the network adjustment step due to errorsin the form of the RINEX file caused by mistakes of the users or due to poorquality of the measurement data recorded inside the RINEX file caused by poormeasurement conditions. Therefore, this research starts with a detailedcomparison and analysis of the most used 2.0 and 3.0 versions of the RINEXfile and then uses the Python programming language to design a versatilehandler for RINEX files to solve this problem. The program includes functionsfor processing the header section of large RINEX files and for data qualitycontrol of the data recorded in the files, and also comes with a GIS module forvisualizing RINEX files.

Transition from PSAD56/SAD69 to SIRGAS. Toward a kinematic reference frame for mining in Chile

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Abstract. In February 2022, Law 21420 established that the agency that regulates mining concessions in Chile, Servicio Nacional de Geología y Minería de Chile (SERNAGEOMIN), in English, National Service of Geology and Mining of Chile, must employ SIRGAS (Sistema de Referencia Geodésico para Las Américas) since 2023 as a modern reference frame (RF). Law replaced PSAD56 (Provisorian South American Datum 1956) and SAD69 (South American Datum 1969) with SIRGAS to manage mining geospatial information in Chile. In this project, the SIRGAS geodetic processing and analysis centre of the University of Santiago (USC-SIRGAS) shows how it developed the strategy to allow SERNAGEOMIN to implement law 21420, transitioning from a classic RF to the modern RF called REDGEOMIN (Red Geodésica para Minería) which is aligned with SIRGAS. REDGEOMIN is a kinematic RF, where a deformation model called ADELA (Analysis of DEformation beyond Los Andes) has also been generated.

The classic geodetic infrastructure is highly deteriorated in Chile and doesn't have maintenance. It has poor densification and information, and the coordinates have metric errors. Military Geographic Institute must maintain the national geodetic network to generate cartography in Chile. For this reason, in 2008, it changed from PSAD56/SA69 to SIRGAS, specifically to one static densification called SIRGASChile. Because its objective is purely cartographic, the parameters obtained do not have the necessary precision for engineering and mining. This project has two motivations, the first to obtain transition parameters between both systems and the second to implement a kinematic RF that includes seismic events.

The study consists of three phases: first, calculation of REDGEOMIN-ADELA, and second, calculation of transformation parameters. By law, the parameters must maintain the mining concessions' size, shape and dimensions. The last step is the implementation of REDGEOMIN as a kinematic reference frame, leaving PSAD56-SAD69 behind.

Comparison Analysis of Network Adjustment of 5000 Unified Control Points in South Korea using Bernese and GAMIT/GLOBK

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Abstract. GAMIT/GLOBK and Bernese are internationally recognized GNSS processing software that supports double-difference correction on the Network adjustment data processing. This article briefly introduced GAMIT/GLOBK and Bernese. More than 16,000 observation data (from 2002 to 2020 of 437 days) of 5,000 Unified Control Points located in South Korea were applied in GAMIT/GLOBK and Bernese. This article analyzed determination of the solution strategy and compared the solution results. 17 GNSS Continuously Operating Reference Stations located in South Korea were chosen as fixed station. The absolute velocities indicated an overall displacement of the South Korea region along the south-east direction (GAMIT =3.04 cm/yr, Bernese =3.33 cm/yr). The value of RMSE solved with the GAMIT/GLOBK version 10.71 software was an average of 0.0104 m in the N direction and 0.0124 m in the E direction. The value of RMSE solved with the BERNESE version 5.2 software was an average of 0.0068 m in the N direction, in the E direction, the average was calculated as 0.0072 m. There are differences in the coordinate results of the two software programs at the millimeter levels, respectively, in the case of a consistent solution scheme. The average difference between the result of Network Adjustment using GAMIT/GLOBK and Korean Geodetic Datum 2002 was 0.0013 m in the N direction, and 0.0039 m in the E direction. The average difference between the result of Network Adjustment using Bernese and Korean Geodetic Datum 2002 was 0.0071 m in the N direction, and 0.0092 m in the E direction. GAMIT/GLOBK was slightly more accurate in solving baselines. We speculated that the millimeter difference is due to the difference in the software themselves.

ETRS89 Realization and Maintenance in Spain

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Abstract. The implementation of ETRS89 in Spain was stablished by law in 2007, based on a passive geodetic network. At the same time, most of regional cartographic agencies installed their own GNSS permanent network, mainly for the purpose of real-time positioning, while the IGN active national network (ERGNSS) was growing. The geodetic reference frame for most of these active networks was usually given by their own processing and in some cases by IGN, but not in a common reference epoch, neither in an unique realization of ETRS89 or a common and homogeneous processing.

A Working Group was created with the aim of harmonizing and standardizing a common reference framework in ETRF00 for all public GNSS networks in Spain (excepting the Canary Islands). National and regional institutions were involved working together in processing all existing GNSS permanent stations, combining the solutions to obtain precise coordinates, velocities, time series and discontinuities.

First solution was published in 2018, in which about 250 stations were processed in the period between April 2011 and January 2017, obtaining a homogeneous set of coordinates in ETRF00 that were adopted by all public GNSS existing networks in Spain.

Two updates were obtained since then, combining a total period from April 2011 to January 2022. For each solution, a monitoring of the coordinates of stations is done and criteria for defining an update in coordinates or not are taken. If a change in the official coordinates is required, these updated coordinates are published and distributed to all institutions involved.

The combination process to obtain the station coordinates, the maintenance works, and update of the coordinates are presented in this contribution.

On the stability of regional reference frames in Greece using GNSS permanent stations

Dimitrios Anastasiou (National Technical University of Athens), Xanthos Papanikolaou (National Technical University of Athens) and Maria Tsakiri (National Technical University of Athens)

Abstract. Dionysos Satellite Observatory (DSO) has been actively involved in GNSS data processing since the late 80s. For the last decade, DSO has been routinely processing GNSS data from a list of permanent stations, installed maintained and distributed by various institutes.

Over the last years, this routine processing scheme has been enlarged with in-house software, to include coordinate time-series analysis tools and surface deformation modeling, including estimation of strain rates. This complex, multi-step, crustal deformation monitoring platform enables an in-depth study of the tectonic setting of Greece, and its influence in the stability of regional reference frames used within the country.

Currently, GNSS data from over 300 stations in Greece have been or are routinely analyzed, efficiently divided in subnetworks. Satellite data processing is followed by subsequent, routine, time series analysis. Results from the latter are in turn used to periodically monitor crustal deformation patterns.

In this study, results from up to 100 stations with available data for a period greater than 2.5 years, distributed throughout the region of Greece have been used. Respective daily coordinate estimates were stacked to form position time series, and analyzed to estimate an as dense as possible velocity field.

Different kinematic models for the region were investigated with the aim of utilizing them in the implementation of regional reference frames in the region of Greece.

Finally, strain tensor rates are calculated from the velocity field for the whole region using StrainTool software and with different algorithms.

Strategies for the optimal combination between local 3D modern GNSS and 2D classical networks, expressed in different reference frames: Case study in Greece

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Abstract. The advent of GNSS during the last three decades facilitated a lot the daily geodetic/surveying practice, giving the opportunity of estimating coordinates in 3D (or even 4D) in a straightforward way. Nevertheless, the main geodetic/surveying infrastructure of a country/region relies even at present on classical 2D networks, i.e., network which has been observed and adjusted based on classical observations like angles, directions, and spatial distances. A major, and sometimes cumbersome, issue is the combination of the new 3D information into the existing 2D one. A basic tool in this direction is the Helmert-type transformation (3D/2D options), which is commonly used worldwide. However, a Helmert-type transformation cannot be applied in all cases, for it carries some significant drawbacks, which may distort the accuracy. The present study deals with a variety of strategies for the optimal combination of 3D and 2D reference frames in a rigorous way. The methodological variations stem from the (un)availability and types of the 2D network observables. The various strategies are tested in Drama region, Northern Greece, where two local networks were established; A 3D one expressed in ITRF2008 and a 2D one which refers to the official Greek Geodetic Reference System. The results show that the combination schemes provide in general improved accuracies compared to using solely one of the networks.

Saudi Arabia - National Spatial Reference System (SANSRS)

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Abstract. SANSRS is an accurate framework that unifies all geospatial activities within the Kingdom, it allows users to precisely determine and express locations in the Kingdom of Saudi Arabia. SANSRS consist of the following components:

• National Geodetic Reference Frame (KSA-GRF) is based on ITRF2014, coincides with it at epoch of 2017.0 (KSA-GRF17) and is co-moving with the stable part of the Arabian tectonic plate.

• National Vertical Reference Frame (KSA-VRF) is using the Helmert-Orthometric above Mean Sea Level height system at the Jeddah Tide Gauge. It was determined using satellite data (altimetry & gravity) and terrestrial observations from national tide gauge, gravity and leveling networks. KSA-VRF14 is the current realization fixed to MSL epoch 2014.75.

• National geoid model (KSA-GEOID) – hybrid geoid model determined by using satellite data (altimetry & gravity), more than 500000 offshore and onshore pointwise gravity observations, airborne gravity measurements, and 3522 GPS-leveling points. The most recent realization is KSA-GEOID21.

The following geodetic networks beside SANSRS forms SA National Geodetic Infrastructure (NGI)

• KSA-CORS: a network of over 200 active CORS installed according to the international standards and providing GNSS services in KSA-GRF17.

• National Vertical Network (KSA-NVN): a network of 3893 geodetic BMs grouped into 88 lines and observed by precise spirit leveling, providing orthometric height in KSA-VRF14.

• National Gravity Network (KSA-NGN) – consists of 41 absolute gravity stations with the accuracy of 10 µGal and 3836 relative gravity stations with the accuracy of 20 µGal. In addition, a gravity calibration baseline of 14 stations is established.

In order to follow the technical development in geodesy and to improve the accuracy and reliability of SANSRS, Currently GASGI is working on developing the concept for transition from static to a dynamic/time varying SANSRS.

GeoNetGNSS, a newly established CORS network in Northern Greece in support of high-accuracy positioning applications

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Abstract. Modern day surveying and mapping applications customarily use GNSS observations to collect positional data for both thematic, lower accuracy, and geodetic, higher accuracy, applications. In the latter case, the increased availability of continuously operating reference stations (CORS) during the last years have offered unique opportunities for every-day surveying and mapping applications, with reduced costs and improved accuracies. In the frame of the GeoNetGNSS project, a newly established network of CORS stations has been planned to cover the geographic area of the Region of Central Macedonia (RCM), Greece. The main scope of the project is to establish the necessary infrastructure, perform additional GNSS/Levelling and gravity observations, integrate the new CORS stations to national, European (EUREF) and global (ITRF) reference frames, and finally deliver high-accuracy horizontal positions and orthometric heights in both real-time kinematic, rapid-static, based-rover and PPP modes. The latter refer to both geodetic and surveying, as well as, to mapping applications with UAVs and drones. In the present work we describe the main steps for the establishment of the CORS stations, first results acquired from the analysis of the collected observations, as well as results from the first campaigns in the wider area of RCM to collet collocated GNSS/Leveling and gravity observations in support of developing a high-resolution and high-accuracy geoid model.

Development of GNSS-based crustal Deformation monitoring system

Seung Jun Lee (SUNGKYUNKWAN UNIVERSITY), Hong Sic Yun (SUNGKYUNKWAN UNIVERSITY), Myeong Hun Lee (SUNGKYUNKWAN UNIVERSITY), Jinzhen Han (SUNGKYUNKWAN UNIVERSITY), Canying Shen (SUNGKYUNKWAN UNIVERSITY) and Minkyung Cho (SUNGKYUNKWAN UNIVERSITY)

Abstract. Earthquakes occurring at the boundary and fault of each tectonic plate occur when stress in the tectonic plate accumulates at a constant speed is discharged at a constant period. To calculate the stress accumulated in the crust, data from 85 GNSS CORS(continuously operating reference stations) in south Korea were used. The period of data used was from January 1, 2016 to February 26, 2022, and three S/Ws were used: Gamit/Globk, Bernese, and Gipsy. The three S/Ws were developed to be automatically released every day using 85 GNSS CORS data, and were designed to upload calculated results on the website. The GNSS Orbit Products used in the calculation process are calculated using Ultra Rapid at the time Rinex Data is uploaded, Rapid after 5 days, and Final after 23 days. The Delaunay Triangle was constructed using X, Y, and Z of 85 calculated GNSS CORSs, calculated as geodesic lines for each baseline, and designed to be calculated to 13 decimal places to reduce errors. The main stress generated in the triangular network was calculated based on the tensile strength and compression of the baseline, and the possibility of earthquake occurrence was predicted based on the main stress. All calculations are designed to be calculated by anyone on the website, and the period is free.

Development of the Crustal Deformation Model of the Korean Peninsula Using Polymer Regression

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Abstract. Observation data of the GNSS continuous operating reference stations(CORS) were collected using software developed by the Geodetic Laboratory of SUNGKYUNKWAN UNIVERSITY. 17 out of 60 satellite reference points in Korea points were selected to perform GNSS relative positioning, and the speed fields of three academic GNSS Software (GAMIT, bereness, and gipsy-oasis) were calculated using data from 2016 January 1 to March 10, 2022. The speed field model was obtained by using the polymer regression for the speed field of the GNSS relative position using the GAMIT, bereness and gipsy program. We developed a Crustal Deformation Model by converting frames from ITRF 2014 used by the GIPSY-OASIS program to KGD2002. The speed field of gamit in Korea has a speed field of 2.767 to 2.862cm/yr in the east direction and -1.256 to –0.812cm/yr in the south direction every year. The speed field of bereness in Korea has a speed field of 2.905 to 3.240cm/yr in the east direction and -1.461 to –0.982cm/yr in the south direction every year. The speed field of gipsy-oasis in Korea has a speed field of 2.787 to 3.206cm/yr in the east direction and -1.309 to –0.929cm/yr in the south direction every year.

Reference Frame Modernization in Canada

Catherine Robin (Natural Resources Canada), Geoff Banham (Alberta Ministry of Environment and Parks), Ron Berg (Ontario Ministry of Transportation), Michael Craymer (Natural Resources Canada), Gabriel Cross (Service New Brunswick), Brian Donahue (Natural Resources Canada), Joe Harrietha (Natural Resources Canada), Jianliang Huang (Natural Resources Canada), Raphael Messier Paquin (Direction de la référence géodésique du Québec), Rene Tardiff (Natural Resources Canada) and Yves Thériault (Direction de la référence géodésique du Québec)

Abstract. The United States National Geodetic Survey (NGS) is planning to adopt a new geometric reference frame for the U.S. in 2025 (NATRF2022), which will be based on ITRF2020 and separated from NAD83, the currently adopted frame in both Canada and the U.S., by up to 1.5 meters at the Canada-U.S. border. The Canadian Geodetic Survey (CGS) also plans to adopt NATRF2022 as a new national standard following U.S. adoption, and is collaborating with NGS to define and realise NATRF2022 to ensure reference frame compatibility across both countries. In parallel, CGS is leading an effort to adopt NATRF2022 as a unified reference frame across provincial and other jurisdictions, which have the authority to adopt reference systems used within their own jurisdictions. In this paper, we describe Canadian considerations for the definition and realisation of NATRF2022, and outline efforts and challenges in migrating to NATRF2022 as a unified reference system throughout all jurisdictions in Canada, and maintaining such unification in the future. We will also discuss a new geoid-based height system (NAPGD2022) to be adopted by the U.S. together with NATRF2022, and its implications for Canada, where a geoid-based height system (CGVD2013) has been in place since 2013.

Modernizing Regional Reference Frames in North America: Current and Future Activities of IAG Regional Sub-Commission SC1.3c

Michael Craymer (Natural Resources Canada), Daniel Roman (U.S. National Geodetic Survey) and Phillip McFarland (U.S. National Geodetic Survey)

Abstract. In collaboration with the IAG community, its service organizations and the national geodetic organizations of North America, the IAG Regional Sub-commission SC1.3c (Regional Reference Frames for North America) provides international focus, cooperation and coordination for issues involving the geodetic reference frames and control networks of North America. These issues include the establishment, maintenance, future evolution and inter-relation of reference frames throughout the continent, and the specification of consistent standards and guidelines. In order to realize these objectives, the Sub-commission has been organized into three working groups dealing with:

(1) densification of the ITRF and IGS reference frames in North America (NAREF);

(2) replacing the existing, non-geocentric NAD83 reference frame with new geocentric, ITRF2020-based, plate-fixed regional reference frames in North America (NATRF2022), the Caribbean (CATRF2022), and U.S. territories on the Pacific (PATRF2022) and Mariana plates (MATRF2022);

(3) maintenance of the relationship between the existing NAD83 reference frame and the various versions of ITRF, including its IGS and WGS 84 realizations.

Over the last few years there have been many activities in all of these working groups, in particular, preparations for the implementation of the new ITRF2020-based reference frames. In particular, we highlight the fundamental work of defining the plate-fixed frame though an Euler pole rotation in ITRF2020, as well as GNSS reprocessing efforts in both Canada and the U.S. based on IGS Repro3 products and standards. Other important activities include updating to a new realization of NAD83 based on ITRF2020 to facilitate the transition to NATRF2022.

NAD83(CSRS) Version 8: A New Realization of NAD83 for Canada based on ITRF2020 and IGS Repro3 Products

Michael Craymer (Natural Resources Canada), Babak Amjadiparvar (Natural Resources Canada), Mike Piraszewski (Natural Resources Canada), Earl Lapelle (Natural Resources Canada) and Yanlai Zhao (Natural Resources Canada)

Abstract. The North American Datum of 1983 (NAD83) is the geometric reference frame of the Canadian Spatial Reference System (CSRS) and has been adopted by the federal and provincial agencies for georeferencing in Canada. In collaboration with the U.S., NAD83 was redefined in 1998 as a seven-parameter Helmert transformation from ITRF96. The transformation parameters were effectively definitional and considered errorless. Referred to as NAD83(CSRS), the frame was kept aligned with the North American tectonic plate using the NNR-NUVEL-1A plate motion model. NAD83(CSRS) has since been updated to later realizations of ITRF using the transformations between ITRFs published by the IERS and identified by version numbers. Several realizations or versions of NAD83(CSRS) have been released based on each new realization of ITRF. The current NAD83(CSRS) version 7 is based on the transformation from ITRF2014 and was realized from a reprocessing of all continuous and high accuracy GPS campaign data up to the end of 2017 using stations in Canada, the bordering areas of the U.S., all of Greenland, and a set of approximately 80 global IGS stations for alignment to IGS14. A new NAD83(CSRS) version 8 is now under development based on the recently released ITRF2020. A fully consistent weekly reprocessing of all data up to 2022 is now being initiated with the latest version of the Bernese GNSS software, and IGS Repro3 products and processing standards. In addition, a detailed re-analysis of all station position and velocity discontinuities using MATLAB-based visualization and analysis tools is nearly complete. The weekly Bernese solutions will be combined into a final cumulative solution with and without the estimation of seasonal signals for comparison purposes. The version 8 crustal motion model will also be improved through updated GIA models and the use of 5 more years of data, resulting in more accurate velocities for the many new stations used to densify the GNSS network throughout Canada.

Update of ITRF densification in Cyprus using IGS repro3 products

Chris Danezis (Cyprus University of Technology), Miltiadis Chatzinikos (Cyprus University of Technology) and Christopher Kotsakis (Aristotle University of Thessaloniki)

Abstract. The aim of this paper is to present an updated multi-year solution of the CYPOS network based on the ITRF2014 frame and the IGS repro3 products and processing standards. The CYPOS national network operates since 2008 in support of the Cyprus Positioning System under the auspices of the Department of Lands and Surveys, and it consists of seven permanent GNSS stations equipped with different types of receivers/antennas at an average distance of about 60 km. The NICO Cypriot station which belongs to the IGS network is also included in our data processing, along with 34 additional reference stations from the EUREF-EPN and IGS networks which are located mostly in the continental part of Europe.

Daily RINEX files from the aforesaid stations, spanning a total period of almost ten years (2012-2021), were processed using the Bernese GNSS software in conjunction with the latest IGS repro3 products in the ITRF2014 frame. A number of auxiliary scripts were applied in the processing steps to investigate various data/network-quality metrics and the precision of the GNSS measurements at the Cypriot stations. The daily solutions obtained from Bernese (SINEX files) were used as input to a time-series stacking procedure in order to compute the final solution for the positions and velocities at the CYPOS stations in the ITRF2014 frame. The results of our stacking solution are externally validated through comparisons with the official ITRF positions and velocities at the used EPN stations, showing an agreement level of 1-2 mm (for the positions) and < 1 mm/yr (for the velocities). Finally, the comparison with a previously estimated multi-year solution of the CYPOS network in the ITRF2008 frame shows minimal differences at the sub-mm level, thus confirming the high quality of the ITRF realizations in the region of Cyprus. This research was carried out in the framework of the CyCLOPS project (RIF/INFRASTRUCTURES/1216/0050), which is funded by the European Regional Development Fund and the Republic of Cyprus through the Research and Innovation Foundation.

Session 4

Celestial Reference Frames
and Earth Orientation Parameters

Annual summary of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC)

Tomasz Kur (Space Research Centre of the Polish Academy of Sciences), Justyna Śliwińska (Space Research Centre of the Polish Academy of Sciences), Jolanta Nastula (Space Research Centre of the Polish Academy of Sciences), Henryk Dobslaw (Section 1.3: Earth System Modelling, GFZ German Research Centre for Geosciences), Małgorzata Wińska (Warsaw University of Technology, Faculty of Civil Engineering) and Aleksander Partyka (Space Research Centre of the Polish Academy of Sciences)

Abstract. Earth Orientation Parameters (EOP) represent the rotational part of the transformation between the current releases of the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). The accurate determination of EOPs requires post-processing of observational data collected from various space geodetic techniques, which causes some delays in the provision of EOP solutions. However, in precise positioning and navigation it is crucial to receive instantaneous information about EOP in real time. Therefore, EOP short-term prediction has become a subject of increased attention within the international geodetic community.

In the light of the developments in the field of advanced geodetic data processing, modelling effective angular momentum functions and developing new prediction methods, a re-assessment of the various EOP predictions is currently pursued in the frame of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC). The campaign started in September 2021 and is run by the Space Research Centre of the Polish Academy of Sciences in cooperation with GeoForschungsZentrum and under the auspices of the International Earth Rotation and Reference Systems Service (IERS).

This presentation provides the status of 2nd EOP PCC one year after its beginning. We focus on the accuracy of EOP predictions based on mean absolute error and root mean square error computed for IERS 14 C04 solution as a reference. Additionally we present early assessment of the single predictions with use of median absolute error to identify outliers and check the potential improvements. Preliminary results show clear progress in combining modern prediction methods with data on the Earth’s surficial fluids. The campaign will be continued until the end of the year 2022.

On the improvement of the consistency and the temporal regularity of combined ERP time series

Lisa Lengert (BKG), Daniela Thaller (BKG), Claudia Flohrer (BKG), Anastasiia Girdiuk (BKG) and Hendrik Hellmers (BKG)

Abstract. Our previous GNSS and VLBI combination studies allow the consistent estimation of Earth Rotation Parameters (ERP) time series with a regular daily resolution and latencies of about 1-2 and 14 days. The established data processing is based on homogenized, datum-free NEQs, which allow a rigorous combination on the normal equation level instead of the observation level. The significant accuracy improvement is achieved for the obtained dUT1 time series in comparison with the individual technique-specific solutions.

Our recent studies focus on the generation of a stable VLBI-only ERP series with a regular daily resolution using a continuous ERP parameterization. This approach of stacking of the VLBI Intensive (INT) NEQs of several consecutive days aims to stabilize the dUT1 time series and improve the accuracy compared to the classical single-day VLBI INT dUT1 solution. Contrary to the commonly estimated single-technique solution, the accuracy of the multi-day dUT1 time series is less dependent on the irregularity of the VLBI INT observations, thus the dUT1 time series with a daily resolution (e.g. at 12:00 UTC) can be obtained. Besides, the constraints on LOD can be omitted in the multi-day VLBI INT solution. The adding the VLBI 24-hour data to the VLBI INT data further stabilizes the multi-day solution and enables the estimation of a full set of ERPs including the celestial pole offsets. The improved combination method is intended to be extended to the operational ERP products at BKG.

Potential of Lunar Laser Ranging for the determination of Earth orientation parameters

Liliane Biskupek (Institute of Geodesy, Leibniz University Hannover), Vishwa Vijay Singh (Institute of Geodesy, Leibniz University Hannover), Jürgen Müller (Institute of Geodesy, Leibniz University Hannover) and Mingyue Zhang (Institute of Geodesy, Leibniz University Hannover)

Abstract. The distance between the observatories on the Earth and the retro-reflectors on the Moon has been regularly observed with Lunar Laser Ranging (LLR) since 1970. In recent years, LLR observations have been carried out with bigger telescopes (APOLLO) and at infrared wavelength (OCA, Wettzell), resulting in a better distribution of LLR normal points over the lunar orbit and retro-reflectors with a higher accuracy, also leading to a higher number of LLR observations in total. The analysis of LLR observations has also been improved through refined modeling (e.g., modeling of the lunar core) and changes in the analysis strategy (e.g., optimized calculation of ephemerides). These refinements/modifications enable the determination of various parameters with higher accuracy.By analysing LLR data, Earth Orientation Parameters (EOP) such as the Earth rotation phase ΔUT1, terrestrial pole coordinates, and nutation coefficients, as corrections to the MHB2000 model of the IERS Conventions 2010, can be determined along with other parameters of the Earth-Moon system. Focusing on ΔUT1 and terrestrial pole coordinates from different LLR constellations such as single or multi-station data and for different numbers of normal points per night, the accuracies of the estimated Earth rotation phase and pole coordinates from the new LLR data have improved significantly compared to previous results. We achieved an accuracy of about 20 μs for ΔUT1, about 2.5 mas for xp, and about 3 mas for yp from subsets of the LLR time series containing 10 and 15 normal points per night. Focusing on determining corrections to the nutation coefficients to the MHB2000 model, significantly smaller correction values and higher accuracies with one order of magnitude improvement, i.e., accuracies better than 0.01 mas, are obtained now. Recent results are presented and discussed.This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2123 QuantumFrontiers – 390837967.

The importance of accurate a priori information for VLBI Intensive sessions

Lisa Kern (TU Wien), Matthias Schartner (ETH Zürich), Johannes Böhm (TU Wien), Sigrid Böhm (TU Wien), Axel Nothnagel (TU Wien) and Benedikt Soja (ETH Zürich)

Abstract. So-called Intensive sessions, also referred to as Intensives, are routinely observed one-hour sessions with two to three stations with the primary goal of deriving the Earth's phase of rotation with low latency. Due to the highly restricted number of observations, only a few parameters of interest can be estimated, including zenith wet delays per station, clock offsets, as well as the parameter of main interest, the difference between Universal Time (UT1) and Coordinated Universal Time (UTC). Thus, the remaining EOP, namely polar motion and nutation, and the station coordinates are fixed to their a priori value making the precision of the UT1-UTC estimates strongly dependent on their accuracy. In this study, the impact of realistic errors in the a priori information of polar motion, nutation, and station coordinates (in north-south, east-west or up-down direction) on the UT1-UTC estimate of Intensive sessions are investigated by applying rigorous simulations. To get a global picture, we generated a 10x10 degree grid of artificial VLBI antennas and scheduled and simulated over 240000 Intensive sessions where different errors were introduced in the simulation process. We find that in contrast to errors in the north-south or east-west components of the station coordinates, an error in the station height only slightly affects the UT1-UTC determination. In general, equatorial baselines are very sensitive to any a priori error, as are baselines with a midpoint close to the equatorial plane as well as very long ones. On the other hand, long east-west oriented baselines that enclose a small angle with the equatorial plane seem to be most resistant against errors in the a priori values. This study shows that the contributions from erroneous a priori information, in general, are not negligible and need to be accounted for when investigating the accuracy of the UT1-UTC estimates from Intensive sessions.

VGOS VLBI Intensives between MACGO12M and WETTZ12M for the rapid determination of UT1-UTC

Matthias Schartner (ETH Zürich), Leonid Petrov (NASA Goddard Space Flight Center), Christian Plötz (Bundesamt für Kartographie und Geodäsie), Frank G. Lemoine (NASA Goddard Space Flight Center), Eusebio Terrazas (The University of Texas at Austin), Iván Darío Herrera Pinzón (ETH Zurich), Jeffrey Lynn Dorman (NASA Goddard Space Flight Center) and Benedikt Soja (ETH Zurich)

Abstract. The rapid and highly accurate determination of the Earth's phase of rotation, expressed through the difference between UT1 (Universal Time 1) and UTC (Coordinated Universal Time), is one of the key products of geodetic Very Long Baseline Interferometry (VLBI).To ensure low latency, dedicated 1-hour-long VLBI Intensive sessions are observed daily.Due to the upgrade of the VLBI infrastructure to the next generation VLBI Global Observing System (VGOS), VGOS Intensives are now operationally observed as well.So far, three VGOS baselines have been utilized for VGOS Intensives:one between KOKEE12M (K2, Hawaii) and WETTZ12M (Ws, Germany), one between MACGO12M (Mg, Texas) and WETTZ12M, and one between ONSA12NE/ONSA12SW (Oe/Ow, Sweden) and Ishioka (Is, Japan).In this work, we focus on the Mg-Ws baseline and compare its performance with K2-Ws and other Intensive observing programs.Although the Mg-Ws baseline is approximately 20 % shorter compared to K2-Ws (8271 km compared to 10072 km, projected on the equatorial plane), similar precision of UT1-UTC estimates of 2-5 mus has been achieved.This is remarkably better compared to non-VGOS Intensives that typically have a precision of around 20 mus.We will highlight how the good performance of Mg-Ws can be explained.First of all, the number of observations was significantly increased to around 90 scans per hour.Furthermore, the scheduling approach was adjusted to derive better results.This includes a rapid change of high and low elevation scans, as well as a special focus on observing sources located at the corners of the mutually visible sky.Finally, we will give an outlook on our plans to further improve the VGOS Intensive performance.This includes an increase in bandwidth and a joint analysis of the VLBI Intensives with a GNSS network using the Bernese software.

A Celestial Reference Frame based on parameterized source positions

Maria Karbon (University of Alicante), Santiago Belda (University of Alicante), Jose Manuel Ferrandiz (University of Alicante) and Alberto Escapa (University of Alicante)

Abstract. The latest realization in the radio domain of the International Celestial Reference System (ICRS) is the Third Realization of the International Celestial Reference Frame (ICRF3), as adopted by Resolution B2 of the 2018 General Assembly of the International Astronomical Union (IAU). The positions of the radio sources in the ICRF3 catalog are given as time invariant coordinate pairs. Refusing to acknowledge systematics within the source positions inevitably leads to a deterioration in the quality of the frame, and thus in all derived variables. A proven approach to overcome these shortcomings is to extend the parametrization of source positions using the multivariate adaptive regression splines (MARS), as they allow a great deal of automation, by combining recursive partitioning and spline fitting in an optimal way.

In this study we investigate the impact of the aforesaid parameterization on the reference celestial frame itself. For this purpose, we will empirically analyze the differences in source positions and resulting deformations when compared to the ICRF3 as well as the Gaia-CRF, adopted as the fundamental realization of the ICRS in the optical domain by the 2021 IAU Resolution B3. The aim is to shed light on the origin of known deformations present in the ICRF as well as the differences between ICRF3 and Gaia-CRF.

The impact of parameterized source positions on the free core nutation

Santiago Belda (University of Alicante), Maria Karbon (University of Alicante), Jose Manuel Ferrandiz (University of Alicante) and Alberto Escapa (University of Alicante)

Abstract. The positions of the radio sources in the ICRF3 catalog, representing the newest realization of the Celestial Reference Frame (CRF), are given as time invariant coordinate pairs. Refusing to acknowledge systematics within the source positions leads to a deterioration in the quality of the frame, and thus in all derived variables, such as the Earth orientation parameters (EOP). A proven approach to overcome these shortcomings is to extend the parameterization of source positions using the multivariate adaptive regression splines (MARS). They allow a great deal of automation, by combining recursive partitioning and spline fitting in an optimal way.

As this parameterization changes the instantaneous CRF, consequently it could have a negative impact on the EOP (i.e. slight deterioration of the accuracy/consistency) , especially in the CPO (celestial pole offsets). Here, we present first results on the impact of this parameterization of the source positions on the EOP and the estimation of the free core nutation. This study was carried out from an analysis of VLBI sessions in the period 199X–20XX.

Single-band absolute astrometry

Leonid Petrov (NASA Goddard Space Flight Center)

Abstract. The ionospheric contribution affects path delay at radiofrequencies. When simultaneous dual-band VLBI observationsare used for absolute astrometry, the residual contributionof the ionosphere is at a level of several picoseconds. Butthere are two cases when we need to process VLBI single bandgroup delays: a) some observations provided usable data onlyfor one band; b) an entire experiment used only one band.I have developed a novel approach to utilize GNSS TEC maps to get the best solutions for these two cases and providedrealistic estimates of residual errors. Analysis of dual-bandobservations in the mode when one of the bands was not eitherpartially or entirely used identified the presence ofdeclination errors. Approaches to characterize and mitigate these systematic errors are discussed. Applications of thistechnology is discussed. In particular, the impact ofresidual ionospheric path delays at K-band on estimates ofsource positions is quantitatively evaluated and conclusionsabout advantages and disadvantages of high frequency absoluteastrometry are made.

Earth orientation parameters determined from Very Long Baseline Array experiments conducted at K-band (24 GHz)

Hana Krasna (TU Wien), David Gordon (United States Naval Observatory), Aletha de Witt (South African Radio Astronomy Observatory) and Christopher S Jacobs (Jet Propulsion Laboratory, California Institute of Technology)

Abstract. The terrestrial and celestial reference frames are connected through rotational transformations including the Earth orientation parameters (EOP). The EOP are estimated from space geodetic observations. Very Long Baseline Interferometry (VLBI) is the only space geodetic technique which allows one to directly estimate all five EOP and the only technique providing the access to the celestial pole position. The officially published VLBI estimates of the EOP are based solely on observations from the S/X-band (2.3/8.4 GHz).

We present EOP determined from the Very Long Baseline Array experiments at K-band (24 GHz) which are independent from the traditional S/X frequency band. Our dataset starts in May 2002 and consists of more than 120 24h observing sessions. We calculate comparisons before and after each major change in data rate in order to quantify any change in EOP quality due to changes in the observing system. Furthermore, we assess the impact of the ionospheric delay of the VLBI signal at 24 GHz on the EOP estimates.

Celestial reference frame determined from very long baseline interferometry experiments conducted at K-band (24 GHz) over the past 10 years

Hana Krasna (TU Wien), David Gordon (United States Naval Observatory), Aletha de Witt (South African Radio Astronomy Observatory) and Christopher S Jacobs (Jet Propulsion Laboratory, California Institute of Technology)

Abstract. The current third realization of the international celestial reference frame (ICRF3) was adopted in August 2018 and includes positions of extragalactic objects at three frequencies: 8.4 GHz, 24 GHz and 32 GHz. In this paper we present an update of the celestial reference frame (CRF) estimated from very long baseline interferometry measurements at K-band (24 GHz). The observations of the radio sources are conducted with the Very Long Baseline Array from the U.S. territory and the celestial frame is densified in the southern hemisphere with HartRAO – Hobart26m single baseline observations.

The dataset starts in May 2002 and currently consists of more than 120 24h observing sessions performed over the past 10 years. Since the publication of ICRF3, the additional observations of the sources during the last four years allow maintenance of the celestial reference frame and more than 200 additional radio sources ensure an expansion of the frame. We determine the updated K-CRF with two independent analysis software packages (VieVS and Calc/Solve) and describe the differences in the solution strategy. We compare the updated K-CRF to ICRF3 using the so-called vector spherical harmonics providing information about systematic differences between two astrometric catalogs.

The use of sub-monthly GRACE/GRACE-FO solutions to determine gravimetric excitation of polar motion

Justyna Śliwińska (Centrum Badań Kosmicznych PAN), Jolanta Nastula (Centrum Badań Kosmicznych PAN) and Aleksander Partyka (Centrum Badań Kosmicznych PAN)

Abstract. The Earth's rotation varies in time and these changes can be described with Earth Orientation Parameters (EOP). EOPs represent the rotational part of the transformation between the current releases of the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF).

Here, we focus on the changes in the orientation of the Earth's rotational axis in relation to the terrestrial reference frame known as the polar motion (PM). The main conductor of non-tidal changes in PM is temporal variability of mass distribution of atmosphere, oceans, hydrosphere, and cryosphere. With the launch of the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions, a new era of using global gravity data to determine gravimetric excitation of PM has begun. This can be done with the use of equations that describe linear relationship between degree-2 order-1 coefficients of geopotential and equatorial components of PM excitation.

In this presentation, we use daily and 10-day GRACE/GRACE-FO gravity field solutions provided by the Institute of Geodesy at Graz University of Technology (ITSG) and Centre National d'Études Spatiales (CNES) to determine gravimetric excitation of PM. Specifically, we test the usefulness of those data to analyse PM excitation at sub-monthly time scales. This is the first study of this type, because so far only monthly solutions have been used for this purpose. We study several types of oscillations in PM excitation series and make a comparison between gravimetric excitation (computed from GRACE/GRACE-FO data) and geodetic excitation determined from observations of pole coordinates after removing atmospheric and oceanic signals. This analysis aims to check whether the daily and 10-day solutions carry any additional information about PM that is not provided by monthly data.

Operational prediction of Earth orientation parameters and effective angular momentum at ETH Zurich

Benedikt Soja (ETH Zurich), Mostafa Kiani Shahvandi (ETH Zurich), Matthias Schartner (ETH Zurich) and Junyang Gou (ETH Zurich)

Abstract. Earth orientation parameters (EOP) define the transformation between terrestrial and celestial reference systems and are needed for precise navigation on Earth and in space. EOP are typically determined by different space-geodetic techniques and combinations thereof. In order to overcome latencies in the processing and combination of space-geodetic observations, accurate predictions of EOP are essential for many real-time applications.

The Space Geodesy group at ETH Zurich has recently established its Geodetic Prediction Center (GPC; https://gpc.ethz.ch) to operationally provide predictions of several geodetic variables, including EOP. The prediction of EOP is performed based on past values of EOP and effective angular momentum (EAM) time series, as well as forecasts of EAM. Data sources for the EOP time series include products provided by IERS, SYRTE and JPL. EAM data is obtained from GFZ Potsdam. Furthermore, we now also provide EAM predictions to enhance and expand the products provided by GFZ. Our predictions are based on various novel machine learning approaches, which are specifically tuned for the respective EOP components and forecast horizons.

In this contribution, we will give an overview of the activities at ETH related to the prediction of EOP and EAM. In particular, we will focus on a comparison of predictions based on different EOP and EAM input time series. The underlying EOP time series are derived with different space-geodetic data sets and combination strategies and a quality assessment will thus be beneficial for improving EOP products. Furthermore, we will investigate the impact of different EAM data sources on the prediction of EOP.

Session 5

Usage & Challenges of Reference Frames for Earth Science Applications

Application of the ITRS2020 realizations for precise orbit determination of SLR and altimetry satellites

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Abstract. In 2022, three new realizations of the International Terrestrial Reference System (ITRS), namely, ITRF2020, DTRF2020 and JTRF2020 are to be published. Compared to the 2014 realizations of the ITRS, they are based on a 6-year longer data time span (extended by 2015.0-2021.0), observations from new tracking stations, improved modelling of geophysical and other effects as well as technique-specific biases. For the first time in ITRS realization, long-term mean satellite laser ranging (SLR) range biases were determined and applied. A precise and stable reference frame realization is the basis for the computation of precise satellite orbits. In this study, we hence discuss the application of the new ITRS2020 realizations for precise orbit determination of some spherical SLR satellites at the altitude between 690 and 19135 km, as well as of some non-spherical (altimetry) satellites at the altitude of about 1300 km. We investigate the impact of the new ITRS realizations on the root-mean-square (RMS) and mean fits of observations and remaining range biases. For altimetry satellites, we additionally investigate the impact on the RMS and mean of the sea surface height crossover differences as well as geographically correlated errors. We also compare the results derived with the new 2020 realizations to those derived with the previous 2014 realizations of the ITRS.

ITRF2020 application in the geodetic products for IVS

Anastasiia Girdiuk (Federal Agency for Cartography and Geodesy (BKG)), Daniela Thaller (Federal Agency for Cartography and Geodesy (BKG)), Gerald Engelhardt (Federal Agency for Cartography and Geodesy (BKG)) and Dieter Ullrich (Federal Agency for Cartography and Geodesy (BKG))

Abstract. ITRF2020 is the most recent international terrestrial reference frame. The corresponding a priori corrections are applied for the station positions in the routine VLBI solution. The IVS products are derived from this solution. The obtained solution was built with respect to the ITRF2020 campaign requirements on the parameterization of a VLBI solution. The stability of the produced geodetic products is reviewed by evaluating the ITRF2020 impact on the computed residuals of the station positions and the other estimated parameters. The most prominent benefit of the applied a priori corrections is seen in the obtained residuals for the VGOS antennas. The VGOS antenna coordinates were available before ITRF2020 only from the internal VLBI solution. The lack of the legacy network in the VGOS sessions restricts moderately this type of a revisionary solution. The EOP products derived from the analysis of these VGOS sessions are affected by mismodeling of the a priori station positions. In particular, the deficiencies in the a priori corrections originate an offset of the obtained ERP time series. The ITRF2020 comes with the new PSD model, which seems to contribute to the geodetic products marginally. We consider also the smaller impact of the other relevant VLBI reductions on the geodetic products.

EUREF's contribution to EPOS' GNSS Services

Carine Bruyninx (Royal Observatory of Belgium), Rui Fernandes (University of Beira Interior, Collaboratory for Geosciences), Martin Lidberg (Lantmäteriet) and Wolfgang Söhne (Federal Agency for Cartography and Geodesy)

Abstract. The European Plate Observing System (EPOS) is establishing a multidisciplinary research platform for Solid Earth sciences in Europe (https://www.ics-c.epos-eu.org/). The European Research Infrastructure Consortium (ERIC) has provided to EPOS a legal personality and capacity that is recognized in all European Union Member States. EPOS is currently in its Pilot Operational Phase, which is a 3-year transition period that started in 2020 in preparation of the Operational Phase of EPOS. The system gathers input from e.g., geology, seismology, satellite data, and GNSS. By linking hundreds of individual research infrastructures located in European countries, EPOS ERIC is providing open access to a large pool of integrated Solid Earth science data, data products, and facilities.

The GNSS component of EPOS (EPOS-GNSS) provides access to GNSS data, metadata, and products from as many as possible permanently tracking GNSS stations in Europe. These efforts are made together with the EUREF community from which many members helped to construct EPOS and contribute with data and pre-operational services to EPOS. Therefore, the partnership between EUREF and EPOS is crucial and it is formalized through a Memorandum of Understanding (MoU). In this MoU, EUREF and EPOS engage to use harmonized standards and guidelines, develop common components, inform each other on progress, projects or initiatives, and raise awareness of the complementarity of EUREF and EPOS.

We will show an overview of the status of EPOS' pre-operational GNSS services. In addition, we will illustrate how EUREF, with expertise in reference frames, and EPOS, aiming at supporting Earth science applications, are in practice collaborating towards the delivery of common services.

Predicting Non-tidal Loading Contributions Induced by Environmental Loading

Kyriakos Balidakis (GFZ German Research Centre for Geosciences, Earth System Modelling), Robert Dill (GFZ German Research Centre for Geosciences, Earth System Modelling) and Henryk Dobslaw (GFZ Potsdam)

Abstract. Earth’s surface is elastically deformed by time-variable surface mass loads such as variations in atmospheric surface pressure, ocean bottom pressure, and terrestrial water storage. We look at the individual environmental loading contributions from the three different sub-systems (atmosphere, terrestrial water storage, ocean) as well as from sea level variations induced by the global water mass balance between land and ocean. Dividing the contributions into a set of period bands by means of a Wavelet decomposition, we show that non-tidal atmospheric surface loading (NTAL) by far dominates non-tidal ocean (NTOL) and hydrospheric loading (HYDL) for periods as long as a few months. The contribution of terrestrial water storage is continuously growing for increasingly longer periods and dominates atmospheric pressure at periods of 300 days and above. Ocean dynamics including sea level variations due to the seasonal global mass balance are only important in the immediate vicinity of the coast. In representative regions we compare environmental loading estimates (NTAL, NTOL, HYDL) from ESMGFZ based on ECMWF operational atmospheric data with station coordinate time-series from different GNSS solutions. Depending on the geographical location and considered frequency range, the different GNSS solutions (individual analysis center contributions to ITRF2020 as well as the combined solution) can exhibit large differences. To evaluate the ability of different GNSS solutions to confirm the vertical deformations predicted by the geophysical fluid models, we compared at selected sites the vertical station coordinates from six GNSS solutions (IGS' contribution to ITRF2020, IGS repro 3) with the loading model predictions. For station location where the dominant loading signal is generated from atmospheric surface pressure most GNSS solutions fit very well to the model predictions. In contrast, the GNSS derived variations and the model predictions show large deviations from each other for seasonal and annual variations.

Improved Hydrological Loading Models in South America: Analysis of 3D GPS Displacements Using M-SSA

Joelle Nicolas (ESGT/GeF), Jérôme Verdun (ESGT/GeF), Jean-Paul Boy (EOST/ITES), Frédéric Durand (ESGT/GeF), Achraf Koulali (School of Engineering, University of Newcastle) and Peter Clarke (School of Engineering, University of Newcastle)

Abstract. Environmental loading, in particular from continental water storage changes, induces geodetic station displacements up to several centimeters for the vertical components. We investigate surface deformation due to loading processes in South America using a set of 247 permanent GPS (Global Positioning System) stations for the 2003–2016 period and compare them to loading estimates from global circulation models. Unfortunately, some of the hydrological components, and in particular surface waters, may be missing in hydrological models. This is especially an issue in South America where almost half of the seasonal water storage variations are due to surface water changes, e.g., rivers and floodplains. We derive river storage variations by rerouting runoffs of global hydrology models, allowing a better agreement with the mass variations observed from GRACE (Gravity Recovery and Climate Experiment) mission. We extract coherent seasonal GPS displacements in the east, north and vertical directions using Multichannel Singular Spectrum Analysis (M-SSA) and show that modeling the river storage induced loading effects significantly improve the agreement between observed vertical and horizontal displacements and loading models. Such an agreement has been markedly achieved in the Amazon basin. Whilst the initial models only explained half of the amplitude of GPS, the new ones compensate for these gaps and remain consistent with GRACE.

Glacial induced uplift variations in Svalbard – is it a challenge for the reference frame?

Halfdan Pascal Kierulf (NorwegianMapping Authority), Jack Kohler (Norwegian Polar Institute), Jean-Paul Boy (University of Strasbourg, EOST/ITES), Emily C. Geyman (California Institute of Technology), Anthony Memin (Université Côte d'Azur, Géoazur Valbonne), Ove Omang (Norwegian Mapping Authority), Holger Steffen (Lantmäteriet) and Rebekka Steffen (Lantmäteriet)

Abstract. The geodetic observatory in Ny-Ålesund is a key station in the global geodeticnetwork. It is the northernmost fundamental station, containing all the maingeodetic techniques important for the realization of the ITRF. However, itsstability has been questioned. The observatory experiences variations in theuplift on seasonal, inter-annual, decadal, and longer time-scales. The upliftfor a moving window of 5-years periods has increased from below 6 mm/yr in the1990 to more than 12 mm/yr today. This has challenged the realization andstability of global and regional reference frames.Svalbard, as other Arctic areas, is heavily affected by climate change. Thetemperature is increasing, the permafrost is melting, the sea ice isdisappearing and the glaciers are retreating. The elastic response of thechanges in the glacier affects the earth crust. We have constrained the recentglacier retreat on Svalbard using a series of digital elevation models andcomputed the induced elastic response.Data from the geodetic observatory in Ny-Ålesund and the GNSS network inSvalbard are analyzed with the software Gamit, GipsyX and Gins. The time seriesare compared with the elastic response of the glacier changes. We found that thevariations in the uplift can be explained by the glacier changes and that theuplift after removing the elastic signal is almost constant for the differenttime-intervals.

Spatio-temporal consistency of the stochastic component of the ZTD time series over Europe

Anna Klos (Military University of Technology), Janusz Bogusz (Military University of Technology), Rosa Pacione (e-GEOS S.p.A, ASI/CGS), Vincent Humphrey (Institute for Atmospheric and Climate Science, ETH Zürich) and Henryk Dobslaw (GFZ German Research Centre for Geosciences)

Abstract. We use a unique atmospheric dataset over Europe provided by the EUREF Permanent GNSS Network (EPN) in the form of Zenith Total Delay (ZTD) time series. We use solutions provided by the ASI (Agenzia Spaziale Italiana Centro di Geodesia Spaziale, Italy) and GOP (Geodetic Observatory Pecny, Czech Republic) analysis centers and the combined product of EPN Repro-2 solution; different processing options are applied to these solutions. We show that the trends and seasonal amplitudes of the ZTD time series are only slightly affected by changing the processing strategy, while the temporal patterns of autoregressive noise present in the stochastic component are reduced in favor of white noise during the combination procedure. Although combination reduces the stochastic properties for individual stations, the change in stochastic character does not affect the correlations and spatial patterns determined between stations. We demonstrate that the ZTD residuals for different locations are strongly spatially correlated with the spatial correlation between station pairs being time-varying. We find clear annual oscillations in the time series of correlation coefficients for stations up to 1,000 km apart. We use empirical orthogonal functions and prove that for all four solutions they are generated by the same sets of stations and are strongly correlated with each other in the time domain. To search for possible contributions of non-tidal atmospheric loading to the ZTD residuals, we compute differences from two GOP solutions that differ only in the unmodeled, non-tidal atmospheric loading and cross-compare them with temporal and spatial responses of non-tidal atmospheric loading residuals. We show that the similarity between the ZTD differences and the non-tidal atmospheric loading is only apparent for unusual loading events, such as significant interannual signals or large seasonal peaks.

Reference Frame and Identifying Localized vs Regional Deformation: Examples from Hawaii and the North Atlantic

Jeff Freymueller (Michigan State University)

Abstract. Separating multiple sources of deformation can be difficult in places like Hawaii and Iceland. In both cases, there are time-dependent signals from multiple active volcanoes, and active faulting. In Iceland, ongoing glacier mass loss and glacial isostatic adjustment produce large signals, also time-dependent. In Hawaii, all GPS sites show an additional subsidence signal likely caused either by ongoing flexural loading under the growing volcanic load, or dynamics of the deep magma system. Because some of the deformation signals are longer wavelength than the islands themselves, an accurate regional or global reference frame is critical for analyzing the geophysical causes of these motions. In turn, if any sites from these places are included in a regional or global reference frame model, it is important to understand the time-dependence of the geophysical signals affecting those sites, so that their coordinate model is estimated appropriately.

In this study, I analyze continuous GPS data from the Pacific and the North Atlantic to assess plate motions and vertical reference. Each daily GPS solution is constructed by combining point positioning solutions (done with GIPSY goa-6.4) into a global solution, which is then aligned with ITRF globally. Velocities are estimated from the time series for those cases where a linear velocity (with offsets, if needed) is an appropriate description of the motion. The horizontal velocities can then be compared to models for plate motion, and the vertical velocities to a combination of loading models, or to co-located tide gauge data, to identify localized and regional sources of deformation.

CyCLOPS: Establishment of a Strategic Integrated Permanent GNSS and InSAR Array in Cyprus to Enhance Monitoring of Geohazards and Promote Infrastructure Resillience

Chris Danezis (Cyprus University of Technology), Dimitris Kakoullis (Cyprus University of Technology), Kyriaki Fotiou (Cyprus University of Technology), Marina Pekri (Cyprus University of Technology), Miltiadis Chatzinikos (Cyprus University of Technology), Christopher Kotsakis (Aristotle University of Thessaloniki), Marios Nikolaidis (Cyprus University of Technology), George Ioannou (Cyprus University of Technology), Michael Eineder (German Aerospace Center), Ramon Brcic (German Aerospace Center), Andreas Christofe (Cyprus University of Technology), George Melillos (Cyprus University of Technology), Yiannis Vacanas (Cyprus University of Technology), Michalakis Christoforou (Cyprus University of Technology), Sylvana Pilidou (Cyrpus Geological Survey), Marios Tzouvaras (Cyprus University of Technology), Christiana Papoutsa (Cyprus University of Technology), Kyriacos Themistocleous (Cyprus University of Technology) and Diofantos Hadjimitsis (Cyprus University of Technology)

Abstract. CyCLOPS is a novel strategic research infrastructure for studying solid earth processes and geohazards, such as earthquakes and landslides via the integration of the two most prominent space-based Earth Observation deformation monitoring technologies; Global Navigation Satellite Systems (GNSS) and Interferometric Synthetic Aperture Radars (InSAR). CyCLOPS was designed and developed by the Cyprus University of Technology Department of Civil Engineering and Geomatics (CUT-CEG) in collaboration with the German Aerospace Center (DLR) and supported by a wide range of national stakeholders. The objective of this endeavor is to augment the national geophysical and geodetic infrastructure and actively contribute to the growing demand for more precise positioning services aligned with important global frameworks and initiatives, such as the UN SENDAI Framework for Disaster Risk Reduction and the recommendations of the UN-GGIM (and its Subcommittee of Geodesy). In this context, a network of Tier-1/2 permanent GNSS Continuously Operating Reference Stations (CORS) co-located with permanent Trihedral Corner Reflectors (TCRs), precise weather stations and tiltmeters was established throughout the government-controlled areas of the Republic of Cyprus. Furthermore, the infrastructure is augmented by a mobile segment of GNSS receivers and CRs, which are deployed in areas of interest. One of the major challenges faced while setting such an integrated infrastructure was the selection and layout of the permanent sites for the co-located sensor configuration to achieve maximum performance and deliver the most possibly precise deformation products. Therefore, key parameters, such as monumentation specifications, equipment orientation and localization were seen, studied and dealt in accordance with the most stringent specifications set by international standards (i.e. UNAVCO, IGS and EPN) and scientific literature. Concordantly, the objective of this paper is to present an overview of the system architecture, the considerations followed and developed en-route to its realization and an initial performance assessment during the first months of its operation.

Velocity and strain field estimation from episodic GNSS campaigns (2012-2021) for the region of Attica, Greece

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Abstract. The region of Athens is essentially a transition area between the region of Corinth Gulf/Viotia, characterized by intense seismic activity, and the regions of South Attica and Cyclades Islands with low deformation rates.

A network of 14 campaign sites was established in 2012 in the framework of ARCHIMEDES research project, 13 of which are pillars of the Hellenic trigonometric network. In 2021 GNSS observations were repeated out on these sites. Also, permanent GNSS stations DYNG and TEIA were used to validate the results and implement the reference frame.

GNSS data were analyzed using two different methods, Precise Point Positioning and Double Differences processing. For the both processing methods, ITRF2014 has been implemented as a reference frame. With the exception of some specific sites with challenging observation environment, the differences between the two methods are of the order of centimeters.

A velocity field was calculated in ITRF2014 and with respect to a stable Europe, using the results from Double Differences processing. The velocities with respect to a stable Europe range from -20 to -27 mm/yr in the North – South direction and from -12 to -19 mm/yr in the East - West direction. The region of Attica moves uniformly to the SW direction. Comparing velocities of selected points with the officially published velocities of the DYNG station, as well as with recent published studies, it is clear that despite the episodic campaigns of observations the results are reliable.

Finally, different kinematic models were estimated for the region and the strain tensor parameters were calculated for a grid of points and delaunay triangles covering the region.

Seasonal glacier and snow loading in Svalbard recovered from geodetic observations

Halfdan Pascal Kierulf (Norwegian Mapping Authority), Ward van Pelt (Uppsala University), Leonid Petrov (NASA Goddard Space Flight Center), Michael Dähnn (Norwegian Mapping Authority), Ann-Silje Kirkvik (Norwegian Mapping Authority) and Ove Omang (Norwegian Mapping Authority)

Abstract. We processed time-series from seven GNSS stations and one VLBI station in Svalbard. The goal was to capture the seasonal vertical displacements caused by elastic response of variable mass load due to ice and snow accumulation. We found that estimates of the annual signal in different GNSS solutions disagree by more than 3 mm which makes geophysical interpretation of raw GNSS time-series problematic. To overcome this problem, we have used an enhanced Common Mode (CM) filtering technique. The time-series are differentiated by the time-series from remote station BJOS with known mass loading signals removed a priori. Using this technique, we have achieved a substantial reduction of the differences between the GNSS solutions. We have computed mass loading time-series from a regional Climatic Mass Balance (CMB) and snow model that provides the amount of water equivalent at a 1 km resolution with a time step of 7 d. We found that the entire vertical loading signal is present in data of two totally independent techniques at a statistically significant level of 95 per cent. This allowed us to conclude that the remaining errors in vertical signal derived from the CMB model are less than 0.2 mm at that significance level. Refining the land water storage loading model with a CMB model resulted in a reduction of the annual amplitude from 2.1 to 1.1 mm in the CM filtered time-series, while it had only a marginal impact on raw time-series. This provides a strong evidence that CM filtering is essential for revealing local periodic signals when a millimeter level of accuracy is required.

Recent advances in the modelling of glacial isostatic adjustment – A report from the IAG Joint Study Group on "Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment"

Rebekka Steffen (Lantmäteriet) and Erik R. Ivins (Jet Propulsion Lab, California Institute of Technology)

Abstract. Glacial isostatic adjustment (GIA) is a process that drives a dynamic present-day displacement, gravitational changes, rotational parameters, stress state, and sea-level, both in the open ocean and at coastal environments. These changes occur over the entire globe. Furthermore, they may be integrally related to changes in massive ice sheets as measured from space. The computation of forward and inverse GIA models is critical to proper simulation of past, recent, and future changes in Earth's topography, gravity, rotation, stress state, sea-level, and the stability of the reference frames. Current models depend on many parameters, including the structure of the Earth's interior, including both the radial and lateral structure. As part of a newly established joint study group within IAG, we draw together new model capabilities from several disciplines: geodesy, seismology, mineral physics, laboratory-based creep laws, and geodynamics to create a dialogue between these disciplines to better inform the implementation of state-of-the-art Earth models and quantify their influences on geodetic observations. Here, we will present an overview of recent advances and upcoming procedures to better characterize and determine a higher fidelity estimate of GIA variables (e.g., velocity, time-varying sea surface and gravity fields). These estimates will, in turn, serve as important input parameters for use across many different geoscientific disciplines.

Tide and storm surge analysis in Thermaikos Gulf, Greece

Nestoras Papadopoulos (Hellenic Military Geographical Service), Vassilis Gikas (National Technical University of Athens)

Abstract. Sea level monitoring is a key element for reference frame establishment and realization as it represents the actual signal whereby the height datum originates from. Tide gauge stations provide time series of sea level observations tied to a local geodetic benchmark on the shore. Sea level measurements consist of two primary elements: an astronomical tide signal and a meteorological component. Astronomical tide is the consequence of the combined gravitational effects of the moon and the sun as their position alters in relation to the rotating earth. Atmospheric effects including variations in the air pressure and the wind result in storm surges which contribute to sea level fluctuations too. In this study a methodological approach for sea level estimation has been formulated and standardized taking into account the combination of the astronomical tide and storm surge effects. Implementation of the proposed model was realized using a dataset of tide gauge and meteorological observations spanning 21 years of observations. Field data originate from Thessaloniki (Greece) tide gauge and Thessaloniki National Airport meteorological station respectively. Harmonic analysis of sea level time series concluded in 68 tidal constituents. Synthesis of all contributing constituent parameters revealed the hourly tidal predictions due to astronomical effects. Also, meteorological data have led to the hourly storm surges. Extensive inspection of the raw observables and evaluation of the results obtained and their associated statistical analyses revealed the tidal behavior of Thermaikos Gulf. It is concluded that tides in Thermaikos Gulf are characterized as mixed predominating the semi-diurnal ones (F=0.254). Tidal ranges in each cycle vary from 60 mm (minimum neap range) to 833 mm (maximum spring range). Finally, further statistical analysis of the adopted model based on the Willmott Skill factor show a high (97%) agreement between the raw tidal observations and their predicted suggesting the high performance of the model.

Regional reference velocity model based on extended EPND solution for InSAR applications

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Abstract. EPN Densification (EPND) is a collaborative effort of 30 European Analysis Centers, which are delivering national scale GNSS processing results in SINEX format. The single AC contributions are metadata-harmonized and quality-checked, then a weekly combined series is generated, which enter into a multi-year combination. The EPND position and velocity product is updated each 50 weeks. The latest update uses input from GPSweek 1500 to 2200 (October 2008 – March 2022) and includes almost 3000 stations and published at the EPND web portal (https://epnd.sgo-penc.hu). The generated velocity field plays paramount role as input to various geoscience products and programs.

As a new key application EPND serves the GNSS reference for the InSAR-based product of the European Ground Motion Service (EGMS). In EGMS everything from landslides and infrastructure deformation to volcanoes and tectonic movements is measured in a consistent, standardized manner in a well defined reference frame exploiting the synergies between GNSS and InSAR. For this purpose a grided GNSS velocity model is implemented, which represents the long wavelength part of the EGMS ground motion model. As EPND has data gap over some territories a so called assisted EPND solution is generated, where the velocity product of the Nevada Geodetic Laboratory (NGL) is also involved. The NGL solution provides unique opportunity for quality checks at overlapping stations and also to fill in gaps, where no EPND solution is accessible.

The presentation will review the methodology and input data used to produce the assisted EPND grid and also provides examples to show its performance. We implemented the classical least-squares collocation approach in a remove-restore process adding special features to better model the trend in the input data. Low-pass filtering was also deployed to generate a solution well representing the long wavelength part of the velocity field needed for EGMS.

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