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PREFACE

Investigations of reference systems for monitoring global change and for precise navigation in space: preface to the special issue on reference systems

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Reference frames are the linking elements between the Earth's geometry, gravity field, and rotation. They are thus central components of all geodetic investigations and form the backbone of knowledge about the physical and geometric properties of our planet. Any insights into Global Change, from sea level rise to tectonic deformations, are quantified with respect to reference frames. They are also needed for any applications requiring precise positions on Earth and in space including navigation. In the era of space-geodetic observing techniques with man-made satellites and extra-galactic radio sources such as quasars, the spatial scales of reference frames are not restricted to the Earth itself but extend much further out even to the known frontiers of our observable universe. In this context, it is increasingly important to distinguish between reference systems and reference frames. While reference systems contain the theoretical considerations and conventions needed for realizations, reference frames consist of physical markers which are attributed with coordinates determined with real measurements. Decisions on conventions for ambiguous properties, such as the directions of coordinate axes, and on which phenomena should be included in geophysical models are important for the definition of reference systems. Realizing them through reference frames necessitates high-precision observations and processing capabilities for state-of-the-art results.

For these reasons, reference systems and reference frames form their own realm of research with many open questions on a variety of spatial scales. One of the key targets of all endeavors is to achieve consistency between the various system definitions and the realized frames. For this purpose, integrative observations, methods and procedures have been developed for a consistent definition and realization of geodetic reference systems on Earth and in space. In key parts, the respective research has been carried out in a research unit *Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space* (FOR1503) funded by the *Deutsche Forschungsgemeinschaft* (DFG), the *Austrian Fonds zur Förderung der wissenschaftlichen Forschung* (FWF) and the *Schweizerische Nationalfonds zur Förderung der wissenschaftlichen Forschung* (SNF). During the final phase of this research unit, the idea of a joint publication of its major results in a Special Issue of Journal of Geodesy was born. A respective call for papers was sent out to the participants, extended also to the wider community working in the field of reference systems and frames.

The result of this call is the volume at hand with ten articles starting as far apart as planet Mercury and reaching the tie problem of different ground-based observing techniques at co-location sites and in space. All articles provide valuable contributions to solving research issues related to reference frames and their consistency. The issue starts with reference frame studies of distant objects, namely Mercury and the moon of Mars, Phobos. The first article describes refinements of geodetic reference frames of Mercury. Here, several different definitions of reference systems are available, realized by a dynamical frame, a principal-axes frame, an ellipsoid frame, and a cartographic frame using data provided by instruments on board of spacecraft MESSENGER (Stark et al. 2018). The second contribution deals with an inertial frame bundle block adjustment for the determination of the rotational parameters of Phobos. New is the develop-

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ment of a functional model for a bundle block adjustment in the inertial reference frame. The model is applied to a data set of images from the Mars Express and the Viking mission (Burmeister et al. 2018).

The next two articles are devoted to studies of the moon. Lunar laser ranging (LLR) observations up to the end of 2016 provide various quantities related to reference frames such as Earth orientation parameters, coordinates and velocities of terrestrial ground stations in the Earth-fixed frame and selenocentric coordinates of the lunar retro-reflectors (Hofmann et al. 2018). In another article, 5 years of Doppler observations of the Lunar Reconnaissance Orbiter (LRO) are used to determine precise orbits of LRO. The orbits computed and presented here are the first independent validation of the LRO science orbits from NASA and show an impressive level of agreement (Löcher and Kusche 2018).

Nearer to Earth, satellite laser ranging (SLR) observations of up to 11 satellites are employed to consistently estimate geodetic parameters of interest. If multiple satellites with various altitudes and orbit inclinations are combined in a joint solution, correlations between estimated parameters are significantly reduced. Furthermore, parameters can be estimated with higher precision compared to the standard 4-satellite constellation which is currently used by the International Laser Ranging Service (ILRS) (Bloßfeld et al. 2018).

Another area of research in the direct vicinity of the Earth is very long baseline interferometry (VLBI) observations of the E-GRASP satellite. These can help to provide satellite-based co-locations of multiple observing techniques in space. According to Monte Carlo simulations, it was found that the standard VLBI technique is limited, in part, by the present lack of knowledge of the absolute offset of VLBI time to coordinated universal time (UTC) at the level of microseconds. Time-of-flight (TOF) measurements using a time-encoded signal in the spacecraft transmission seem to be able to overcome this problem and provide frame ties with uncertainties in translation and scale nearly a factor of three smaller than those yielded from VLBI measurements (Anderson et al. 2018).

The consistent realization of celestial and terrestrial reference frames is described in another article emphasizing one of the key goals of the research unit. It was demonstrated by the authors that inconsistencies arising from single-technique solutions are overcome by combining normal equation systems of all geometric space-geodetic observing systems and all parameters of interest, i.e., terrestrial reference frame, Earth orientation parameters, and celestial reference frame (Kwak et al. 2018).

On Earth itself, the process for achieving long-term stability of predictions of terrestrial reference frame solutions based on Kalman filtering is elaborated on. Based on VLBI terrestrial reference frames, the predictions are computed by extrapolating the deterministic part of the coordinate model. It was found that the results significantly depend on the level of process noise used in the filter (Soja et al. 2018).

The last group of two articles deals with investigations at sites where multiple geodetic space technique are co-located. In the first one, a selected number of local GNSS baselines at co-location sites is assessed in a global multi-year analysis. The aim was to produce homogeneous time series of coordinates and to analyze system-specific error sources in the local baselines. Results based on the comparison of different GNSS-based solutions with the local survey ties show discrepancies of up to 10 mm despite GNSS coordinate repeatabilities at the sub-mm level (Herrera-Pinzon and Rothacher 2018). The second article of this sub-group focuses on the development of new technologies and procedures for co-located geodetic instrumentation to identify and remove systematic measurement biases within and between the individual measurement techniques. For this purpose, a multi-technique reference target for co-location of space-geodetic techniques has been developed at the Geodetic Observatory Wettzell (Kodet et al. 2018).

With the ten articles in this special issue, the colleagues involved have addressed important issues related to establishing consistent reference systems and construct and maintain the respective frames. We are grateful to all authors for their efforts to submit their manuscripts following a strict timeline. A great number of international colleagues served as reviewers for the manuscripts and this work is certainly quite laborious and time-consuming. We thank all of them for their important and diligent work.

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