Integration of Space Geodetic Techniques as the Basis for a Global Geodetic-Geophysical Observing System (GGOS-D): An Overview

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1. Introduction

In view of the alarming global change in the Earth system and the multitude of natural hazards with huge effects on humans and economy it is of greatest importance to develop a better understanding of the processes that describe and excite these continuous as well as abrupt changes. To achieve this, the structure of all elements of the Earth system (primarily the geosphere, the oceans, the hydrosphere and the atmosphere) have to be measured and monitored exactly, and the interactions between them have to be modeled correctly, i.e. a comprehensive global Earth observing system has to be built up. The expected outcome of such a system are consistent geodetic-geophysical time series that refer to a highly accurate reference frame that is stable over decades. Based on the knowledge of the past (resulting from having high-precision long-term series available), conclusions may be drawn for the future development of the Earth system. On the international level, the Global Geodetic Observing System (GGOS), now a full component of the International Association of Geodesy (IAG), is the geodetic contribution to a comprehensive global observing system as it is presently setup by the Group on Earth Observation (GEO) in the form of the Global Earth Observing System of Systems (GEOSS). On the national level, the project GGOS-D can be considered an important German contribution to GGOS (and to GEOSS in the broader sense).

The integration and combination of the various space geodetic techniques is one of the major goals and challenges of GGOS and of the project GGOS-D. This integration is important not only for the realization of a highly accurate and long-term stable reference frame as the basis of all Earth observation, but also for the generation of homogeneous, high-quality time series of geodetic/geophysical parameters describing the processes in the Earth system.

Because of the very close cooperation between the partner institutions, that are working together within the GGOS-D project, we have the chance to go far beyond the level of consistency and homogeneity that can be reached at present on an international level.

The major improvements of GGOS-D compared to the international status of today are:

- Implementation of common standards for modelling and parameterization in all software packages involved.
- Extension of the parameter space to link for the first time geometry, Earth rotation, sea surface heights and gravity field from SLR, VLBI, GPS, altimetry and Low Earth Orbiters (LEOs). Additional parameters (not yet considered in solutions of the official services) are quasar coordinates, nutation offsets

and rates, tropospheric zenith path delays and gradients and low-degree coefficients of the Earth gravity field.
- Higher resolution in time, as, besides weekly, also daily solutions are generated and Earth rotation parameter (ERPs) with sub-daily time resolution.
- Usage of the SINEX (Solution INdependent EXchange) format for the exchange of all time series of parameters and solutions.
- The definition of a meta data standard for the SINEX format to allow the exchange of meta data.

The experiences of the GGOS-D project will help considerably to establish new guidelines for GGOS also on the international level.
The time series of global solutions produced based on these improvements are the basis for the generation of a very precise and stable reference frame and long-term, consistent and homogeneous time series of geodetic/geophysical quantities that can be used to monitor, model and, finally, predict the processes in the Earth system.

2. Common Standards and Parameterization

The consistency among the various solutions from the different techniques used within the GGOS-D project is of crucial importance. Because the solutions are not only compared but rigorously combined, the definition of common standards and a unique representation and parameterization of the relevant quantities is absolutely necessary to be able to interpret the combined solutions. As seven different software packages are used to generate the solutions of the different techniques contributing to GGOS-D, all these packages had to be modified to follow the same common standards. A first set of standards was implemented during the first phase of the project (Steigenberger et al. 2006). These standards were then reviewed based on the experience gathered with the initial set and a second, more demanding and complete set was agreed upon by the partners and subsequently implemented into the seven different software packages used within this project. The most important standards are listed in Table 1.

Not just the standards for the modelling of geodetic and geophysical effects had to be homogenized but also the parameterization of the solutions. The following was achieved:

- Site coordinates: a common, very detailed list of site coordinate discontinuities for all techniques was composed. These discontinuities are mainly due to equipment changes at the stations and earthquakes.
- Earth rotation parameters (polar motion and UT1): common parameterization as piece-wise linear, continuous functions and with a time resolution as high as 1 hour.
- Nutation offsets and rates were set up for VLBI and GPS.
- Quasar coordinates estimated by VLBI were included into the SINEX files.
- Low-degree harmonics of the gravity field up to degree/order 2 were setup for the SLR and integrated GPS/Low Earth Orbiter solutions to allow for the connection of gravity field, geometry and Earth rotation.
- Troposphere zenith delays and gradients: a common parameterization as piece-wise linear, continuous functions was realized with exactly the same binning starting at the full hours.

The implementation of all these features and options was quite a challenge and took a considerable amount of time of the project. But this effort had to be made, as it is crucial for all the combination efforts and results.

3. Generation of Fully Reprocessed Time Series (SINEX Files)

Based on these parameterizations and the common standards mentioned above (second realization), the data of the various space geodetic techniques involved in this project have been completely reprocessed once again. Table 2 gives an overview of the present status of the reprocessing effort.
From Table 1 we see that most of the time series have been completed applying the sec-

Table 1: Common standards for the 2nd iteration of GGOS-D. Changes with respect to the first iteration are given in bold

Station coordinates/Sea surface heights	
Solid Earth tides	IERS Conventions 2003
Permanent tide	Not considered for coordinates
Ocean Tides	FES2004, *Letellier* (2004)
Pole tides	Linear trend for mean pole offsets: IERS Conventions 2003
Ocean Loading	FES2004 including the CoMcorrection for the motion of the Earth due to the ocean tides[1]
Atmospheric Loading	Not applied
Earth Orientation Parameters	
A priori information	Daily values of the **C04 05** series[2] (x-pole, y-pole, UT1)
Interpolation polar motion	linear interpolation between daily values of x-pole and y-pole
Interpolation UT1	1) reduction of UT1 to UT1R 2) linear interpolation between daily values of UT1R 3) conversion of UT1R to UT1
Subdaily ERP Model	IERS2003
Nutation	IAU2000A (without free core nutation), *Mathews et al*. (2002)
Lower harmonics of the Earth's gravity field	
A priori model	EIGEN-GL04S1[3] including temporal variations of C_{20}, C_{30}, C_{40}
Troposphere modeling radio techniques	
Hydrostatic delay	**Computed from 6-hourly ECMWF grids**[4]
Mapping function for hydr. delay	**Hydrostatic VMF1** (*Boehm et al.*, 2006)
Wet delay	No a priori model, wet delay estimated (see Table 1)
Gradients	Zero a priori values
Troposphere modeling SLR	
Troposphere model	*Mendes and Pavlis* (2004)
Technique-specific effects GPS	
Phase center model	**igs05 1421.atx**[5], *Schmid et al*. (2007)
Radome calibrations	**igs05 1421.atx**
Antenna height	igs.snx[6] + IGSMAIL/IGSSTATION[7]
Hor. antenna offsets	Applied
2nd and 3rd order iono. corr.	**Applied** according to Fritsche et al. (2005)
Technique-specific effects SLR	
CoM corrections (reflector offsets)	ILRS conform[8]
Range bias For selected stations,	ILRS conform
Arc length	7 days
Technique-specific effects VLBI	
Thermal deformations	Applied, IVS conform (*Nothnagel et al.*, 1995; *Skurikhina*, 2001), mean value of the temperature recordings during the VLBI sessions used as station-specific reference temperature
Gravitational sag	Not applied

1 http://www.oso.chalmers.se/~loading/
2 http://hpiers.obspm.fr/iers/eop/eopc04_05/eopc04.62-now
3 http://www.gfz-potsdam.de/pb1/op/grace/results/
4 http://mars.hg.tuwien.ac.at/~ecmwf1/GRID/
5 ftp://igscb.jpl.nasa.gov/igscb/station/general/
6 ftp://igscb.jpl.nasa.gov/igscb/station/general/
7 http://igscb.jpl.nasa.gov/mail/mailindex.html
8 http://ilrs.gsfc.nasa.gov/satellite_missions/center_of_mass/index.html

Table 2: Generation of consistent time series (SINEX-Files)

Technique	Work package	Institution	Software	Period
SLR	WP3200	DGFI	DOGS	11/1992–05/2007
SLR	WP3200	GFZ	EPOS	10/1992–01/2007
VLBI	WP3300	DGFI	OCCAM	01/1984–12/2006
VLBI	WP3300	GIUB/BKG	CALC/SOLVE	01/1984–12/2005
GPS	WP3400	GFZ	EPOS	Several months
GPS	WP3400	GFZ	Bernese V5.0	01/1994–03/2007
LEOs	WP3500	GFZ	EPOS	01/2004–12/2004
Altimetry	WP3600	DGFI	DGFI-Software	01/1993–12/2005

ond iteration of the standards and parameterization. The second GPS solution (EPOS) is not yet finished, because of the huge effort it requires. We expect it to be fully available in the first quarter of 2008. To the extent possible, the SLR time series will be prolonged further into the past (i.e. back to 1984) and the LEO integrated solutions will be extended to cover at least a few years.

Special solutions were also produced for VLBI and GPS with a 1-hour (instead of a 1-day) resolution for the Earth rotation parameters. These are very interesting solutions to study the subdaily variations of Earth rotation, mainly caused by the ocean tides and, to a smaller part, by the atmosphere.

4. Comparison and Combination Studies

Many interesting comparisons and combination studies were already performed with the first version of SINEX files from the individual techniques. But with the second version available, not only the consistency was once more improved but also the number of common parameter types was significantly extended (adding troposphere zenith delays and gradients to both VLBI solutions, quasar coordinates, and low-degree harmonics coefficients).

The following list contains some of the studies performed so far (as examples for the wide variety of studies possible with the data material now available):

– Comparisons of station coordinate time series between GPS, VLBI and SLR: Many interesting differences were found between the techniques, but also fascinating signals common to all techniques.
– Detailed comparison studies of the time series of troposphere zenith delays and gradients from VLBI and GPS: These studies showed once again the importance of having more than one technique available to assess the quality and possible systematic biases in the solutions. Antenna changes or changes in the elevation cut-off angle for the processing may cause considerable biases in the troposphere parameter series and have to be carefully identified and corrected.
– Combination of time series from VLBI and GPS including the tropospheric zenith delays and gradients as common parameters: These combination tests gave interesting insights into how to combine the troposphere parameters (»local troposphere ties«), if the instruments are located at different altitudes and how systematic effects from GPS antenna phase center pattern show up in the troposphere zenith delays. It became also clear that »troposphere ties« can be used to validate, to a certain extent, the quality of the terrestrial geometrical local ties.
– Comparsions of subdaily Earth rotation parameters from VLBI and GPS and the estimation of ocean tidal terms from the long homogeneous time series. Also the combination of subdaily ERPs has been done.
– Initial solutions for a global combined reference frame realizations have been genera-

ted. They already indicate a considerable improvement compared to the last international realization ITRF2005. The strategy of how to apply local tie information has to be further refined, as it is crucial for the accuracy and consistency between the individual technique frames.
- Based on the solutions including low-degree spherical harmonics, the relationships and correlations between parameter types have been studied (degree-1 terms of the gravity field and geocenter coordinates, degree-2 terms and Earth rotation, GM and scale).

More details on the results achieved within the GGOS-D project are given in specific papers contained in this volume.

5. Next Steps

Whereas the main focus of the first two years was on the generation of the consistent and homogeneous time series and on the implementation of the necessary software options and algorithms, the last year will be used to:

- Finalize the consistent realization of a terrestrial and celestial referenced frame (TRF and CRF) based on the GGOS-D time series as a high-quality product for the international community.

- Interpretation of the various time series computed by using the high-precision reference frames mentioned in the previous item and the comparison with global geophysical fluid information and external results.

- Assess the benefit from a combination of the three pillars of geodesy: the geometry, the Earth rotation and the gravity field (low-degree coefficients).

The project is proceeding according to the time schedule. Many new interesting insights may be expected for the final year of the project, where the focus can be put much more on the interpretation of the outcome.

6. Conclusions and Outlook

Compared to the international efforts to develop consistent and rigorously combined products for the Global Geodetic Observing System (GGOS), the GGOS-D project has already made enormous progress. Not only the implementation of common standards and parameterizations, but also the variety of parameters included into the combination work has reached a status far beyond that of the international IAG Services and the many analysis centers (ACs). Whereas »only« seven software packages had to be adapted within the GGOS-D project, around 30 packages will have to be considered on the international level, a huge effort of coordination still to be achieved. The GGOS-D project, which we may consider to be a very small copy of the international services (IGS, IVS, ILRS, IDS, IERS), is an extremely valuable project for the international community to see the benefits of a rigorous combination of the space geodetic techniques on the one hand and the problems, hurdles and intricatenesses to be overcome on the other hand. GGOS-D may be considered a major step forward toward the realization of a consistent, highly accurate set of time series for all major geodetic-geophysical parameters and, thus, a crucial contribution to GGOS. Especially, it is to be expected that the consistency of the GGOS-D solutions will allow for a realization of the terrestrial and celestial reference frames with an accuracy and consistency well beyond that of the present realizations (i.e., the ITRF2005 and the ICRF). The reference frames, however, are the critical basis for all other geodetic-geophysical results and their interpretation and, thus, for the understanding of the processes in the Earth system.