MODELS FOR HIGH ACCURATE SPACE GEODETIC OBSERVATIONS

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ABSTRACT. Since the introduction of modern space geodetic techniques, such as Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS), the precision of instruments and observations has been constantly increasing. Within the process of transferring the observations into results a multitude of assumptions has to be applied for modeling phenomena concerning signal dispersion, site displacement and reference point deformation, earth orientation, geopotential and relativistic effects. Thus it is desirable that the used models are always improved concurrently to the technological development of the space techniques so as to provide the best possible results. The consistent combination and integration of the various space geodetic techniques and their related models is the main task of IAG's Global Geodetic Observing System (GGOS). In this paper we give examples about conventional models and recent progress in modeling. Focus is paid on the characterization of geophysical phenomena related to the Earth's crust, atmosphere, and rotation, and the effects on VLBI and GNSS observations and some relevant results are shown.

1. INTRODUCTION

One of the big challenges for the Global Geodetic Observing System (GGOS) organization is the development of an observing system capable of measuring variations in the Earth's shape, gravity field, and rotation with an accuracy and consistency of 0.1 to 1 ppb, with high spatial and temporal resolution (GGOS, website). For example target accuracy of the terrestrial reference frame is to determine station positions better than 1 mm/year. This is a very ambitious goal which requires, besides the improvement of the observation techniques themselves, highly accurate models. Roughly estimated this implies that if we apply up to let us say ten astronomical and geophysical models during the data processing each model needs to be precise to approximately 0.1-0.2 mm in order to reach the anticipated accuracy for the station position. Depending on the technique a variety of model assumptions has to be considered, which cannot be treated exhaustively in this paper. For a complete register of the conventional models we refer to the Conventions of the International Earth Rotation and Reference Systems Service (IERS Conventions, 2003). The aim of this paper is to highlight some of the current advances in modeling and to discuss necessary steps for the future evolution of the model assumptions related to

- Earth rotation parameter (ERP) variations,
- troposphere modeling - mapping functions,
- site displacements
  - thermal deformation of VLBI antennas and definition of the reference temperature,
  - tectonic plate motion and modeling non-linear effects,
  - atmosphere loading and choice of the reference pressure.

2. EARTH ROTATION PARAMETER VARIATIONS

At present tidally induced variations of the ERP are considered in the parameter estimation. The tidal variations are subclassified to diurnal and sub-diurnal ocean tidal variations in all three ERP (pole coordinates x_p, y_p, and dUT1) and zonal tidal variations with periods from around 5 days to 18.6 years in dUT1 or the length of day (LOD), respectively. Zonal tidal variations are primarily caused by the deformation of the solid Earth due to the zonal part of the tidal potential from Sun, Moon, and the planets. A minor part of these variations is also generated by the deformation of the world oceans, i.e. by long-period ocean tides. The model for zonal tidal ERP variations recommended in the IERS Conventions currently does not treat these two effects separately. Recent studies (Englich et al., 2008; Gross, 2009) show that this joint model exhibits some deficiencies especially for the fortnightly term. A revision of the modeled contribution of the long-period ocean tides is recommended and also a separation of the two effects in the Conventions would be advisable for the sake of clarity. The present conventional model for the effects of diurnal and sub-diurnal ocean tides is based on empirical ocean tide models deduced from satellite altimetry measurements. In Steigenberger et al. (2008) this model was compared to sub-daily ERP variations derived from observation data of Very Long Baseline Interferometry (VLBI) and the Global Positioning System (GPS). The comparison showed that the space geodetic techniques are sensitive to the effect of the triaxial shape of the Earth on the ERP, which also occurs in the sub-daily frequency band. Deviations to the IERS model, which confirm these results were also found in a study by Englich et al. (2008). The effect of the triaxiality on polar motion is already covered in the IERS Conventions, whereas the effect on the Earth rotation rate, the so-called semi-diurnal spin libration is not yet considered. Keeping in mind the goal to provide the most accurate models, the short-period dUT1 variations should be extended with a model for the semi-diurnal spin libration.

3. TROPOSPHERE MODELING - MAPPING FUNCTIONS

On the occasion of the inclusion of the Vienna Mapping Function 1 (VMF1) and the Global Mapping Function (GMF) to the IERS Conventions we would like to show an example of the advantageous performance of the VMF1 compared to the Niell Mapping Function (NMF) (Boehm et al., 2006a and 2006b). Changes of the station heights due to changes in the mapping functions can very well be predicted by a rule of thumb (Boehm et al., 2006a). The left part of figure 1 shows such predicted station height changes determined on a global 15° by 15° grid as provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The right part of figure 1 displays the estimated station height changes determined from the analysis of one year of global GPS observations (Boehm et al., 2007). The largest estimated changes appear at the coast of Antarctica with 1.3 cm, which is in very good agreement with the predictions for this region (dark red in the figure 1 corresponds to a height change of 13-15 mm).

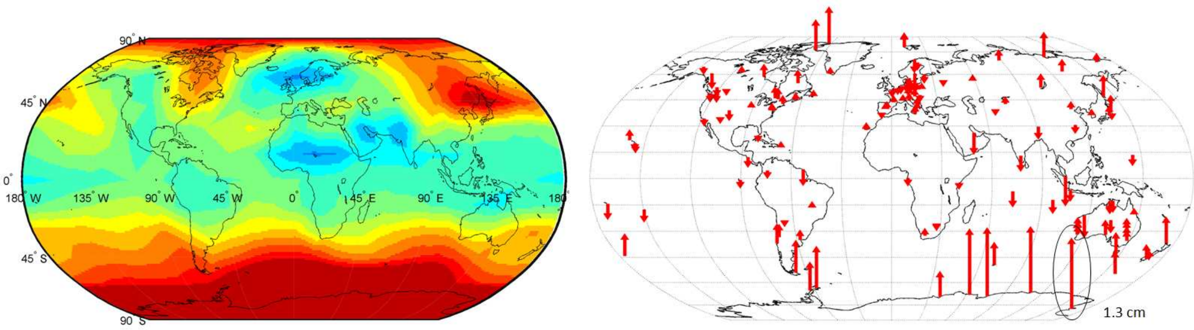

Figure 1: Predicted and estimated station height changes when using VMF1 instead of NMF.

4. SITE DISPLACEMENTS

For the comprehensive treatise of all effects causing a change of the station positions please refer once more to the IERS Conventions. Here we only pick out some interesting new approaches or indicate open questions, starting with the thermal deformation of VLBI telescopes and the need for a clear definition of the reference temperature.

4.1 Thermal deformation of VLBI antennas

VLBI antennas are subject to structural deformations due to temperature variations, which can cause variations of the coordinates of the reference point of several millimeters. Therefore a model for VLBI antenna thermal deformation is proposed in the IERS Conventions to be used in routine VLBI processing. This model requires thermal expansion coefficients of the material the antenna is built of and usually the surrounding temperature as input. In a paper by Wresnik et al. (2007) it could be illustrated for two exemplary antennas that the application of the surrounding temperature is not always appropriate, but that it would be preferable to use the real structure temperature. In the normal case the structure temperature of the telescopes is not available. The alternative to providing all sites with temperature sensors to collect the structure temperature would be the development and application of temperature penetration models, as shown in the paper referred above. Another important input to a thermal deformation model is the already mentioned reference temperature. For the definition of the reference temperature (which has still not been defined by the international community) there are three options:

- mean air temperature from temperature records of stations,
- mean temperature during a certain time period from numerical weather models,
- temperature according to the Global Pressure and Temperature model (GPT), see Boehm et al. (2007b).

For further details and a discussion of these three options see Boehm et al. (2008a).

4.2 Tectonic plate motion

As a second example we present a work by Heinkelmann et al. (2008), which deals with modeling of tectonic plate motion in reference frame solutions. Conventionally, tectonic plate motion is modeled within a terrestrial reference frame (TRF) solution by a constant velocity, i.e. as linear motion or piecewise linear function of the observing sites. This approach is not always appropriate, especially in case of episodic events such as large earthquakes. These incidents are often followed by co- and post-seismic deformations causing local site displacements, which are not necessarily linear. In special cases TRF solutions could be improved by non-linear deformation models for stations suffering from the consequences of an earthquake. In the study a post-seismic relaxation model for the 2002 Denali earthquake from GPS deformation analysis was applied to VLBI data. One TRF solution including a refined non-linear model for the motion of the VLBI site GILCREEK was compared to other TRF solutions and to the ITRF2005 (using linear deformation models) and to single VLBI session solutions. The root mean square of the coordinates with respect to the single VLBI solutions is given in table 1. IGG07R04 denotes a former VLBI TRF solution with a linear deformation model for station GILCREEK, whereas IGG08R01 stands for the new solution comprising the refined non-linear station model. The application of such a refined model is especially mandatory when fixing station coordinates or developing a time-dependent solution.

RMS	ITRF2005	IGG07R04	IGG08R01	GPS data
Latitude (mm)	3.8	6.1	3.1	13.8
Longitude (mm)	3.8	5.1	3.1	17.6
Height (mm)	8.3	7.8	7.5	10.5
3D (mm)	9.8	11.2	8.7	24.7

Table 1: RMS w.r.t. single VLBI solutions (Heinkelmann et al., 2008)

4.3 Atmosphere loading

Atmosphere loading can cause vertical crustal displacements of up to 25 mm (the horizontal displacement amounts to about 1/3 of the vertical). In principle there are two methods to calculate the effect of atmosphere loading on the station coordinates:

- using geophysical models (Green's functions, numerical weather models, load Love numbers, ...),
- using empirical models based on site-dependent data.

One simple form of such an empirical model is e.g. $dh = (p - \underline{p}) \cdot r$, with p: pressure at the station, $\underline{p}$: reference pressure and r: empirically determined regression coefficient. Currently atmosphere loading is applied in VLBI but not in GNSS solutions. For reasons of consistency it would be important to find a common way of considering atmosphere loading by both communities. Basically, there are various options concerning the application of atmosphere loading corrections. It can either be accounted for at the observation level or considered as a posteriori corrections to the final coordinate time series. If normal equations of different space techniques are to be combined, atmosphere loading could also be applied at the so-called "stacking" level, which requires very careful book-keeping and data treatment. A very detailed investigation of this issue can be found in Boehm et al. (2009). Another open question related to this issue is the definition of the reference pressure to which given or computed station coordinates are related. Referring to the ambitious accuracy goals stated at the beginning the following estimations can be made for the reference pressure: 1. If we consider the simple model for the atmosphere loading and assume a regression coefficient of -0.5 mm/hPa then the reference pressure has to be known to at least 2 hPa to reach the millimeter level; 2. Since a pressure difference of 1 hPa corresponds to approximately 10 m height difference, the heights to which the pressure values refer have to be known better than 20 m. General requirements for the reference pressure field are:

- It should be "accurate enough" (mostly < 2 hPa).
- The mean pressure should refer to a height field.
- Easy calculation for any point on the Earth surface (subroutine for coordinates).
- Unambiguously determinable now and in future.

One possible option for the realization of the reference pressure would be the usage of a rather simple model for global pressure and also temperature like the GPT (Global Pressure and Temperature model, Boehm et al., 2007b), which has already been mentioned in section 4.1. For a more detailed treatment on reference pressure refer to Boehm et al. (2008b).

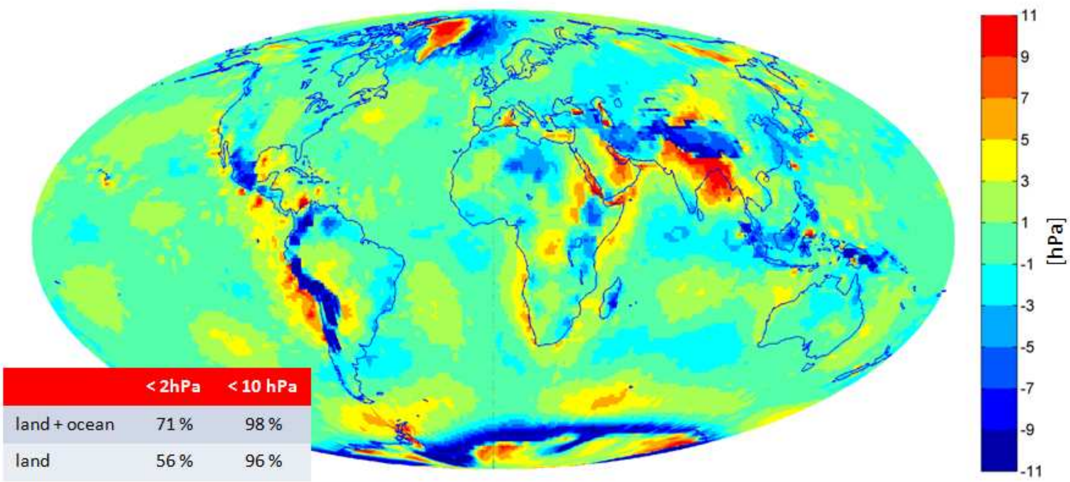

Figure 2: 2.0 ° x 2.5 ° grid of mean surface pressure values (ECMWF) vs. GPT model (differences in hPa)

5. CONCLUDING REMARKS

- We gave an overview and examples about models for highly accurate geodetic observations without claiming the list to be exhaustive.
- Having the sights on the sub-millimeter there are still pending tasks and open questions to deal with regarding the applied models.

- It is of major importance for GGOS that the same geophysical model constants and standards are applied consistently for all geodetic techniques.
- It is advisable to agree on the treatment of surface loading effects and to clearly define reference pressure and temperature.

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