Report of the IAG/ETC/WG6/1 (VLBI)

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1. Introduction

The Working Group 6 (WG6), 'Solid Earth Tides in Space Geodetic Techniques', of the Earth Tide Commission (ETC) of the International Association of Geodesy (IAG) has the following three Terms of Reference (ToR):

1. Extension of the recommendations concerning the tidal influences given in the IERS Conventions (1996) to facilitate their practical use for space geodetic techniques.

2. Evaluation and comparison of the potential of different space geodetic techniques to monitor tidal effects and to determine tidal parameters. Techniques such as VLBI, SLR, LLR, GPS and GLONASS, DORIS and PRARE, satellite altimetry will be covered.

3. Determination of parameters of the tidal models by space geodetic techniques. This requires a priori corrections due to atmospheric and oceanic influences on the Earth's surface and on the geopotential and precise models for tidal influences on the Earth orientation parameters. The effect of the pole-tide has also to be considered. The results will have to be compared and interpreted.

ToR 1 has been worked on during 1998/1999 and the results have been compiled and published. The Working Group 6 was separated into smaller subgroups during the last working meeting at the IUGG General Assembly, July 1999. These smaller subgroups are directly related to the specific space geodetic techniques and have the task to address ToR 2 and ToR 3. The following report concludes the work done by subgroup 1 (VLBI) with respect to these two ToRs.

2. Tidal effects to be considered in geodetic VLBI

Geodetic VLBI uses radio telescopes on the earth's crust to observe extragalactic radio sources. The microwave signals of the radio sources are received and recorded together with precise time information on magnetic tapes. The basic observations of geodetic VLBI are the time delays between the arrival of the radio signals at two telescopes forming a baseline. These time delays are obtained in a correlation process.

In order to analyse the geodetic VLBI data, a model has to be implemented that describes the geometric situation during the observation precisely. Thus, the three-dimensional positions of the radio telescopes and the rotation of the earth have to be modeled. This requires to include the tidal influences on either of the latter.

The solid earth tides are the most important tidal effect for the modeling of the station positions. Crustal loading due to redistribution of oceanic mass is the second largest effect and accordingly has to be modeled. The deformation effect caused by polar motion, the so-called pole-tide, has also to be accounted for. A further crustal loading effect to be considered is the deformation due to the changing atmospheric pressure, though it is not a tidal effect. Furthermore, the thermal deformation of the radio telescopes has to be modeled which does not belong to the tidal effects either. The two last mentioned effects do not belong to the category of tidal effects but show similar temporal behaviour and therefore are included in the list at this point.

Concerning the modeling of earth rotation the solid earth tide effects on polar motion and UT1 have to be modeled. Also the oceanic effects on the latter have to be considered.

2.1. Solid earth tides

Most of the analysis software packages for geodetic VLBI data today follow the model for solid earth tides as recommended by the IERS Conventions (1996) (IERS, 1996). The only exception is the permanent tide where the actual treatment does differ from the recommendations of the IERS Conventions (1996). VLBI data analysis programs neither reduce the data to the so-called 'mean-crust' that includes the permanent, zero-frequency deformation of the earth which is called 'permanent tide', nor do they reduce the data to the so-called 'tide-free-crust' which describes an earth without any tidal deformation (Mathews, 1999). This is done by purpose in order to keep consistency with the way the permanent tide was treated during the last decade in space geodesy and to avoid any discontinuity of the VLBI results and an irritation of their users. However, the IERS Conventions (1996) recommend to use the concept of the 'mean-crust'.

2.2. Ocean tide loading

Ocean tide loading is modeled according to the recommendations of the IERS Conventions (1996) in most VLBI analysis software packages. This means the application of the ocean tide loading model according to Scherneck (1991) based on the ocean tide model by Schwiderski (1980) and Le Provost *et al.* (1994). There are more recent ocean tide loading models and some VLBI analysis groups use for example models by Scherneck (1996) and Scherneck (2000) which are based on ocean tide models by Eanes and Bettadpur (1995) and Ray (1999). Some of the VLBI analysis groups also apply refined ocean loading models by introducing a large number of interpolated tides using addmittance calculations.

2.3. Pole-tide

The so-called pole-tide describes the rotational deformation effect of the earth due to polar motion. It has been discussed by Wahr (1985) and Gipson (1998). The topic was also treated by Andersen *et al.* (1999) in detail.

2.4. Atmospheric loading

The effect of atmospheric loading for the vertical site displacement is accounted for by some VLBI analysis groups via an admittance coefficient to be multiplied with the local pressure. There also exists an extensive database of three-dimensional atmospheric loading effects calculated by global convolution of atmospheric pressure data from the European Centre for Medium Weather Forecast (ECMWF) with loading Green's functions (Scherneck *et al.*, 2000). However, so far no VLBI analysis group uses these atmospheric loading effects based on global convolution calculations in routine analysis.

2.5. Thermal deformation of radio telescopes

A model for thermal deformation of radio telescopes has been described by Haas *et al.* (1999). For the application of this model the outside air temperature as logged in the VLBI databases and the dimensions of the radio telescopes are needed to calculate the thermal expansion effects. The radio telescope dimensions are collected by Nothnagel and Haas for all VLBI telescopes structures worldwide on the webpage http://giub.geod.uni-bonn.de/vlbi/thermal-ex/parameters.html . Currently the model is being tested based on the invar-rod measurement systems at Onsala and Wettzell which directly measure the vertical change of the radio telescopes due to temperature influences.

2.6. Solid earth tide and ocean tide effects on earth rotation

The periodic variations in UT1 due to solid earth tides are described by Yoder (1981) and modeled accordingly in the VLBI analysis programs. Dickman (1993) added the long period influence of ocean tides on earth rotation. Models for diurnal and subdiurnal earth rotation variations due to ocean tides are applied in routine VLBI data analysis by most VLBI analysis groups. The model by Brosche *et al.* (1989) is based on theoretical considerations while the model by Ray *et al.* (1994) is based on results from satellite altimetry observations. Latter is recommended in the IERS Conventions (1996). Besides these models derived either from pure theory or external information there are also extensive empirical models, e.g. by Gipson (1996), which are derived from VLBI observations themselves.

3. Results from geodetic VLBI

Already during the eighties, first results for Love and Shida numbers derived from geodetic VLBI were presented by Herring *et al.* (1983) and Ryan *et al.* (1986). During the last years more recent results analysing more extensive VLBI data sets were obtained.

Mitrovica *et al.* (1994) determined complex Love numbers for seven diurnal tides and resolved the Free Core Nutation (FCN) resonance frequency and phase lag.

Herring and Dong (1994) estimated frequency dependent Love and Shida numbers for eleven diurnal and eleven semi-diurnal tides from the analysis of eight years of VLBI data.

Results for Love and Shida numbers in the diurnal and semi-diurnal frequency bands have also been presented by Haas and Schuh (1996), Haas and Schuh (1997) and Schuh and Haas (1998). The investigations covered real and imaginary Love and Shida numbers and more than 16 years of VLBI data. The resonance period of the Free Core Nutation (FCN) and its quality factor have been reported by Haas and Schuh (1996) Haas and Schuh (1997) and Schuh and Haas (1998).

Gipson and Ma (1998) investigated the pole-tide effect and determined real and imaginary Love numbers associated with the deformations. They also studied the influence of the polar motion induced ocean loading effect.

Recently, Petrov (2000) derived complex Love and Shida numbers for long-period tides, using an extensive data set of 20 years of VLBI data.

Estimates of vertical ocean tide loading parameters have been presented by Sovers (1994) and Haas and Schuh (1998). Furthermore, three-dimensional ocean tide loading amplitudes and phases have been determined from VLBI data by Haas and Scherneck (1999) and Scherneck *et al.* (2000) for a number of VLBI sites and ocean loading tides. It was shown at the example of the VLBI station Westford that the refinement of global ocean tide models by regional models leads to an improved agreement of theoretical and empirical ocean loading parameters.

Results for atmospheric loading effects investigated using VLBI data have been reported by VanDam and Herring (1994), MacMillan and Gipson (1994) and Haas *et al.* (1997). Admittance coefficients between vertical site displacement and local atmospheric pressure have been determined.

A model for the thermal deformation effect on radio telescopes has been presented by Haas *et al.* (1999). Using a very simple approach taking only a mean temperature for each 24 hours VLBI experiment, the change of the vertical position of the telescopes at Onsala and Wettzell can be modeled with an agreement of about 0.5 mm with respect to the vertical changes as observed by the invar-rod measurement systems. Further refinements and test of the model are ongoing.

Titov and Yakovleva (2000) presented an investigation on seasonal variations in VLBI baseline length measurements based on VLBI data up to 1995.

Tidal effects on earth's rotation have been studied already in the eighties using geodetic VLBI and concentrated first on the tidal periods as predicted by Yoder *et al.* (1981). During the nineties the investigations focused then on high frequency variations in earth's rotation.

Campbell and Schuh (1986) determined tidal variations in UT1 with periods of 9.1 and 13.6

days from intensive VLBI observations. Luo *et al.* (1987) and Schuh (1988) reported variations in UT1 for several tidal periods between seven and 35 days.

Brosche *et al.* (1991) detected short period UT1 variations from VLBI in the diurnal and semi-diurnal tidal bands and compared them to the predictions of their theoretical model for ocean tide effects on earth's rotation (Brosche *et al.*, 1989).

Sovers *et al.* (1993) determined ocean tidal effects for four diurnal and four semi-diurnal frequencies in both, polar motion and UT1, in a direct approach analysing VLBI data.

Herring *et al.* (1994) determined high frequency tidal signals in polar motion and UT1 for 22 frequencies analysing eight years of VLBI data.

The tidal effects on high frequency earth orientation variation have been studied in great detail by Gipson (1996) analysing a VLBI data set of 15 years.

Scherneck and Haas (1999) showed the importance of ocean tide loading for the investigation of high frequency earth orientation variations. Neglect of horizontal ocean tide loading in the analysis of space geodetic data leads to a rotation of the space geodetic network used. In turn these disturbances are absorbed in the estimated results of high frequency earth orientation variations. There is also a second order effect due to the differences in the currently existing theoretical ocean tide loading models.

4. Limitations of geodetic VLBI

Geodetic VLBI is sesitive to all tidal effects mentioned before, i.e. tidal effects on site displacements and earth's rotation. Thus the VLBI technique can be used to investigate tidal effects and to determine tidal parameters. However, one effect that is beyond the possible investigation is the permanent tide. No space geodetic method is sensitive to the permanent tide.

Since VLBI is a geometric method and does not use artifical satellites orbiting the earth, it is not sensitive to tidal effects on the geopotential.

A limiting factor in geodetic VLBI is the geometry of the current international VLBI network. There is a concentration of geodetic VLBI telescopes in the northern hemisphere, while the southern hemisphere is equipped with only few telescopes.

The investigation of the latitude depedence of the Love and Shida numbers may suffer from this uneven distribution of VLBI sites. However, the investigation of global tidal parameters, e.g. the frequency and quality factor of the Free Core Nutation resonance, are not affected.

The uneven distribution restricts to some extend the investigation of ocean tide loading effetcs, since the ocean models are not sensed equally well by the current distribution of the VLBI sites.

The uneven distribution might create a problem to separate plate tectonic motion and earth rotation for the long frequency range. But since tidal effects on earth rotation are mainly in the short frequency rage, there is no limitation for the study of tidal influences on earth rotation.

Another limitation of geodetic VLBI is that there are no permanent obervations. Geodetic VLBI is conducted on the basis of single experiments of usually 24 hours length. Since the observing process still requires human interaction, it has to be more automised before permanent observations will be possible. There are breaks in the observing program and so the temporal distribution of the VLBI results is not evenly spaced in time. The only automised VLBI system today is the Keystone Project in the metropolitan area of Tokyo, Japan (Kiuchi *et al.*, 1999). But even there, the observations are conducted every second day only. The problem of non-permanent observations will be solved partly when the CORE program (MacMillan *et al.*, 1999) comes to full implementation during the year 2003. There will be observations every week day with at least one intercontinetal VLBI network of four to five participating stations.

Geodetic VLBI does not allow real-time analysis of the observed data. Usually the magnetic tapes with the recorded data have to be transported to a central correlator first. Then the correlation process has to be performed and the resulting delay observations to be distributed to the analysis centres. Today the fastest turn-around times between conducting a VLBI experiment and analysing the data are 3–5 days. In contrast to this standard routine, the VLBI data from the Keystone network in Japan get available for the data analysis in near real-time, i.e. 1 hour after the end of an observing session of 24 hours length. However, for the investigation of tidal effects, a real-time or near real-time availability of the data is not of major importance.

5. Future perspectives

The full implementation of the Mark IV technique will improve the precision of the VLBI system. This will in turn also lead to higher accuracy of the tidal results derived from VLBI data.

With the start of the routine CORE program, VLBI data will be available more regularly. This will lead to improved temporal resolution of the VLBI results.

The installation of the transportable integrated geodetic observatory (TIGO) (Hase, 1999) in the southern-hemisphere at Concepcion, Chile (Schüter *et al.*, 2000), will improve the geometry of the international VLBI networks.

The application of high speed data links for VLBI will possibly become reality in a few years and speed up the turn-around time between the actual observations and the data analysis. Thus, results from VLBI data will be available sooner.

All technical improvements mentioned so far will lead to higher precision of the VLBI data and in turn to improved accuracy of the results derived from VLBI data. Thus, the investigation of tidal effects and the determination of tidal parameters will benefit in particular.

Besides the purely technique oriented improvements, there are also the analysis aspects. The routine introduction of three-dimensional atmospheric loading effects in the VLBI data analysis, the application of recent ocean tide loading models and the inclusion of thermal deformation effects in the VLBI data analysis will lead to improved results for tidal parameters derived from VLBI.

Using all VLBI data available, one challenge will be to investigate solid earth tides and ocean tide loading effects simultaneously. A separation of the tidally driven effects seems to be possible by exploiting the site-specific, complicated phase behaviour of the ocean tide loading effects. A further point of investigation is to continue the studies of seasonal variations in baselength and station components.

Geodetic VLBI links directly the terrestrial and celestial reference frames and is the only space geodetic technique that contributes to earth orientation investgations by delivering nutation corrections. Latter are affected by the Free Core Nutation resonance effect, so are the tidal deformations. A combined approach to investigate the FCN effect from these two sides by using VLBI data seems very interesting. This will become possible by introducing a new nutation model and a new solid earth tide model that both are expressed in the frequency domain.

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