TIDAL EFFECTS IN GPS/GLONASS DATA PROCESSING

R. Weber[(1)], Carine Bruyninx, H.G. Scherneck, M. Rothacher,P.H. Andersen, T.F. Baker, T. van Dam

[(1)]Institute of Geodesy and Geophysics, TU-Vienna, Gusshausstr.27-29,A-1040 Vienna, Austria, email: rweber@luna.tuwien.ac.at

1. INTRODUCTION

Considering the present quality of modelling satellite orbits the microwave space-techniques GPS and GLONASS are in principle sensitive to a variety of tidal effects. This holds especially for GPS, claiming an almost unbelievable orbit precision level of about 5cm. This paper covers in principle the results of the IAG/ETC Working Sub-Group 6/4, *Solid Earth tides in space geodetic techniques-GPS/GLONASS*. We discuss the list of tidal signals which have to be considered in GNSS data processing, followed by a survey on how different Analysis Center of the IGS handle these effects. Furthermore we briefly touch upon the still unsolved problem how to treat the permanent tide and conclude with remarks on future perspectives.

2. GPS/GLONASS ORBIT MODELLING AND ORBIT CONSISTENCY

In order to achieve ultimate accuracy in processing GPS data in postprocessing or near-realtime mode it has become common practice to pick up IGS precise or rapid orbits, available at various data centers. Nowadays these ephemerides, obtained as a weighted combination of up to eight IGS Analysis Center submissions, are a quasi standard for a large number of applications. According to the Terms of Reference the ultimate goal of the IGS is ‘to provide a service to support geodetic and geophysical research activities, through GPS data and data products’. All IGS products are based on tracking data from a real global permanent station network shown in figure 1.

Various improvements in GPS orbit modelling over the past years led to a current orbit precision level of a few centimeters. To evaluate the real accuracy of these ephemerides we may compare the microwave results with orbit calculations based on a different technique, in particular on laser data (two GPS satellites carry laser reflectors). Both solutions still agree at the 5cm level. This level of precision asks for taking into account a number of tidal effects and for looking very careful at the consistent handling of these effects to avoid systematic differences between the various Analysis Center solutions.

GLONASS orbits, on the other hand, are currently not of a quality comparable to the GPS ephemerides. This is caused by a less populated tracking network (about 35 stations) as well as a smaller number of satellites. Nevertheless, orbits are at the 25cm precision level but heavily constrained to the GPS frame. In the near future the situation might improve considerable because of scheduled launches of new satellites as well as new strategies in orbit modelling within the IGLOS-Pilot Project of the IGS.

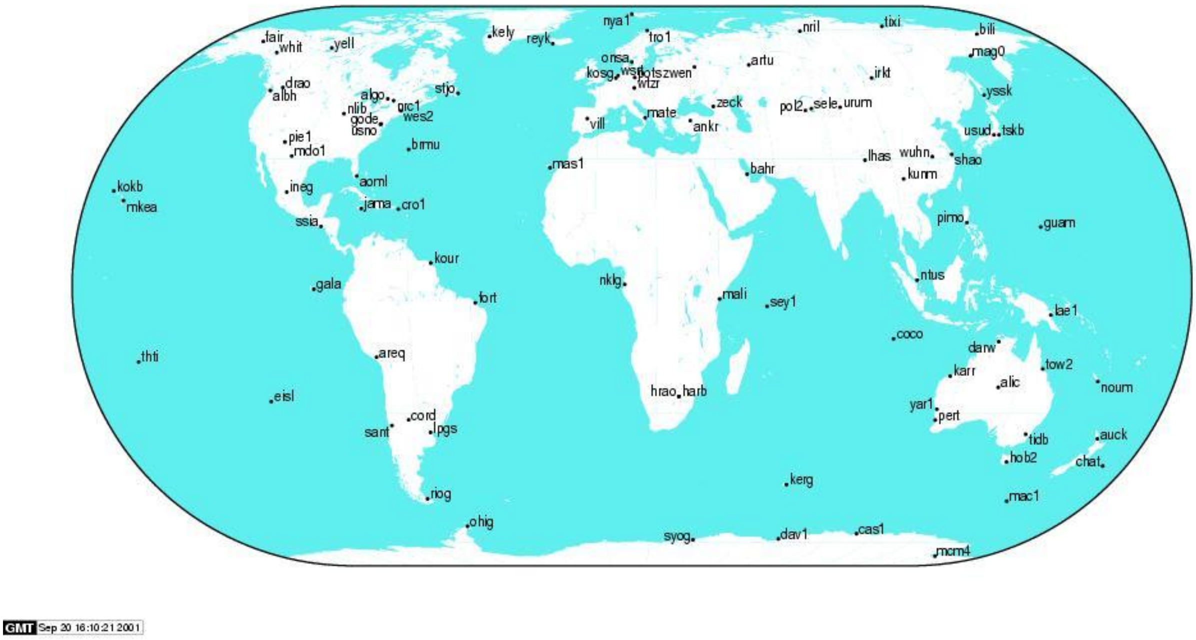

Figure 1 : IGS Global Tracking Network, status September 2001

3. TIDAL EFFECTS TO BE CONSIDERED IN THE GPS/GLONASS DATA PROCESSING

In the first place **local site displacements** due to **solid earth tides** and **ocean loading** have to be taken into account. The effect of solid earth tides is discussed extensively in (McCarthy , 1996). Application of the given equations describe the radial motion as well as the transverse diplacements at the 1mm level. A two step procedure is recommended, accounting in step one for motions by means of nominal real love numbers $\boldsymbol{h}$ and $\boldsymbol{l}$ common to all degree 2 tides. The second step corrects for the frequency dependence of these numbers (diurnal band, long periods). An improved precision demands in addition the calculation of displacements due to degree 3 tides. Movements induced by ocean loading may reach the range of a few centimeters in the vertical (Scherneck, 1996) based on the models FES94 (Le Provost et al., 1994), CSR4.0 (Eanes and Bettadpur,1999), or, alternatively GOT99.2 (Ray, 1999). Displacements are available now for almost all global stations of the IVS, ILRS, IGS, DORIS services.

Although **atmosphere loading** may cause vertical diplacements of several (up to some tens of) millimeters, an adequate correction is not applied by the IGS Analysis Centers at the moment (see list below). This goes together with the discussion about the reliability of the available models and the question at which periods the inverted/non-inverted barometer assumption for the response of the oceans due to changes in air pressure is valid.

As part of the **orbit model**, the **tidal forces** are most conveniently described as variations in the standard geopotential coefficients. The tidal contributions are expressible in terms of the potential Love number $\boldsymbol{k}$. Modelling the solid earth tides usually starts with frequency independent Love numbers up to degree and order 3. Subsequently frequency dependent corrections are applied for up to 34 constituents. The effects of ocean tides are also incorporated by periodic variations in the Stokes' coefficients. Coefficients used in GPS orbit modelling were obtained in most cases from the UT CSR3.0 (Eanes et al., 1996) ocean tide height model or from the model of Schwiderski (Schwiderski, 1983).

Ocean and atmosphere tides induce a motion of the coordinate frame of tracking stations of all satellite techniques relative to the Earth's center of mass. Viewed from the rigid crust-fixed frame, the motion of the coordinate system origin is known as 'geocenter-motion' and the tidal induced components as '**geocenter tides**'. Presently, these centimeter-size motions may not be seen in GPS/GLONASS analyses, thinking of the current accuracy of the orbits. However, in SLR the terms are clearly resolvable and in order to foster a uniform data processing for all techniques, these variations should be taken into account.

Ocean tides (matter and motion terms) induce variations in the axial (LOD) as well as in the equatorial **earth rotation components** (polar motion) in three frequency bands: semidiurnal, diurnal and long-periodic. The former can be monitored very precisely by satellite techniques like GPS. Apriori correction for daily and subdaily tidal variations in the Earth rotation and polar motion by means of the Ray model (Ray, 1996; 8 constituents) has become standard in IGS data processing since 1997.

See below (Table 1) an overview (extract from the analysis center log files available at the IGS Central Bureau System: Dec 2001) is given of how the different IGS analysis centers correct for tidal effects. At first glance the results of this survey look not very homogeneous, but we should keep in mind that testing and applying different models is an essential step for innovation. Also, in a few cases, this information might not mirror the current situation. An update, if necessary, has been requested by this Working Group.

	CODE	EMR	ESOC	GFZ	JPL	NOAA	SIO	USNO
Solid Earth Displacement	Model IERS96 nominal h_2 / l_2 0.6078/0.0847 +corrections	Williams	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:-0.089	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:-0.089	Model IERS00	Model IERS96 nominal h_2 / l_2 0.6067/0.0844 +corrections	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:-0.089	Williams
Force	frequ. indep. Love's Nr: k_2 =0.300	frequ. indep. Love's Nr: k_2 =0.300	frequ. depend.; Wahr model; nominal k_2 =0.300	frequ. depend.; Wahr model; nominal k_2 =0.300	nominal $k_{2(0-2)}$ 0.299/0.3/0.302 $k_{3(0-3)}$=0.093 +34 frequ.dep. corrections	frequ.depend.; Wahr model; nominal k_2 =0.300	frequ. indep. Love's Nr: k_2 =0.300	nominal $k_{2(0-2)}$ 0.299/0.3/0.302 $k_{3(0-3)}$=0.093 +34 frequ.dep. corrections
Perm. Tide		no info	no info		no info		no info	no info
Displacement	not removed			not removed		not removed		
Force	applied			applied		applied		
Pole Tide	applied IERS96 mean m1/m2 0.033/0.331	applied	not applied	applied IERS92	applied IERS00	applied IERS96	not applied	applied
Ocean Loading Displacement	Scherneck	Scherneck	Scherneck	Pagiatakis	Scherneck	Ray/Schrama	not applied	Pagiatakis
Force	UT CSR	UT CSR	Schwiderski	Schwiderski	UT CSR + TEG-2B data	Ray/Schrama	UT CSR	UT CSR + TEG-2B data
Atmosphere Loading	not applied	not applied	not applied	not applied	not applied	not applied	not applied	not applied

Table 1: Tides related part of the Analysis Strategy Summaries of the IGS ACs (December 2001)

4. TREATMENT OF THE 'PERMANENT TIDE PROBLEM' WITHIN GPS/GLONASS DATA PROCESSING

Basically, in order to allow intercomparison and combination of the solutions of different techniques the recommendation is that every technique handles the permanent tide in the same way.

The current working standard is to subtract a permanent tide from the individual ((quasi-) instantaneous) observations of the station position. The amplitude of this permanent tide displacement is governed by the elastic Love numbers at semi-diurnal frequencies. An additional simplification implies is that a spherical earth is a sufficient model for this tide and that linear superposition holds. The model taken into account contains the full effect of the solid earth tides, but using unfortunately the nominal (semidiurnal,diurnal) Love-number ($\boldsymbol{h}_2 \approx 0.60$) for the secular part (instead of the secular Love-number 1.94).

A zero-tide definition including a permanent tide in a fluid approximation could be chosen to derive a physically plausible tide-free reference frame. However, no independent observation method exists which could uniquely separate the permanent tidal flattening of the earth from the rotational flattening without additional assumptions (finite elasticity in the crust for instance) which are again difficult to verify contemplating the fact that we deal with an infinite-time response.

There is a recommendation of the IAG to work on the Earth's crust. This implies, that the correction of the permanent tide should not be applied. We have to apply the nominal correction not taking into account the secular term.

If station positions have to be expressed on the 'tide-free' crust, they must be corrected for the complete response of the earth to tidal force. Thus, again we have to apply the nominal correction and afterwards account for the difference between the semidiurnal and the secular Love number. Both proposals (recommendations) are satisfying the scientific point of view but they are in conflict with the present practice.

Analysis experts insist on their 'working position', because it would be extremely dangerous to change the convention. If the transition has to be performed, each site coordinate file would have to be firmly ear-marked as to what definition is implied. Also, during the transition phase incompatible versions of analysis procedures and subroutines might coexist. Therefore, it appears viable to (continue to) stipulate the implication of a purely conventional permanent elastic tide in the computed tide displacement of a station in the reduction of space geodetic observations.

If in future more exact formulations of tide displacements come about (which would employ the frequency response method based on a harmonic expansion of the tide potential in the tradition of Doodson), we propose to

(1) exclude the zero-frequency term delivered by this method, and
(2) include instead the conventional zero-frequency term.

With sufficient accuracy, this term is

$$u = -0.6026 * 0.19844 * (1/2)(3\sin^2 \theta -1)$$
$$v = -0.0831* 0.19844 * (3/2)\sin(2\theta)$$

where u is vertical and v north displacement in meters, and theta is the geocentric latitude. The numbers in front are the basic Love numbers of the 1996 Conventions, and the second factor is the amplitude coefficient. In the IERS Standards (McCarthy, 1992) these quantities were h_2 = 0.6090, l_2 = 0.0852 and the amplitude coefficient was 0.19841.

In order not to introduce jumps in station coordinates each time the response parameters are changed, the tide model must recreate the original permanent tide.

5. THE DETERMINATION OF TIDAL PARAMETERS

Last but not least we should discuss the capability and limitations of the microwave satellite techniques to investigate tidal effects (including oceanic and atmospheric tides) and to determine tidal parameters ?

First of all we may distinguish between longer periods and the diurnal/subdiurnal band. In terms of periods of several days and more three formal approaches can be considered :

(1) Do not correct for the long period solid earth tides within the data analysis, but correct for ocean (and atmospheric) loading. Then, the 13.66 days, 27 days and one year periods will show up in the residuals. This should allow to extract information about the Love numbers for these frequencies for the solid earth tides (using the known tide generating potential).

(2)Correct in the data analysis as completely as possible for the solid earth tides (and for atmospheric loading), extract ocean loading from residuals.

(3)Correct in the data analysis as completely as possible for the solid earth tides and correct for ocean loading, extract atmospheric loading from residuals.
Preliminary results using Precise Point Positioning (PPP) as well as differencing schemes when processing regional continuous GPS networks show that atmospheric loading effects are somewhat attenuated (in Scandinavia effects are found that are a factor of three smaller than predicted using load convolution methods; the inverted barometer assumption does not seem to be the critical factor). Together with earlier results (van Dam, Herring, 1994), the resolution of atmospheric loading effects is expected at the 1-3 mm level (implying that vertical motion is better resolved than horizontal).

In terms of daily and subdaily periods we may conclude that:

(1) studying (ocean) tidal effects from a series of 2-hourly ERP values, based on 3 years of data of the global GPS network of the IGS, has shown (Rothacher et al., 2000) that tidal amplitude models, currently available from VLBI, SLR, GPS and Altimetry, agree within

$10\,\mu as$ in Polar Motion and $1\,\mu s$ in UT1.

(2) On the other hand, tides with periods close to 12 and 24 hours (S1, $\psi 1$; K1, S2, K2) seem to be biased because of orbit errors. The residual spectrum, that remains after removal of the main tidal terms contains non-tidal signals up to $50\,\mu as$ in polar motion and $3\,\mu s$ in UT1. These effects might be due to the resonance effect (12 sidereal hours revolution period of the GPS satellites) or, alternatively, due to atmospheric or oceanic normal modes. To add GLONASS data seems to be a very promising way to overcome some model deficiences. First of all, the revolution period of $11^h\ 15^m$ is not in resonance with earth rotation and, moreover, the increased orbital inclination reduces the impact of along track orbit errors on LOD estimates.

6. PERSPECTIVES

Future perspectives are of course closely tied to modelling improvements in the non-gravitational forces acting on the satellites and to tropospheric effects. Another important point is the impact of improved ocean loading tides (altimetry models) on orbits and subsequently on the ERP estimation or for the accurate determination of water vapour from GPS measurements. Advantages of analyzing data from different satellite navigation systems were discussed above. Last but not least the steady increase of available ERP and station coordinate time series involves decreasing formal errors in the derived tidal parameters.

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