Update on VLBI Data Analysis at ESA/ESOC

C. Flohrer, E. Schönemann, T. Springer, R. Zandbergen, W. Enderle

Abstract ESA's Navigation Support Office is providing the geodetic reference for ESA missions mainly based on the processing of the satellite-geodetic techniques GNSS, SLR and DORIS. Since 2016 the Navigation Support Office is extending its expertise to include VLBI processing and analysis. This effort will establish ESA's capability to determine the absolute orientation of the Earth and therewith enable the Navigation Support Office to provide a fully independent set of Earth orientation parameters for ESA missions. ESOC's software package NAPEOS will become capable of combining all four geodetic techniques on the observation level and thus supporting GGOS, the Global Geodetic Observing System.
The VLBI delay model is now fully implemented following the IERS 2010 standards. With the current implementation in NAPEOS observation residuals of the level of 2-3 cm are reached. This result is expected and can be further improved by applying a better clock model and allowing for VLBI parameter estimation. The paper discusses briefly the current status and future plans of the VLBI implementation in NAPEOS and shows example residuals. The question as to which space-time coordinate systems to use for the various parameters of the VLBI delay model is addressed as well.

Keywords VLBI data analysis, NAPEOS, space-time coordinate systems

1 Introduction

In 2015 ESA's Navigation Support Office started to extend its processing capabilities for VLBI tracking data to complete ESA's capabilities in generating independent Earth Orientation Parameters (EOP). In addition this capability would allow ESA to contribute to the IVS service as an analysis centre and to enhance its contribution to the IERS service with UTI-UTC and nutation products. Finally it would enable ESOC's software package NAPEOS (ESA/ESOC, 2009) to combine all space-geodetic techniques at the observation level, bringing together the strengths of the individual techniques.

NAPEOS (NAvigation Package for Earth Orbiting Satellites) is capable of processing data from various satellite-geodetic techniques, such as GNSS, SLR, DORIS, and altimetry, individually but also combined at the observation level. This leads to the challenge to incorporate a new observation type into an existing software package. On the one hand it has the advantage that the developer can access already existing modules and algorithms and the combined processing of the various techniques comes almost for free. On the other hand, however, it implies a lot of integration and testing effort and proper book-keeping.

In Section 2 we briefly review the results achieved in 2016, followed by the current status of the VLBI implementation in NAPEOS in Section 3. The next steps planned for the VLBI data processing in NAPEOS are highlighted in Section 4. Finally, in Section 5, we discuss the problem of different coordinate time scales involved in the VLBI delay model and their proper usage.

Claudia Flohrer · Erik Schönemann · Tim Springer · René Zandbergen · Werner Enderle
Navigation Support Office, ESA/ESOC, Robert-Bosch-Str. 11, DE-64293 Darmstadt, Germany

2 Results achieved in 2016

Various implementation steps are needed to enable basic VLBI data processing in NAPEOS. The main ones can be summarised as:

- radio source and VLBI station database set up
- VLBI observation reading
- VLBI observation modelling
- VLBI observation corrections
- VLBI parameter estimation

In 2016 we were able to present initial results at the 9th IVS General Meeting (Flohrer et. al, 2016). Our data processing starts with VLBI observations read from NGS card files. In the future, this format can be replaced by the vgosDB format based on NETcdf files. A basic VLBI observation model was implemented in NAPEOS, only considering the main terms. Observation corrections such as the gravitational delay, axis offsets, and cable delays had not been included. Also, no parameters had been estimated, with the exception of constant clock offsets w.r.t. a reference clock. With this basic implementation we could present O-C residuals at the 0.5 m level. By correcting the observations for the instrumental delay caused by the axis offset we could reduce the O-C residuals to the 10 cm level.

3 Current status

Meanwhile we fully implemented the Consensus model from Eubanks et.al (1991) into NAPEOS, adding also the gravitational delay according to the recipe provided in the IERS 2010 conventions (Petit and Luzum, 2010). The entire observation modelling was successfully validated against the VieVS software (Böhm et. al, 2012).

Table 1 summarises the processing standards and models used in our current implementation of VLBI in NAPEOS. We use the observed VLBI delay as provided by the correlator, which is considered to be equal to a Terrestrial Time (TT) coordinate time interval d_{TT}. No transformation is done to Geocentric Coordinate Time (TCG). With this choice we follow the generally accepted approach of the VLBI analysis centres. The space coordinates resulting from the VLBI analysis x_{TT} are thus called TT-compatible. They can be transformed into a TCG system (as recommened by the IAU), i.e. the Geocentric Celestial Reference System (GCRS), by a simple rescaling

$$x_{TCG} = \frac{x_{TT}}{1 - L_G} \qquad (1)$$

(see Petit and Luzum, 2010).

NAPEOS uses the latest IERS models and standards (Petit and Luzum, 2010) for Earth Orientation Parameters (EOPs) and displacement of reference points. See Table 1 for further details.

We use the Saastamoinen model for the a priori tropospheric delay model together with the GMF mapping functions. The antenna axis offset is applied using the antenna information file provided by Nothnagel (2009). Other technique-specific effects are not yet taken into account, such as cable delay and thermal deformation of the antenna.

We have not yet enabled the parameter estimation of the main VLBI parameters, such as EOPs, station coordinates, and source coordinates. These parameters are kept fixed w.r.t. their a priori values.

A simple clock model is applied using a piece-wise linear function. For each station clock, one offset and a drift every 6 hours is estimated w.r.t. a chosen reference clock. No automatic clock jump detection has been implemented yet, neither a polynomial function for the clock model. Both are foreseen in a next implementation step.

We enabled the estimation of tropospheric parameters, namely tropospheric wet zenith delays and tropospheric gradients with North and East component mapped with the wet GMF mapping function. Troposphere parameters are set up as piece-wise linear functions every 1 hour. Tropospheric gradients are estimated every 24 hours.

With this approach we processed 24 h sessions obtaining O-C residuals on the order of 2-3 cm. As an example, Figure 1 shows O-C residuals in centimetres for session 15MAR23XA_N004, for 2850 observations of 21 baselines to 50 sources. There are three different solutions marked in different colours. Orange labels the solution without any troposphere estimates. Only piece-wise linear station clocks have been estimated every 6 hours. The light blue solution is similar to orange but adding piece-wise linear zenith wet delays every 1 hour. Dark blue adds tropospheric gradients every 24 hours on top.

Table 2 summarises the RMS values of the residuals in cm (and in ps for convenience). Without allowing for the estimation of any troposphere parameter, the RMS value is at the 10 cm level. Estimating wet zenith delays decreases the RMS significantly to 2.77 cm. It can be slightly further decreased to 2.61 cm by estimating tropospheric gradients.

The achieved residual level is still a factor of two higher then the standard residual level achieved by the IVS analysis centres in a routine VLBI data processing. However, with the current state of the VLBI implementation in NAPEOS this result is very satisfying. Further improvements are expected by applying a better clock model and allowing the parameter estimation for station coordinates and EOPs (see next section).

4 Next steps

With the current implementation status we are ready to participate in the next VLBI Analysis Software Comparison Campaign (VASCC), see Klopotek et. al (2016), to validate our VLBI delay model.

Table 1: VLBI processing standards and models used for the current VLBI implementation in NAPEOS.

Reference frames	
Time argument	coordinate time TT is used for the VLBI observations leading to TT-compatible TRS spatial coordinates, the VLBI delays provided by the correlators are equivalent to a TT coordinate interval (assuming that the proper time of the station clocks, used to record the signal, has the same rate as TT)
Inertial frame	• Barycentric (BCRF): ICRF2 reference frame realised by a set of source positions consistent with J2000.0, given in the IVS source name translation table (https://gemini.gsfc.nasa.gov/ solve_save/-IVS_SrcNamesTable.txt) mainly based on IERS TN35 (Fey et al., 2009) • Geocentric (GCRF): mean equator and equinox of 2000 Jan 1.5 (J2000.0)
Terrestrial frame	ITRF2008 reference frame realised through a set of station coordinates and velocities given in the IVS internal realisation ITRF2008-TRF-IVS.SNX
Precession	IAU 2006/2000A precession-nutation model
Nutation	IAU 2006/2000A precession-nutation model, daily dx and dy corrections (celestial pole offset) from IERS Bulletin-A are applied
Polar motion, UT1	interpolated from IERS Bulletin-A, updated daily, with the restoration of subdaily variations due to ocean tidal and libration effects using IERS 2010 (Petit and Luzum, 2010) models: • ocean tidal effects: diurnal and semi-diurnal variations in pole coordinates and UT1 applied (using IERS routine ORTHO_EOP.F) • libration effects: prograde diurnal and semi-diurnal nutations in polar motion applied (using IERS routine PMSDNUT2.F), semi-diurnal libration in UT1 applied (using IERS routine UT-LIBR.F)
Displacement of reference points	
Solid Earth tides	IERS 2010
Solid Earth pole tides	IERS 2010, mean pole removed by quadratic trend until 2010 / linear trend from 2010
Oceanic pole tides	not applied
Ocean tidal loading	consistent with IERS 2010, site-dependent amps/phases from free ocean tide loading provider (Bos and Scherneck, 2017) for FES-2004 (Lyard et al., 2006) tide model including centre of mass correction, NEU site displacement computed using HARDISP.F from D. Agnew
Atmospheric pressure loading	not applied
Non-tidal loading	not applied
Ionospheric delay	Ionospheric group delay correction applied from observation file (NGS)
A priori tropospheric delay model	
A priori hydrostatic zenith delay	Saastamoinen model (Saastamoinen, 1972), with meteorological data from observation file
A priori wet zenith delay	none
Mapping function	GMF dry (Böhm et. al, 2006)
A priori gradients	none
Technique-specific effects	
Antenna axis offset	applied using the antenna information file (http://vlbi.geod.uni-bonn.de/Analysis/Thermal/ antenna-info.txt) provided by Nothnagel (2009)
Cable delay	not applied
Thermal antenna deformation	not applied
Station eccentricities	not applied
Source structure	not applied
Geometric/relativistic delay model	
Consensus model	applied following the IERS 2010 conventions
Planetary ephemerides	DE405 (Standish, 1998) for all planets, Sun, Moon using coordinate time TDB as input
GM values	from IERS 2010 and DE405 (see Section 5 for details)
Parameter treatment	
Polar motion	fixed
Nutation (Celestial pole offset)	fixed
UT1-UTC	fixed
Source coordinates	fixed
Station coordinates	fixed
Station clocks	estimated piece-wise linear every 6 hours (w.r.t. a fixed reference clocks)
Troposphere	• Wet zenith delay: estimated piece-wise linear every 1 hours • Mapping function: partial is GMF wet (Böhm et. al, 2006) • Gradients: North and East gradients estimated piece-wise linear per 24 hours

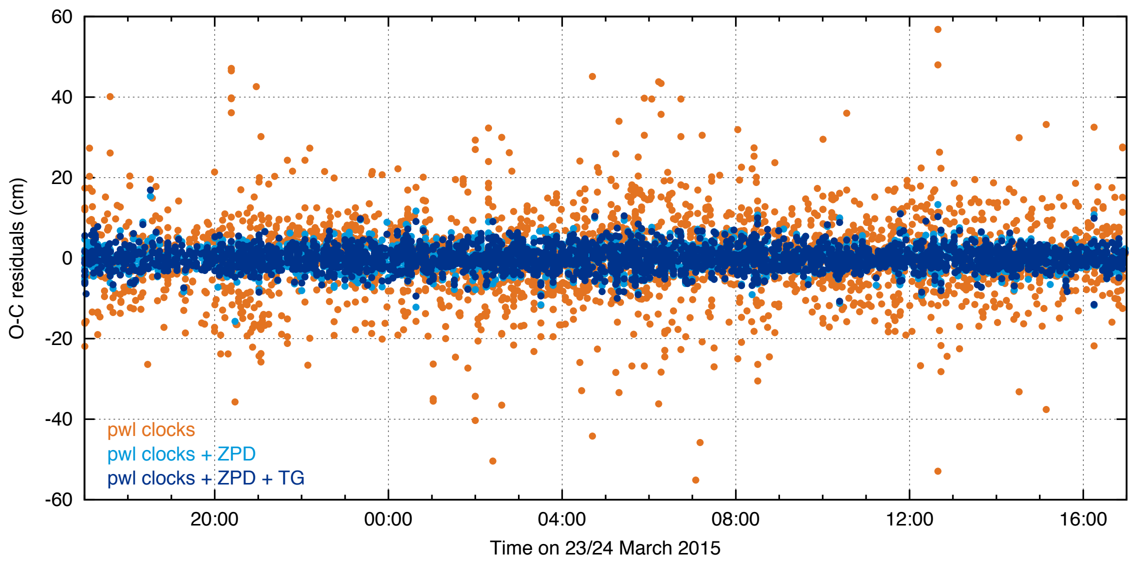

Fig. 1: O-C residuals (in cm) from the example session 15MAR23XA_N004 for three different solutions: (pwl clocks) with piece-wise linear clocks estimated every 6 hours, (pwl clocks + ZPD) additionally with piece-wise linear tropospheric zenith wet delays every 1 hour, (pwl clocks + ZPD +TG) additionally with tropospheric gradients every 24 hours.

In the upcoming future we plan to extend the current VLBI implementation in NAPEOS by the following steps:

- implement observation weighting and outlier detection
- add observation correction due to cable delay
- add observation correction due to instrumental delay caused by thermal deformation
- implement automatic clock jump detection algorithm
- implement polynomial function for clock model
- add partial derivatives for remaining parameters (EOPs, station coordinates)

Once these steps have been achieved a full VLBI based parameter estimation can be done. As NAPEOS has already the capabilities to process and combine various observation types, we also aim for a combined parameter estimation (combining at the observation level), starting with GNSS and VLBI.

Table 2: RMS values of O-C residuals from the example session (in cm and ps) for three different solutions: (a) with piece-wise linear clocks estimated every 6 hours, (b) additionally with piece-wise linear tropospheric zenith wet delays every 1 hour, (c) additionally with tropospheric gradients every 24 hours.

Solution ID	RMS (cm)	RMS (ps)
(a) pwl clocks	10.46	348.9
(b) pwl clocks + ZPD	2.77	92.4
(c) pwl clocks + ZPD + TG	2.61	87.1

5 On the sound usage of space-time coordinate systems in the Consenus model

The Consensus model (Eubanks et.al, 1991) given in the IERS conventions (Petit and Luzum, 2010) has become an agreed standard to model the VLBI delay. It was derived from a combination of five different relativistic models and combines quantities defined in both reference systems, the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS). Both reference systems have corresponding coordinate time scales, namely Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG). In addition there are scaled versions, Terrestrial Time TT (renamed from Terrestrial Dynamic Time TDT, being a scaled version of TCG)

Table 3: Parameters of space-time coordinate systems and their relationships. Scaling factors are defined as $F = 1 - L_B$ and $L = 1 - L_G$, with the defining constants L_B and L_G (Petit and Luzum, 2010), from Klioner (2008).

BCRS	**TCB**	**TDB**
Coordinate time	$t = TCB$	$t^* = TDB = Ft + t_0$
Spatial coordinates	x	$x^* = Fx$
Mass parameter	μ	$\mu^* = F\mu$
GCRS	**TCG**	**TCB**
Coordinate time	$T = TCG$	$T^{**} = TT = LT$
Spatial coordinates	X	$X^{**} = LX$
Mass parameter	μ	$\mu^{**} = L\mu$

and Barycentric Dynamic Time (TDB, being a scaled version of TCB). Both scalings have no physical meaning, but were chosen for convenience in order to make the difference between the proper time of an observer on the rotating geoid and these two coordinate time scales evaluated along his trajectory as small as possible.

The post-newtonian equations hold irrespective of the use of TCB and TDB time, if additional scalings are also used for derived quantities as the spatial coordinates and mass parameters of Sun, Earth, Moon and planets. The equations given in Table 3 allow, according to Klioner (2008), to scale coordinate time, spatial coordinates and mass parameters from one space-time coordinate system to another, using the defining constants $L_B = 1.550519768 \times 10^{-8}$ and $L_G = 6.969290134 \times 10^{-10}$. These scalings make it possible to retain exactly the same form of the principle dynamical equations in the BCRS and the GCRS.

When implementing the VLBI delay model into a software package one gets inevitably confronted with the following questions: Which space-time coordinate systems have to be used for spatial coordinates and mass parameters in the Consensus model? And consequently, are there any quantities which have to be rescaled? The authors did not find clear answers to these questions. This may be due to the fact that the coordinate time scales TCB and TCG were introduced at the same time or even after the definition of the Consensus model, i.e. by IAU resolutions A4 (in 1991) and B1.9 (in 2000).

We found another aspect worth addressing, as it may be a potential source of confusion. Earth and solar parameter mass values can be found in the IERS conventions as well as in the JPL ephemerides files. The IERS conventions give the TCB-compatible value for the solar mass parameter and the TCG-compatible value for the Earth mass parameter. The JPL ephemerides give TDB-compatible values for both Earth and solar mass parameters. Table 4 summarises the mass parameter values from the latest three IERS conventions (1996, 2003, 2010) and from the JPL ephemerides files DE403, DE405, and DE241. The values in blue are the original values taken from the reference. All other values are derived from the blue ones by using the scaling factors L_B and L_G. We found that values from the IERS conventions and the JPL ephemerides differ and also change over time. Note that TCB- and TCG-compatible values of the mass parameters are the same in both GCRS and BCRS.

In the following, we summarise the parameters of the Consensus model under question. Our assumptions of the parameter values to be used within the model are stated in italic type.

Spatial coordinates from JPL ephemerides: The barycentric position of Sun, Earth, Moon, and planets are derived from the JPL planetary ephemerides. To request the spatial coordinates the input time argument needs to be TDB. The numerical value of the spatial coordinates provided by the JPL ephemerides are TDB-compatible x^*. Are the barycentric spatial coordinates used in the Consensus model supposed to be TCB-compatible? If yes, we have to rescale the numerical values of spatial coordinates derived from the JPL ephemerides from TDB-compatible to TCB-compatible values by

$$x = F^{-1} x^*. \tag{2}$$

Note, as the TCB-compatible velocities coincide with the TDB-compatible velocities, no rescaling is required for velocities.

The authors assumption: to use TCB-compatible values x for the position of Sun, Earth, Moon, and planets, i.e. rescale the spatial coordinates derived from the JPL ephemerides.

Solar mass parameter: The solar mass parameter, also named heliocentric gravitational constant, is given in the IERS conventions as TCB-compatible value $\mu_\odot$. It is also provided in the JPL ephemerides but as TDB-compatible value $\mu_\odot^*$. The TCB-compatible value can be derived by

$$\mu_\odot = F^{-1} \mu_\odot^*. \tag{3}$$

It should be noted that the value has changed over time for the different IERS conventions. The latest value from IERS 2010 conventions is derived from the DE421 JPL ephemerides, whereas the value from IERS 2003 conventions is compatible with DE405 JPL ephemerides.

The authors assumption: to use the TCB-compatible value $\mu_\odot$ from the latest IERS conventions.

Planetary mass parameters: The mass parameters of the planets are also available in the JPL ephemerides. They are provided as a ratio of TDB-compatible values $\mu_\odot^*/\mu_J^*$. Are the planetary mass parameters for the gravitational delay computation supposed to be TCB-compatible values? If yes, we have to multiply the inverse of the given ratio by the TCB-compatible solar mass parameter to obtain the planetary mass parameter

$$\mu_J = \frac{\mu_J^*}{\mu_\odot^*} \mu_\odot. \tag{4}$$

This implicitly rescales the planetary mass parameters from TDB- to TCB-compatible values. But special care has to be taken to use a $\mu_\odot$ value consistent with $\mu_\odot^*$ provided in the very same JPL ephemerides file.

The authors assumption: to use the TCB-compatible value μ_J derived from the JPL ephemerides using Equation 4, with $\mu_\odot$ being the TCB-compatible value of the

Table 4: Mass parameters for Sun and Earth (also referred to as Heliocentric and Geocentric gravitational constants) derived from IERS conventions and JPL ephemerides files for different coordinate time scales (TCB, TCG, TDB, TT)). Blue values are given in the reference. Black values have been derived from blue by rescaling using the scaling factors L_G and L_B (Petit and Luzum, 2010).

	IERS Conventions			JPL ephemerides		
	TN21 (1996) (McCarthy, 1996)	**TN32 (2003)** (McCarthy and Petit, 2004)	**TN36 (2010)** (Petit and Luzum, 2010)	**DE403** (Standish et. al, 1995)	**DE405** (Standish, 1998)	**DE421** (Folkner et. al, 2009)
	Heliocentric gravitational constant ($\times 10^{20} m^3 s^{-2}$)					
TCB, TCG	1.32712**400000**	1.32712**442076**	1.32712**442099**	1.32712**442081**	1.32712**442076**	1.32712**442099**
TDB	1.32712**397942**	1.32712**440018**	1.32712**440041**	1.32712**440023**	1.32712**440018**	1.32712**440041**
TT	1.32712**399908**	1.32712**441984**	1.32712**442007**	1.32712**441989**	1.32712**441984**	1.32712**442007**
	Geocentric gravitational constant ($\times 10^{14} m^3 s^{-2}$)					
TCB, TCG	3.986004**418**	3.986004**418**	3.986004**418**	3.986004**418**	3.986004**391**	3.986004**424**
TDB	3.986004**356**	3.986004**356**	3.986004**356**	3.986004**356**	3.986004**329**	3.986004**362**
TT	3.986004**415**	3.986004**415**	3.986004**415**	3.986004**415**	3.986004**388**	3.986004**421**

solar mass parameter derived from the very same JPL ephemerides.

Earth mass parameter: The TCB-compatible value of the Earth mass parameter $\mu_\oplus$ is the very same in latest three IERS conventions (1996, 2003, 2010) and corresponds to the TDB-compatible value as given in the DE403 ephemerides. But it has different values in the DE405 and DE421 ephemerides. Why do the latest JPL ephemerides use a different value then the latest IERS conventions (or vice verca)? And which value should be taken? Special attention has to be paid for software packages that also process data of Earth-orbiting satellites and need to use the TT-compatible value for the geopotential.

The authors assumption: to use the TCB-compatible value $\mu_\oplus$ from the latest IERS conventions.

Although the order of magnitude of the scaling effects is below the 1 ps level accuracy of the Consensus model, it might be worth discussing the presented questions and agreeing on the usage of space-time coordinates systems in the Consensus model. This would remove one potential error source with almost no costs assuming that the required changes are simple scaling factors.

6 Conclusions

ESA's Navigation Support Office continues its efforts toward VLBI data analysis. The VLBI delay model is now fully implemented into our software package NAPEOS. The current O-C residual level is at the 2-3 cm level. This result corresponds with our expectations, in particular considering the current level of implementation. We are confident to lower the residual level by a factor of two with the next implementation steps. Full parameter estimation capabilities still have to be enabled. As a next step we will replace our simple piece-wise linear station clock model by a polynomial function and we will enable parameter estimation for station coordinates and EOPs.

We also presented some open questions related to the topic of space-time coordinate systems and their usage in the Consensus model. We look forward to receiving feedback from the scientific community.

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