Results from the VLBI Analysis Software Comparison Campaign 2015

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Abstract The aim of the VLBI Analysis Software Comparison Campaign 2015 (VASCC2015) was to compare different VLBI analysis software packages on the basis of computed theoretical delays. Eleven research groups and institutes participated in this project, which allowed us to compare software packages that are used in operational VLBI analyses or that are still under development. We present the first results, and we show how well the individual software packages agree at this stage.

Keywords VLBI theoretical delay, IERS Conventions, VLBI analysis software packages

1 Introduction

The IERS Conventions (2010) [11] contain recommendations, definitions, and models for space geodetic techniques including geodetic VLBI. In practice, different analysis software packages follow diverse estimation methods, use a variety of different correction models, and sometimes adhere to conventions that might not be the latest. This may lead to discrepancies in the results that should not appear between analysis software packages dealing with the same observational data sets. Consistency of geodetic VLBI analyses is of great importance for reaching one of the VLBI Global Observing System (VGOS) envisaged goals [9], i.e., 1 mm measurement accuracy on global baselines.

In the VLBI Analysis Software Comparison Campaign 2015 (VASCC2015), existing VLBI analysis software packages were compared on the basis of computed theoretical delays and in accordance with the models described in the IERS Conventions (2010). Eleven research groups and institutes expressed their interest in participating in this project (Table 1). The comparison campaign started in September 2015, and theoretical delays computed with various analysis software packages were investigated thereafter. Preliminary results and conclusions are presented here.

2 Data

Fifteen fictitious consecutive 24-hour sessions (22 June 2015 – 6 July 2015) with one minute resolution formed the basis of this comparison campaign. Two networks, one in the northern and one in the southern hemisphere, were designed in a way that a single source could be tracked at all stations continuously (Figure 1). With that geometry it was possible to compare 16 baseline delays per observation epoch. From all sites of both networks, the source was visible

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Table 1 Participants of the VASCC2015 at the present stage of the project.

	Software	Participant (provision of results)
1.	Bernese [12]	Technische Universität München (TUM)
2.	c5++ [6]	Chalmers University of Technology
3.	Calc11 [5]	Goddard Space Flight Center (GSFC), NASA
4.	Calc11 [5] SCORR [14]	Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences
5.	DOGS-RI [13] OCCAM [17]	Technische Universität München, Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
6.	GEOSAT [7]	Norwegian Mapping Authority (NMA)
7.	GINS [2]	Laboratoire d'Astrophysique de Bordeaux (LAB)
8.	GLORIA [8] Calc11 [5]	Paris Observatory (OPAR)
9.	ivg::ASCOT [1]	University of Bonn
10.	OCCAM [17]	Geoscience Australia
11.	VieVS [3]	University of Tasmania

with varying local elevation angles, allowing us to draw conclusions concerning elevation-dependent effects.

A priori values and displacement models (Table 2) were defined, and all participants were asked to follow the proposed computation routine as closely as possible. Tidal S1 and S2, as well as non-tidal atmosphere loading, zenith wet delay, and station eccentricities, were not considered. Information about the network geometry, a priori values, and meteorological and auxiliary data was provided to all participants using NGS, VGOSDB, MK3DB, and text files created for the purpose of this comparison campaign.

Table 2 Delay computation settings of the VASCC2015.

1.	EOP	High frequency EOP variations Leap second: 30 June, 24:00:00 UTC Constant values for: X_{pol}, Y_{pol}, UT1, dX, dY
2.	Displacement models	Solid Earth tides, pole tide, ocean and ocean pole tide loading
3.	Technique-specific models	Thermal expansion Axis offset
4.	Mapping function	GMF [4]
5.	Meteorological data (all sites)	Pressure: 1000 hPa Rel. hum.: 50 % Temp.: 20 ^{o}C
6.	Cable delays (all sites)	0 s

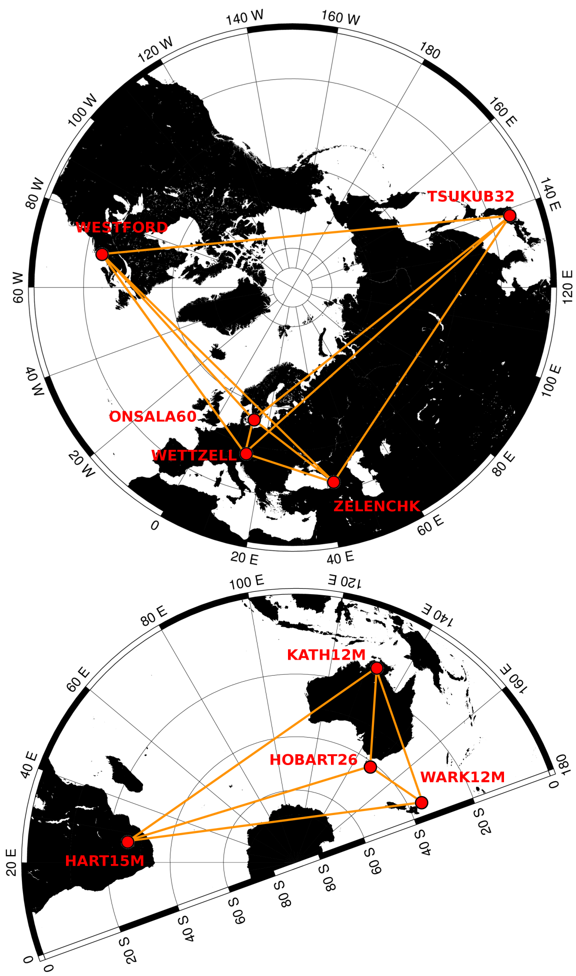

Fig. 1 Networks located on the northern (top) and southern hemisphere (bottom). Eight of the nine sites have alt-azimuth type antennas. In case of HOBART26, the mount type is X/Y with the primary axis set to the east-west direction.

3 Results

The consistency of the theoretical delays from different VLBI analysis software packages was evaluated in terms of RMS. At present, sub-mm RMS agreement of the full VLBI delay model could be achieved for six VLBI analysis software packages (Table 3). The complete theoretical delay model consists of a geometrical part and contributions from effects and models described in the IERS Conventions (2010). As an example, differences between results from two software packages are depicted in Figure 2.

Table 3 RMS of differences between theoretical delays (full delay model) for both networks over a period of 15 days. The acronym in parenthesis refers to the participant providing the solution. No results for the Calc11 - DOGS-RI pair are shown, as no DOGS-RI solution without antenna thermal expansion and zero value celestial pole offsets was available.

RMS [mm]	Calc11(GSFC)	c5++	DOGS-RI	ivg::ASCOT	SCORR	VieVS
Calc11(GSFC)	x	0.43	-	0.38	0.57	0.44
c5++	-	x	0.61	0.17	0.44	0.22
DOGS-RI	-	-	x	0.59	0.71	0.59
ivg::ASCOT	-	-	-	x	0.41	0.17
SCORR	-	-	-	-	x	0.44
VieVS	-	-	-	-	-	x

0.0 - 1.0 mm RMS

In the case of comparisons with respect to Calc11 (GSFC), celestial pole offsets were not considered, and antenna thermal expansion models [10] were excluded as this is not implemented in Calc11. In addition, one needs to be aware that theoretical delays from Calc11 (GSFC) rely on static TRF station coordinates valid at the middle session which, in this case, is June 29th. An increase of the RMS by about 0.1 mm can thus be explained.

Maximum absolute differences between the results are summarized in Table 4. Software packages not listed in Table 3 require further investigation to draw conclusions concerning the agreement on the basis of theoretical delays. We expect to obtain smaller maximum absolute residuals after all participants have validated their software packages and updated them to the latest agreed-on standards.

During the comparison campaign, some discrepancies were detected and studied in more detail. Most differences were caused by unidentified bugs or numerical issues. But it was also noticed that the definition of the source elevation angle is not well-documented in the IERS Conventions (2010). In particular, a recommendation about whether troposphere bending effects [16], for the computation of axis offset and thermal expansion delays, have to be considered or not is missing. Related papers (e.g., [10, 15]) also lack a clear

Table 4 Maximum residual values between theoretical delays (full delay model) from both networks over a period of 15 days.

Max. abs. value [mm]	Calc11(GSFC)	c5++	DOGS-RI	ivg::ASCOT	SCORR	VieVS
Calc11(GSFC)	x	1.76	-	1.82	2.68	2.06
c5++	-	x	1.87	1.04	1.48	1.14
DOGS-RI	-	-	x	1.52	2.05	1.71
ivg::ASCOT	-	-	-	x	1.24	0.83
SCORR	-	-	-	-	x	1.37
VieVS	-	-	-	-	-	x

0.0 - 1.0 mm RMS
1.0 - 2.0 mm RMS
>2.0 mm RMS

recommendation on this issue. Depending on whether bending effects for the calculation of the source elevation angle are considered or not, differences of up to 0.5 mm can be detected for antennas with axis offsets larger than 1 m (Figure 3). This effect should not have any significant impact on the VGOS-type telescopes, which are expected to have zero or mm order axis offsets. But a conventional mathematical formulation for bending effects on elevation angles could definitely be beneficial for software developers and analysts.

Another finding that is worth mentioning is related to the fact that differences between different software packages started to grow significantly as soon as high-frequency EOP variations [11] were introduced. In terms of RMS over a 24-hour period, this effect is represented by an increase of disparities between solutions by about 0.1 mm. Other geophysical models did not reveal such large discrepancies after being turned on in the software packages. Certainly, further investigation is needed in order to understand the causes of these differences.

4 Conclusions and Outlook

VASCC2015 made it possible to find out how well different software packages agree on the basis of theoretical delay models. We were also able to identify numerical issues and to correct several bugs in some of the analysis packages. Initial results show that a sub-mm agreement of theoretical delays, computed by

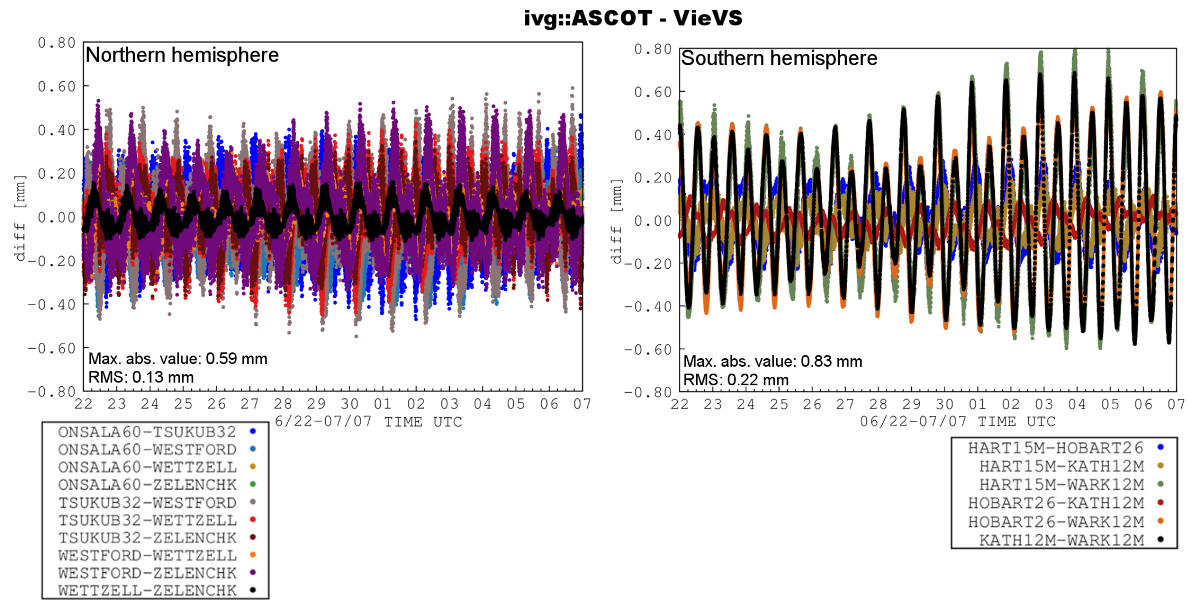

Fig. 2 Agreement between computed theoretical delays (full delay model) from ivg::ASCOT and VieVS over a period of 15 days. The results refer to baselines located in the northern (left) and southern hemisphere (right).

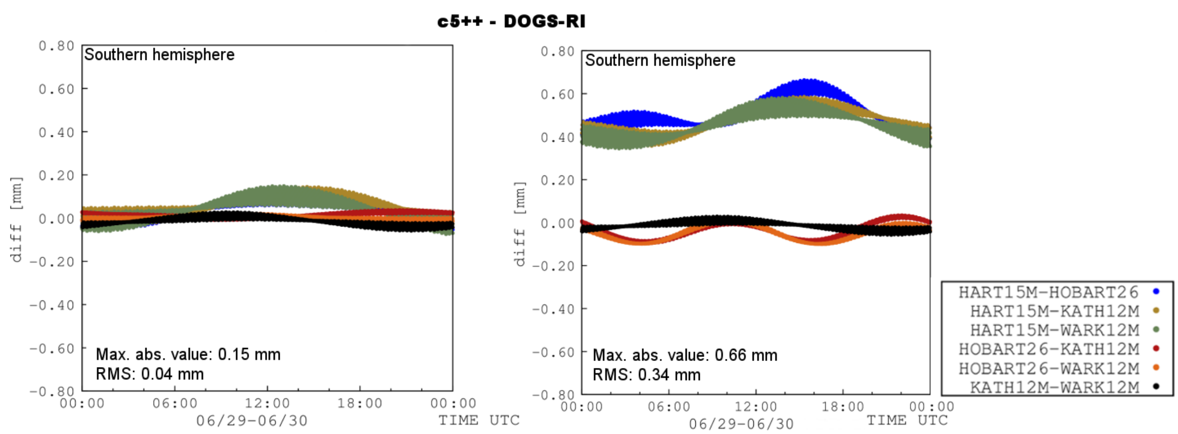

Fig. 3 Effect of tropospheric bending on source elevation angles as shown with the c5++ — DOGS-RI pair over a period of 24 hours. Both plots depict residuals between theoretical delays for the network located in the southern hemisphere. For this particular example, only geometric, gravitational and axis offset delays are considered. The left plot depicts differences when bending delay corrections are applied in both software packages. If such corrections are neglected in c5++, one can notice a significant change of the differences w.r.t. DOGS-RI as depicted in the right plot. These discrepancies can be assigned to the alt-azimuth type antennas having axis offsets of at least 1 m (fictitious $AO_{\mathrm{HART15M}} = 1.4950$ m). Smaller differences occur for antennas with X/Y mount type (e.g., HOBART26).

state-of-the-art VLBI analysis software packages, can be achieved. Nonetheless, this project needs to be continued in order to study remaining discrepancies and to minimize theoretical delay differences. A modification of the network geometry and the use of simulated observations (modeling of stochastic processes) are considered as further steps in order to enhance the agreement between software packages.

We expect that by continuing this comparison campaign it will be possible to get a better picture of the consistency of delay modeling within the IVS. It is assumed that our results and conclusions are helpful for VLBI software developers to maintain, update, and improve their analysis software packages. Thus, this project is expected to have an impact on the reliability and consistency of IVS products and subsequent scientific research.

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