New VLBI Solutions at Analysis Center DGFI-TUM

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Abstract The Deutsches Geodätisches Forschungsinstitut at Technische Universität München (DGFI-TUM) is one of the Analysis Centers (AC) of the International VLBI Service for Geodesy and Astrometry (IVS). In this regard, it provides solutions consisting of Earth Orientation Parameters (EOP), station coordinates and radio source positions for observations obtained from Very Long Baseline Interferometry (VLBI). Until recently, the official solutions were computed with the external VLBI software OCCAM. In 2018, after successful completion of internal and third-party validations, DGFI-TUM started contributing to the IVS with the Radio Interferometry component of its proprietary DGFI Orbit and Geodetic parameter estimation Software (DOGS-RI). In this work, we will summarize the model approaches followed by DOGS-RI and provide analysis results from our latest contributions to extend the quality assessment of DGFI-TUM's new VLBI solutions.

Keywords VLBI Analysis Software, DOGS-RI, IVS

1 Introduction

Since 2008, the Deutsches Geodätisches Forschungsinstitut at Technische Universität München (DGFI-TUM) has been an operational Analysis Center (AC) of the International VLBI Service for Geodesy and Astrometry (IVS, [6]). It provides *daily SINEX* files to the IVS Combination Centers (CC), which contain solutions for the various Very Long Baseline Interferometry (VLBI) experiments conducted. These solutions are given in the form of unconstrained and datum-free normal equations (NEQ), which were established to estimate the following geodetic variables: Earth Orientation Parameters (EOP), the positions of the observing VLBI stations, and the positions of the extra-galactic radio sources (quasars) which were aimed for in the corresponding VLBI session. Based on these NEQ, generated by several Analysis Centers, the Combination Centers can compute the values for the geodetic parameters. This is either done for each AC separately or in a combinatory approach, where the single NEQ are stacked (in terms of a weighted sum) to produce an averaged solution.

The distinct solutions (i.e. *daily SINEX* files) of the AC can be found online[1] and are labelled by names like *gsf2016a*: the first three letters represent the AC (in this example the *Goddard Space Flight Center*), the four digit number is the year in which the solution was provided for the first time, and the last letter reflects the particular quarter of the latter ($a = 1$, $b = 2$, $c = 3$, $d = 4$). Until March 2017, DGFI-TUM used its own branch of the analysis software *OCCAM* (see [9]) to process VLBI sessions (*dgf2009a*). During the last years, however, we implemented a proprietary VLBI analysis tool as part of the DGFI Orbit and Geodetic parameter estimation Software package (DOGS, see [2]). The new component is called DOGS-RI (Radio Interferometry), and since February 2018 it has been used to generate DGFI-TUM's official IVS contribution *dgf2018a*.

In Section 2, we will describe DOGS-RI and the features of the new solution *dgf2018a*. The initial validation of the results of DOGS-RI is described in [5],

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[1] ftp://cddis.gsfc.nasa.gov/vlbi/ivsproducts/daily_sinex/

but since the actual IVS contribution has a different setup, we will show some recent assessments of the latter in Section 3. In Section 4, the current development status of our VLBI analysis software is summarized, before we finalize this document with conclusions in Section 5.

2 VLBI Analysis with DOGS-RI

The DGFI Orbit and Geodetic parameter estimation Software (DOGS) now consists of three major parts:

- **DOGS-RI** (Radio Interferometry) processes VLBI experiments,
- **DOGS-OC** (Orbit Computation) performs Precise Orbit Determination (POD) based on satellite observations (currently SLR and DORIS), and
- **DOGS-CS** (Combination & Solution) aggregates the distinct results of any space geodetic technique (if available in DOGS- or SINEX format) on the normal equation level.

Figure 1 presents a schematic overview of the interaction of DOGS's components. The programming language is Fortran 2003, so DOGS can make use of standard procedures and subroutines already available for geodetic and astrometric applications, like the SOFA-library [3]. All parts share common models and subroutines to ensure a consistent combination of solutions within DOGS.

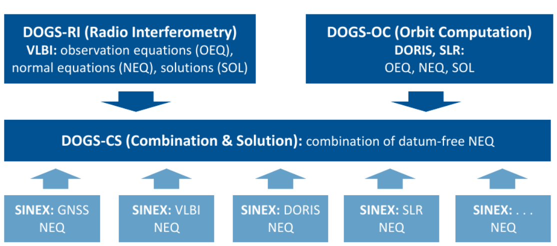

Fig. 1 Consistent combination of various space geodetic techniques with DOGS. Light blue boxes refer to external data.

The VLBI component DOGS-RI is based on a two-step least-squares minimization (the classic Gauss-Markov model) with intermediate outlier detection. Next to station and quasar coordinates and EOP, also tropospheric (zenith and gradient delays) and station clock parameters can be estimated. Optionally, various constraints and datum conditions can be applied. To support the post-processing of equations and solutions, DOGS-RI offers three different output formats, including the binary DOGS-CS format and the SINEX format. DOGS-RI provides great flexibility by containing a wide range of geophysical and signal delay models of previous and current IERS Conventions [7]. Furthermore, a multitude of mathematical functions and interpolation types is available for the representation of estimated parameters. The current setup for solution *dgf2018a* in comparison to that of *dgf2009a* is listed in Table 1.

Table 1 Settings for the IVS contributions by DGFI-TUM.

component	dgf2018a	dgf2009a
software	DOGS-RI	OCCAM @ DGFI-TUM
observation data format	NGS (Mk3)	NGS (Mk3)
precession / nutation	IAU 2006/2000A	MHB 2000 (IAU 2000A)
nutation parameters	ΔX_{CIP}, ΔY_{CIP} (CIO based)	$\Delta\psi$, $\Delta\varepsilon$ (equinox based)
a-priori TRF	ITRF2014	VTRF2008
a-priori EOP	IERS 14 C04	IERS 08 C04
a-priori gradients	GSFC / TU Vienna	zero
IERS Conventions	2010	2003
atmosphere loading	Petrov & Boy [8]	n/a
tidal ocean loading	FES2004 (with CoM correction)	FES2004 (w/o CoM correction)
tropospheric mapping fct.	VMF1	VMF1
delay model	IERS 2010	IERS 1992

3 Assessment of Solution dgf2018a

Before DGFI-TUM could contribute *dgf2018a*, the results of DOGS-RI had to be validated. At a first stage, our new software took part in the VLBI Analysis Software Comparison Campaign [4]. Then, an intermediate solution was provided to the Combination Centers (see [5]). Only after the latter was approved, DGFI-TUM started to provide the current, finally official solution.

The intermediate solution had a setup which was slightly different from *dgf2018a*, in particular with respect to the a-priori EOP and TRF. Hence, we re-assessed the quality of our official solution by comparing it to those of some other Analysis Centers. In the following, we will look at EOP, station and quasar coordinates. Several ACs not only provide normal equations in their *daily SINEX* files but also estimates for the geodetic parameters themselves. Hence, we could simply extract the latter from the corresponding files. Our own estimates are not available in SINEX format, but they are available in the local output files of DOGS-RI.

Earth Orientation Parameters

We perform the common test of subtracting the single AC values of an EOP from the corresponding value of the official IERS 14 C04 series. This is done epoch-wise for every available session between January 2005 and March 2018 per Analysis Center, with exceptionally high differences being removed as outliers. Figure 2 shows the time series of differences between the single AC values of the EOP $\Delta UT1(0h) = UT1 - UTC$ and its IERS 14 C04 value.

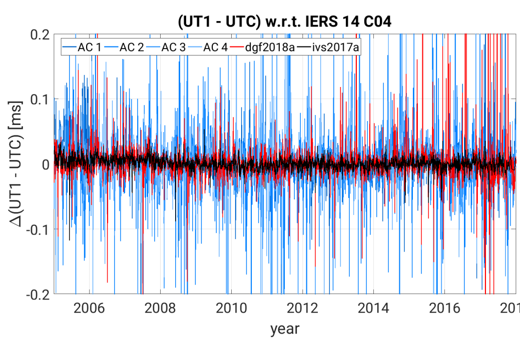

Fig. 2 Time series of the differences between EOP (UT1 – UTC) per AC and the IERS 14 C04 reference value.

ivs2017a is the solution of the IVS Combination Center at *Bundesamt für Kartographie und Geodäsie* (BKG), which provides parameters estimated from a weighted sum of the individual AC's normal equations. As the IERS 14 C04 series is also obtained from a combination of single solutions (see [1]), it can be expected that the deviations will be smallest for *ivs2017a*. The deviations of DOGS-RI, however, have a magnitude similar to those of the other Analysis Centers used in the comparison. This pattern is valid for all EOP, which is also indicated by the weighted means and weighted RMS per EOP and AC as listed in Tables 2 and 3. There, we see that the minimum weighted RMS per EOP is always given by the combined solution *ivs2017a*, and our solution *dgf2018a* stays within the range of the other AC's values, while the weighted means all show comparable magnitudes. (N/A means that the corresponding EOP could not be extracted from the *daily SINEX* files.)

Table 2 Weighted mean for differences to the IERS 14 C04 series. The units for $\Delta UT1$ and LOD are ms and ms/d, respectively. For all the others, they are mas (or mas/d for the rates).

EOP	AC1	AC2	AC3	AC4	dgf2018a	ivs2017a
x_{pol}	0.0574	0.0061	0.0123	-0.0087	-0.0194	0.0030
$\dot{x}_{pol}$	0.0248	0.0258	0.0202	0.0148	0.0283	0.0260
y_{pol}	0.2577	-0.0200	-0.0346	-0.0176	-0.0096	-0.0098
$\dot{y}_{pol}$	0.0133	-0.0003	-0.0000	0.0105	0.0132	0.0073
$\Delta UT1$	0.0020	-0.0004	-0.0013	-0.0052	-0.0023	-0.0008
LOD	-0.0003	-0.0010	-0.0011	0.0020	0.0012	-0.0014
ΔX_{CIP}	n/a	n/a	n/a	0.0234	0.0200	0.0066
ΔY_{CIP}	n/a	n/a	n/a	-0.0069	-0.0047	-0.0076

Table 3 Weighted RMS for differences to the IERS 14 C04 series. The units are the same as in Table 2.

EOP	AC1	AC2	AC3	AC4	dgf2018a	ivs2017a
x_{pol}	0.1652	0.1507	0.1322	0.1558	0.1479	0.0801
$\dot{x}_{pol}$	0.2965	0.2579	0.2732	0.3173	0.2911	0.2320
y_{pol}	0.1939	0.1617	0.1346	0.1765	0.1570	0.0763
$\dot{y}_{pol}$	0.2884	0.2540	0.2685	0.3221	0.2910	0.2307
$\Delta UT1$	0.0154	0.0185	0.0148	0.0164	0.0144	0.0097
LOD	0.0194	0.0173	0.0177	0.0186	0.0189	0.0162
ΔX_{CIP}	n/a	n/a	n/a	0.1680	0.1375	0.0329
ΔY_{CIP}	n/a	n/a	n/a	0.1528	0.1385	0.0358

Station Coordinates

The Cartesian coordinates of the observing stations can be extracted from the Analysis Centers' *daily SINEX* files, too (except for the combined solution *ivs2017a*). We transformed the global (x, y, z) coordinates into local Cartesian ones (North, East, Up) and compared the absolute values directly instead of computing differences to some reference frame. Figure 3 exemplarily shows the time series of the local coordinates for the radio telescope in Ny-Ålesund (NYALES20), again for different ACs and the available VLBI sessions between January 2005 and March 2018. The coordinates estimated by DOGS-RI are in line with those of the other ACs, which generally agree well except for the vertical (Up) component. To highlight the differences in the latter, we apply a linear fit to each time series and plot the corresponding functions (confined to the most recent years) in Figure 4. The spread in the vertical component is mainly created by

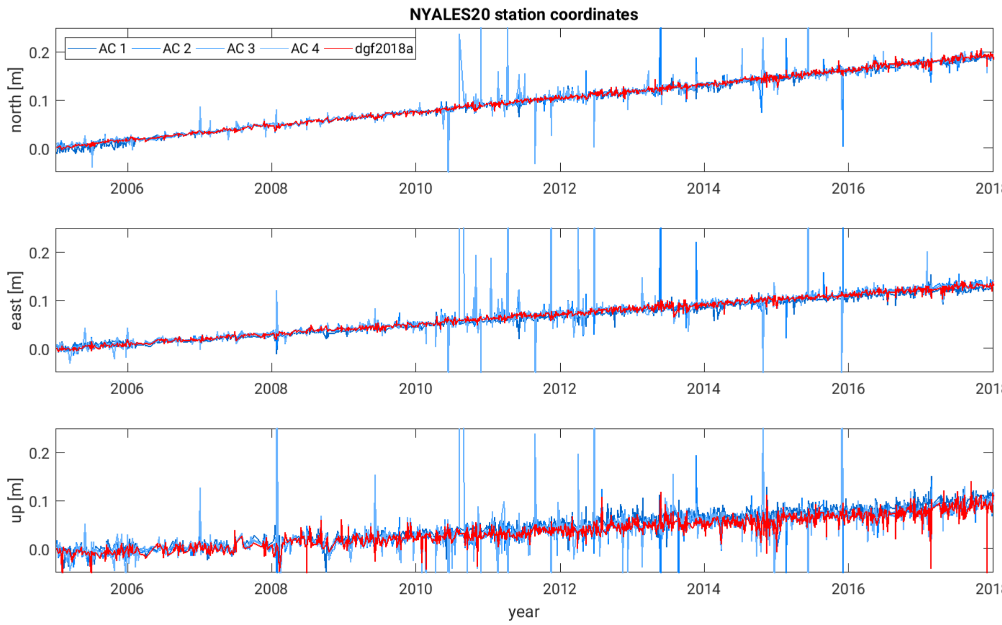

Fig. 3 Local Cartesian coordinates of the VLBI station in Ny-Ålesund per Analysis Center.

the solution of one of the other Analysis Centers, while DGFI-TUM's solution *dgf2018a* matches the results of the remaining ones. We found a similar behavior for other VLBI stations as well.

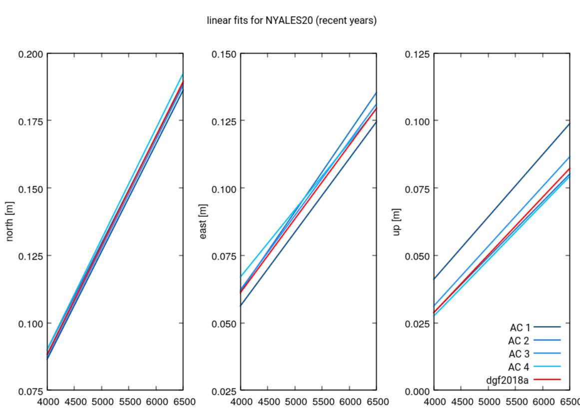

Fig. 4 Linear fit to the local (NEU) coordinates for Ny-Ålesund.

Quasar Coordinates

Finally, we compare the positions estimated for the radio sources in terms of right ascension and declination. These could again be directly extracted from the *daily SINEX* files, at least for most of the Analysis Centers. As an example, Figure 5 shows the time series for the ICRF2 defining source *3C446*. Also for this type of geodetic parameter, the results of DOGS-RI are in line with those of the other VLBI analysis softwares.

4 Ongoing Development

DOGS-RI is permanently updated and extended to incorporate the recent developments in VLBI. The most important modification currently is the inclusion of the new *vgosDB* format. Apart from minor issues and final tests, DOGS-RI is basically able to cope with vgosDB. Further projects for the future are, for example, an automatic detection of jumps in station clocks and a more advanced outlier identification routine.

5 Conclusions

dgf2018a is DGFI-TUM's new official contribution of normal equations to the IVS for estimating geodetic parameters from VLBI experiments. It is now generated with the VLBI analysis tool DOGS-RI, which is part

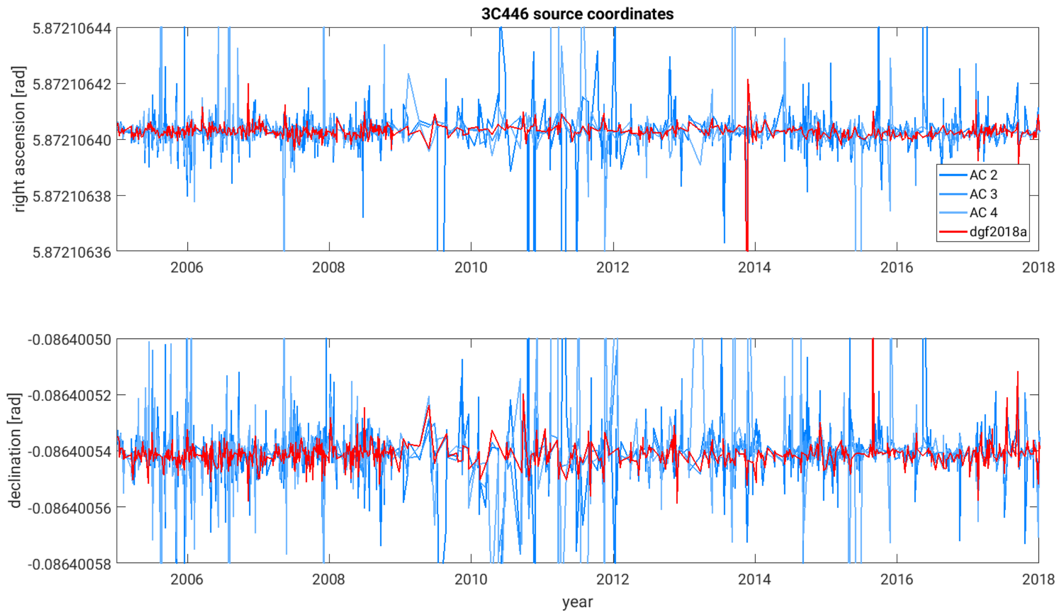

Fig. 5 Coordinates of ICRF2 defining source 3C446 as estimated by different Analysis Centers.

of our proprietary software package DOGS. The latter makes use of the most recent IERS Conventions, and it could be shown in numerous tests that its solutions agree well with those of other IVS Analysis Centers. The vgosDB format will soon be supported.

Acknowledgements

We acknowledge the efforts of the various members of the IVS [6] (here in particular the Analysis Centers and the Combination Center at BKG) for generating and sharing their data, hence enabling us to compare and verify our solutions.

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