BKG/IGGB VLBI Analysis Center

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Abstract In 2015 and 2016, the activities of the BKG/IGGB VLBI Analysis Center, as in previous years, consisted of routine computations of Earth orientation parameter (EOP) time series and of a number of research topics in geodetic VLBI. The VLBI group at BKG continued its regular submissions of time series of tropospheric parameters and the generation of daily SINEX (Solution INdependent EXchange format) files. Additionally a second series of daily SINEX files was generated with estimated source positions for all sources in each session. Quarterly updated solutions were computed to produce terrestrial reference frame (TRF) and celestial reference frame (CRF) realizations. The analysis of all *Intensive* sessions for UT1–UTC estimation was continued. All solutions are based on the Calc/Solve software, release 2014.02.21 [14], following the IERS2010 conventions. At IGGB, the emphasis was placed on individual research topics.

1 General Information

The BKG/IGGB VLBI Analysis Center was established jointly by the analysis groups of the Federal Agency for Cartography and Geodesy (BKG), Leipzig, and the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB). Both institutions cooperate intensely in the field of geodetic VLBI. The responsibilities include both data analysis for generating IVS products and special investigations with the goal of increasing accuracy and reliability. BKG is responsible for the computation of time series of EOP and tropospheric parameters, for the generation of SINEX files for 24-hour VLBI sessions and one-hour *Intensive* sessions, and for the generation of quarterly updated global solutions for TRF and CRF realizations. Besides data analysis, the BKG group is also responsible for writing schedules for the Int2 UT1-UTC observing sessions. Details of the research topics of IGGB are listed in Section 3.

1. BKG
2. IGGB

BKG/IGGB Analysis Center

IVS 2015+2016 Biennial Report

2 Data Analysis at BKG

At BKG, the Mark 5 VLBI data analysis software system Calc/Solve, release 2014.02.21 [14], was used for VLBI data processing. It is running on a Linux operating system. Simultaneously first tests with the newly developed geodetic VLBI software νSolve, a replacement of the interactive mode of Solve, have been realized. Calc/Solve allows the generation of so-called tropospheric path delay (TRP) files derived from the Vienna Mapping Function (VMF1) data. They contain external information about the troposphere on a scan-by-scan basis, specifically the a priori delay, dry and wet mapping functions, and gradient mapping functions. The BKG VLBI group uses TRP files to input data related to VMF1. The VMF1 data were downloaded daily from the server of the Vienna University of Technology. Additionally, the technological software environment for Calc/Solve was refined to link the Data Center management with the pre- and post-interactive parts of the EOP series production and to monitor all Analysis and Data Center activities.

- **Processing of correlator output**
  The BKG group continued the generation of calibrated databases for the sessions correlated at the Max Planck Institute for Radio Astronomy (MPIfR)/BKG Astro/Geo Correlator at Bonn (e.g., EURO, OHIG, and T2) and submitted them to the IVS Data Centers.
- **Scheduling**
  In cooperation with IGGB, BKG continued scheduling the Int2 *Intensive* sessions, which are observed on the TSUKUBA—WETTZELL baseline. Altogether, 204 schedule files for this baseline were created in 2015 and 2016. Due to the planned shutdown of the TSUKUBA antenna in 2017, the first schedule files for the ISHIOKA—WETTZELL baseline were also made available at the end of 2016.
- **BKG EOP time series**
  The BKG EOP time series bkg00014 was continued. The main features of this solution were not changed. But the station coordinates of the VLBI site HART15M in South Africa were estimated as global parameters because of an observation period of more than three years. Further, three new VLBI stations (ISHIOKA in Japan, RAEGYEB in Spain, and WETTZ13N in Germany) could be included successfully in data processing.
  Each time after the preprocessing of any new VLBI session (correlator output database version 1), a new global solution with 24-hour sessions since 1984 was computed, and the EOP time series bkg00014 was extracted. Altogether, 5,149 sessions were processed. The main parameter types in this solution were globally estimated station coordinates and velocities together with radio source positions. The datum definition was realized by applying no-net-rotation and no-net-translation conditions for 25 selected station positions and velocities with respect to VTRF2008a and a no-net-rotation condition for 295 defining sources with respect to ICRF2. The station coordinates of the telescopes AIRA (Japan), CHICHI10 (Japan), CTVASTJ (Canada), DSS13 (USA), ISHIOKA (Japan), KASHIM11 (Japan), KASHIM34 (Japan), KOGANEI (Japan), KUNMING (China), PT_REYES (USA), RAEGYEB (Spain), SEJONG (Korea), SEST (Chile), SINTOTU3 (Japan), TIANMA65 (China), TIDBIN64 (Australia), TIGOCONC (Chile), TSUKUB32 (Japan), UCHINOUR (Japan), VERAISGK (Japan), VERAMZSW (Japan), WETTZ13N (Germany), WIDE85_3 (USA), and YEBES40M (Spain) were estimated as local parameters in each session.
- **BKG UT1 *Intensive* time series**
  Regular analysis of the UT1-UTC *Intensive* time series bkgint14 was continued. The series bkgint14 was generated with fixed TRF (VTRF2008a) and fixed ICRF2. The a priori EOP were taken from final USNO series [16]. The estimated parameter types were only UT1-TAI, station clock, and zenith troposphere.
  The algorithms of the semi-automatic process for handling the *Intensive* sessions Int2/3 with station TSUKUBA after the Japan earthquake [3] were further used but refined by a newly developed extrapolation method; i.e., before the regular analysis can be started, the most probable station positions of TSUKUBA for the epochs of the Int2/3 sessions have to be estimated.
  A total of 5,722 UT1 *Intensive* sessions were analyzed for the period from 1999.01.01 to 2016.12.31.
- **Quarterly updated solutions for submission to IVS**
  In 2015 and 2016, quarterly updated solutions were computed for the IVS products TRF and CRF. There were no differences in the solution strategy compared to the continuously computed EOP time series bkg00014. The results of the radio source positions were submitted to IVS in IERS format. The TRF solution is available in SINEX format, version 2.1, and includes station coordinates, station velocities, and radio source coordinates together with the covariance matrix, information about constraints, and the decomposed normal matrix and vector.
- **Tropospheric parameters**
  The VLBI group of BKG continued regular submissions of long time series of tropospheric parameters to the IVS (wet and total zenith delays and horizontal gradients) for all VLBI sessions since 1984. The tropospheric parameters were extracted from the standard global solution bkg00014 and transformed into SINEX format.
- **Daily SINEX files**
  The VLBI group of BKG also continued regular submissions of daily SINEX files for all available 24-hour sessions for the IVS combined products

and for the IVS time series of baseline lengths. In addition to the global solutions, independent session solutions (bkg2014a) were computed for the station coordinates, radio source coordinates except for 295 defining sources of ICRF2, and EOP parameters including the X,Y-nutation parameters. The a priori datum for TRF was defined by the VTRF2008a, and ICRF2 was used for the a priori CRF information. A second series of daily SINEX files was generated with estimated source positions for all sources in each session as a basis for working on a combination procedure for CRF determination.

- **SINEX files for *Intensive* sessions**
  The generation of SINEX files for all *Intensive* sessions (bkg2014a) since 1999 was continued in 2015 and 2016. The parameter types are station coordinates, pole coordinates and their rates, and UT1-TAI and its rate. But only the normal equations stored in the SINEX files are important for further intra-technique combination or combination with other space geodetic techniques.

3 Research Topics at IGGB

- **ivg::ASCOT: Developement of a new VLBI software package**
  The VLBI group of IGGB started implementing a new analysis toolbox for VLBI observations. The main reason is the need for a flexible environment, which allows for straightforward implementations of new scientific and software-related ideas for VLBI data analysis. Furthermore, we wanted to accumulate the developments, which have been performed in Bonn in recent years, under a unified software package. The software is implemented in C++ and will finally be able to perform scheduling of VLBI sessions and simulation of VLBI observations, as well as geodetic data analysis and intra-technique combination. Thus, it is named: IGG VLBI Group – Analysis, Scheduling and Combination Toolbox (ivg::ASCOT, [1]). Currently, we are able to perform single-session data analysis from a stage where the ambiguities were resolved. For Intensive sessions we are already able to solve the ambiguities automatically. Furthermore, global solutions to derive celestial and terrestrial reference frames can be performed on the normal equation level. Intra-technique combinations of several solutions complete the initial functionality of the software package. Since the end of 2016, we have been able to generate schedules for Intensive sessions and small networks following different approaches for the selection of the next optimal source.
  Further information on ivg::ASCOT can be found at `http://ascot.geod.uni-bonn.de/`.

Fig. 1 Logo of the VLBI analysis software package ivg::ASCOT (IGG VLBI Group - Analysis, Scheduling and Combination Toolbox).

- **ivg::ASCOT: Scheduling and simulation**
  Within our newly developed software package we are able to schedule and simulate VLBI sessions. Our efforts here primarily concentrate on *Intensive* sessions with two or three telescopes and observing durations of only one hour. This is used in cooperation with BKG, and it will be used in 2017 to generate INT2 schedules. Here we focus on the approach of the automatic scheduling method based on the so-called impact factors [11]. This approach has been originally developed within a stand-alone software and is now successfully implemented in ivg::ASCOT. This transfer is also a consequence of the changeover from TSUKUBA-WETTZELL to ISHIOKA-WETTZELL and some issues within the legacy stand-alone scheduling program.
- **ivg::ASCOT: Using the intra-technique combination for CRF determination**
  Currently the third realization of the internationally adopted Celestial Reference Frame (CRF), the ICRF3, is under preparation. In this process, various optimizations are planned to realize a CRF. The new ICRF can benefit from an intra-technique combination as it is also done for the Terrestrial Reference Frame (TRF).
  Here, we aimed at estimating an optimized CRF by means of an intra-technique combination. The solu-

tions are based on the input to the official combined product of the IVS, also providing the radio source parameters. For this purpose, different strategies to improve the combined CRF were investigated and implemented in ivg::ASCOT.

- **ivg::ASCOT: Alternative estimation procedures for atmospheric parameters**
  Although the propagation delay due to the neutral atmosphere is referred to as a perturbation effect in the geodetic community, atmospheric refraction parameters become more and more important for other disciplines because the zenith wet delay (ZWD) estimates can be directly linked to the water vapor content in the atmosphere. However, the traditional model for the atmospheric delays sometimes leads to negative ZWD estimates, which, of course, do not reflect physical or meteorological conditions. To cope with this issue, an Inequality Constrained Least Squares (ICLS) adjustment from the field of convex optimization is used to force the ZWD estimates to non-negative values. Because deficiencies in the a priori hydrostatic modeling are almost fully compensated by the ZWD estimates, the ICLS urgently requires suitable a priori delays. Thus, different strategies to improve the a priori information have been investigated, and the impact of mis-modeling the a priori delay on station positions is shown in [6]. In general, the use of inequality constraints allows more suitable zenith wet delays in a meteorological sense and is possible without disturbing the VLBI target parameters. However, further investigations are necessary to validate other "dirt" effects which are compensated by the atmospheric delay estimates [6].
- **ivg::ASCOT: Modifying the stochastic model of VLBI observations**
  Microscale refractivity variations in the neutral atmosphere lead to elevation-dependent uncertainties and induce physical correlations between VLBI observations. Traditionally, such correlations are not considered in the stochastic model of VLBI observations, which leads to very optimistic standard deviations of the derived target parameters. Thus, a modified stochastic model based on a turbulence model was introduced to describe the dynamics in the atmosphere. One of the main objectives is to realize a suitable stochastic model, which can be used in an operational way. Up to now, it was shown that the new stochastic model leads to far more realistic standard deviations, and, further, the baseline length repeatabilities improve for a turbulence-based solution, particularly for specially designed local VLBI networks [5].
- **Observing the Chang'E-3 Lander with VLBI**
  In December 2013, a landing module was deployed on the Moon by China National Space Administration. In a project called OCEL (Observing the Chang'E-3 Lander with VLBI), a series of twelve observing sessions (four each in 2014, 2015, and 2016) was carried out with the IVS observing network. Part of the observing schedule was designed to observe the lander signal, which consists of five DOR (Differential One-way Ranging) tones. Fringe fitting and group delay determination are a particular challenge due to the fact that a new geodetic fringe fitting scheme needs to be developed to take care of narrow DOR tone spikes in a standard channel bandwidth of 4 or 8 MHz [7].
  At the same time multiple other activities are centered around the lunar observations concerning, for example, the near-field VLBI model and the parameter estimation module in ivg::ASCOT. In this context, the First International Workshop on VLBI Observations of Near-field Targets was held at the Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany, on October 5—6, 2016 (`http://www3.mpifr-bonn.mpg.de/div/meetings/vonft/index.html`).
- **Studies on VLBI observations of Earth satellites**
  VLBI observations of Earth satellites are becoming important for geodesy in order to tie the terrestrial reference frame (TRF) to the celestial reference frame (CRF). However, VLBI observations of near-field targets are different from regular quasar observations in many respects, one major difference being that VLBI observations of near-field targets require special VLBI delay models, because the curvature of the observed wavefronts cannot be neglected as in the usual case of extragalactic radio sources (see [15]). We implemented two near-field VLBI delay models from the literature [12, 2] into the VLBI analysis software ivg::ASCOT. We tested our implementations by investigating the difference between the observed group delays and the computed VLBI delays, a quantity which is essential for further parameter estimation. Results for the VLBI observation of GPS satellites [8, 13] can be found in [10] and for the lunar lander Chang'E-3 in [4].

We are currently working on the development of a geometrical VLBI delay model optimized for Earth satellites. As a first application we are estimating the position of the lunar lander Chang'E-3 on the Moon.

- **Deformation measurements at radio telescopes**
  Another ongoing project is related to deformation measurements at radio telescopes. In November 2015, we visited the Onsala Space Observatory in Sweden and scanned the main reflector of the 20-m telescope with a terrestrial laser scanner (TLS). Difficulties arise from the fact that the surface is extremely accurate, almost like an optical mirror. As a consequence, the intensity of the reflections is extreme where the laser hits the surface perpendicularly, leading to inaccurate distance components of the TLS results. Nevertheless, some first results indicate that the focal length changes by close to 9 mm when tilting the telescope from zenith to 5 degrees elevation.

4 Personnel

Table 1 Personnel at the BKG/IGGB Analysis Center. The international code for all numbers is +49.

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