

ivg::ASCOT: Development of a New VLBI Software Package

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Abstract The VLBI group of the Institute of Geodesy and Geoinformation of the University of Bonn (IGG) has 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 want 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 should 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). Currently, we are able to perform single-session data analysis, at the stage when the ambiguities have been resolved. 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.

Keywords VLBI, C++, software package, scheduling, geodetic VLBI data analysis, intra-technique combination

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1 Introduction

There are several VLBI analysis packages that are used in the VLBI community. However, there are quite good reasons to start developing your own software. At the Institute of Geodesy and Geoinformation (IGG) of the University of Bonn, the main goal is to have a flexible and expandable environment at hand to easily develop new scientific projects. This is hardly the case for contemporary packages due to internal structures or the dependence on proprietary libraries or programs. Thus, the IGG VLBI Group (ivg) started the development of the Analysis, Scheduling and Combination Toolbox (ivg::ASCOT) in December 2014. The programming language is C++, and for the graphical user interface Qt¹ is used. The major goal is to merge the code from the PhD theses prepared at our institute in recent years into one consistent environment.

Currently, a basic VLBI least-squares adjustment in a session-by-session mode is possible. Furthermore, a global solution of pre-processed and pre-reduced datum-free normal equations in Solution INdependent EXchange (SINEX) format² can be performed. With very similar functionality, combinations on the normal equation level can be carried out.

The theoretical modeling of the VLBI delay is currently being validated in the VLBI Analysis Software Comparison Campaign 2015 (VASCC2015, [11]). In this way, we can directly ensure the correctness of our implementation w.r.t. other widely-spread VLBI data analysis software packages.

¹ <http://www.qt.io/>

² <http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html>

2 Structure of the Toolkit

The implementation relies on a variety of external code written in different languages. The basis of the theoretical modeling is the Conventions of the International Earth Rotation and Reference Systems Service (IERS Conventions, [14]). The IERS FORTRAN routines³ are compiled into a library and directly linked within `ivg::ASCOT`. This allows convention updates to be easily and directly adopted as the code on the IERS Web site is updated as well.

Furthermore, the SOFA library⁴ is used for the Earth orientation modeling. The JPL ephemeris is accessed via the CSPICE toolkit⁵ or code from Project-Pluto⁶. For the numerical calculations, we make use of ATLAS⁷/LAPACK⁸ or openBLAS⁹.

The basic internal library incorporating most of the functionality is `libivg`. Here, several classes are compiled which represent, e.g., the sessions with scans and observations, as well as the parameters. Furthermore, classes for the Earth Orientation Parameter (EOP) series as well as the terrestrial and celestial reference frames exist, which are made of stations and sources. Finally, the fundamental classes for the parameter adjustment are included in `libivg`.

In addition, there are different libraries for post-analysis tools (`libAnalysisTools` and `libqtplot`). The library `libAnalysisTools` contains classes to analyze station and source position variations; e.g., baseline length repeatabilities can be calculated. Furthermore, transformations between different reference frame realizations can be performed or estimated. In addition, the library `libqtplot` provides an easily accessible plotting environment as well as a graphical user interface (GUI) for various purposes. Thus, the functionality and the presentation of the results are strictly separated.

³ <http://62.161.69.131/iers/convupdt/convupdt.html>

⁴ <http://www.iausofa.org/>

⁵ <http://naif.jpl.nasa.gov/naif/>

⁶ http://www.projectpluto.com/jpl_eph.htm

⁷ <http://math-atlas.sourceforge.net/>

⁸ <http://www.netlib.org/lapack/>

⁹ <http://www.openblas.net/>

3 Single Session Analysis

The single session data analysis is based on VLBI observations given in the `vgosDB` data format [5] or in NGS card files¹⁰. Currently, an analysis can only be performed if the group delay ambiguities are resolved, the ionospheric corrections are calculated, and clock breaks are earmarked.

In an independent solution, a priori station motions are calculated based on the recommendations of the IERS Conventions, and further variations; e.g., non-tidal atmospheric pressure loading [15] or hydrological loading¹¹ could be applied. The theoretical delay including the relativistic corrections are implemented according to the IERS Conventions 2010 [14]. The EOPs can be used in a format according to the IERS C04 series¹² or USNO finals¹³. For the EOP modeling, additionally subdaily variations are taken into account according to the IERS Conventions 2010.

The parameter adjustment is currently solely based on the classical weighted least-squares adjustment. For the parameterization, a polynomial representation of arbitrary degree and/or continuous piece-wise linear functions with arbitrary interval length can be used. The continuous piece-wise linear functions are always referenced to the epoch of the first observation. The following parameters are currently supported:

- clocks,
- zenith wet delays,
- tropospheric gradients,
- station positions,
- source positions, and
- EOPs.

The weights of the observations are based on the standard deviations which result from the fringe fitting process. However, a stochastic refinement can be performed by applying constant and elevation weights [6] or an additional covariance matrix based on turbulence theory [7]. Finally, a simple data snooping procedure based on a Baarda test [3] can be applied to eliminate outliers.

¹⁰ http://lacerta.gsfc.nasa.gov/mk5/help/dbngs_format.txt

¹¹ <http://lacerta.gsfc.nasa.gov/hydro/>

¹² <http://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html>

¹³ <http://maia.usno.navy.mil/ser7/finals.daily>

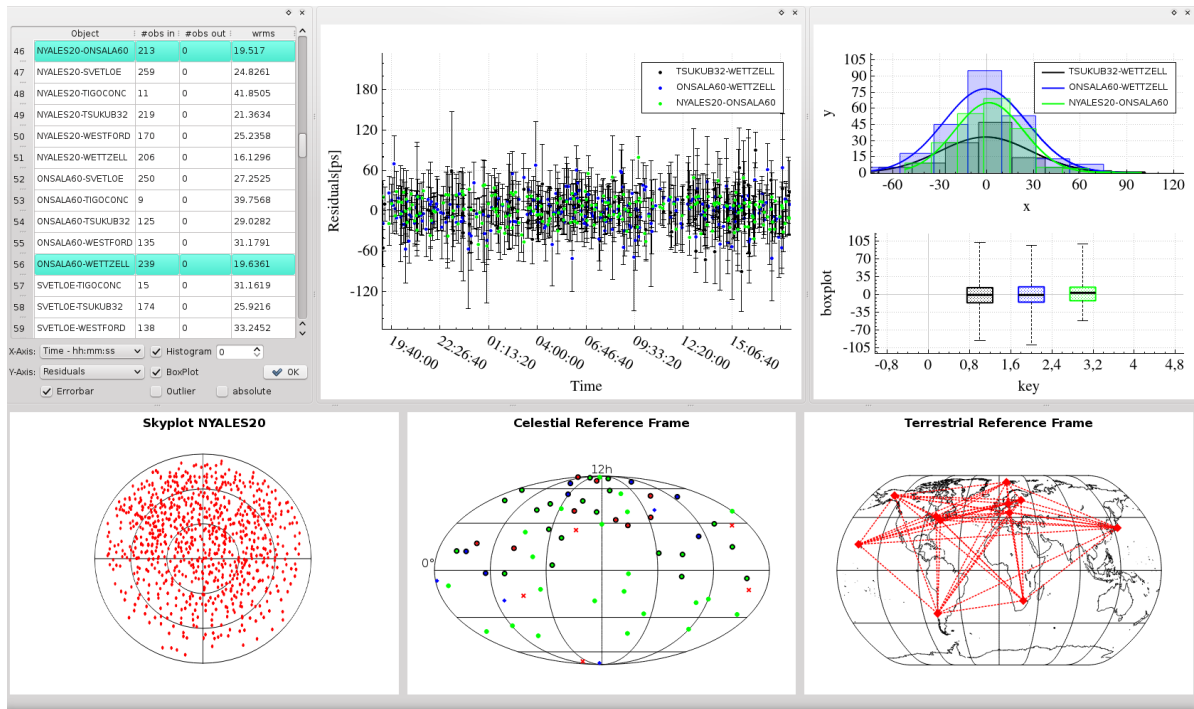


Fig. 1 Window of the residuals plot from a single session analysis including list of stations, baselines, and sources with WRMS of residuals, residual plot, statistical analysis, skyplot, observed sources, and network geometry.

The output of a single session analysis is either datum free normal equations or solutions with covariance matrices in SINEX format. Furthermore, a GUI exists where the residuals can be plotted (see Figure 1) depending on sites, baselines, or sources, and a statistical analysis of the residuals can be performed, e.g., by creating histograms and box plots.

4 Global Solution and Combination

Global solutions are based on pre-processed datum-free normal equations in SINEX format from single-session analysis. Through this functionality, it is also possible to use solutions from other software packages such as regular contributions to the official combined product of the International VLBI Service for Geodesy and Astrometry (IVS, [16]).

It is possible to reduce nuisance parameters and to perform transformations of a priori values. Furthermore, the global solution allows for various manipulations of normal equations such as transformations and

stacking [1]. This would make it possible to easily set up new parameters which are based on original ones such as, e.g., station velocities based on station positions. However, this feature is not implemented at this stage of the development.

Furthermore, session-by-session combination on the normal equation [4] or on the solution level [8] is possible. The major shortcoming at this point of the development is the absence of a reliable weighting procedure for different contributions.

The output of a global solution is again a SINEX file containing the estimates and the corresponding covariance matrix. But, it is also possible to export the stacked datum free normal equations prior to the solution.

5 Analysis Tools

A major feature of ivg::ASCOT is the post-analysis tools, which are based on solutions in SINEX files (see Figure 2). In a GUI, one can select the solutions

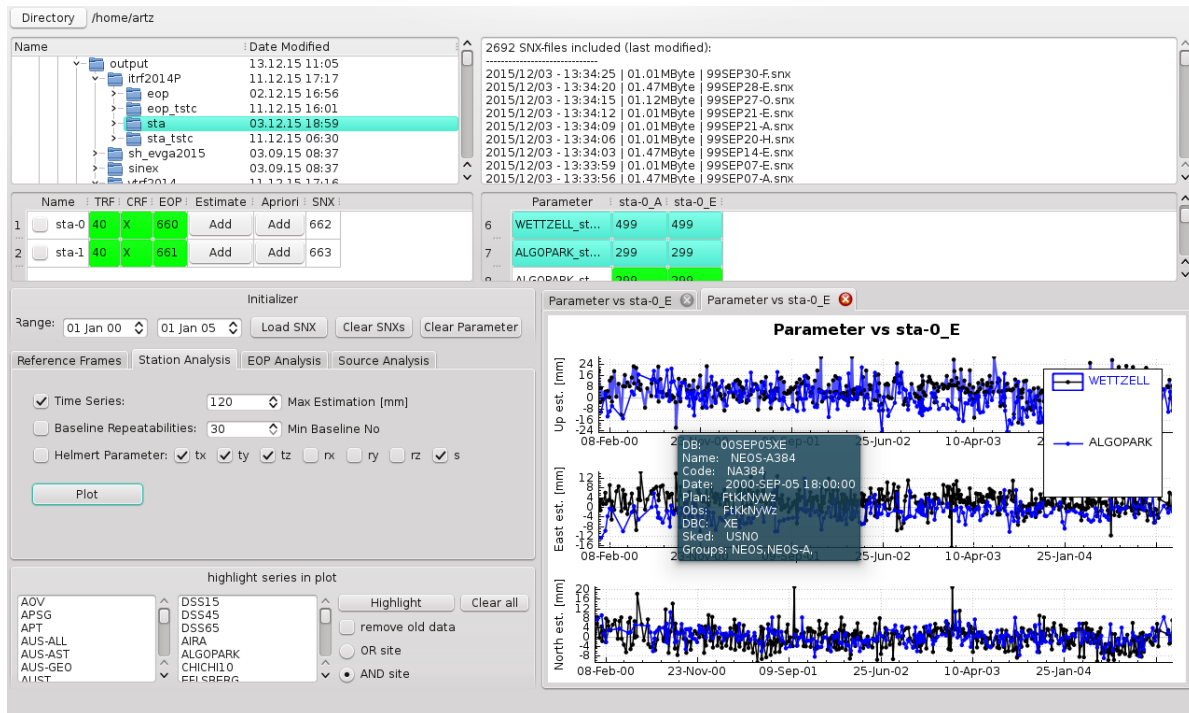


Fig. 2 Post data analysis GUI.

and perform a visualization of time series (stations, sources, and EOPs). Furthermore, a filtering of these time series can be performed based on various criteria, e.g. the session type or individual observing stations. In addition, it is possible to plot terrestrial and celestial reference frames, estimate Helmert parameters between different realizations, and visualize residuals after applying transformations.

6 Scheduling Module

The scheduling is currently not included in `ivg::ASCOT`. However, the implementation is basically based on the fundamental libraries of `ivg::ASCOT`.

The philosophy of the scheduling approach is the analysis of impact factors [12] to realize a geometrical optimization based on the parameters to be estimated. For Intensive sessions, the procedure is already used on a routine basis [13].

The input for the scheduling module is SKED catalogs¹⁴. The output is saved in `skd`-file format.

Porting the scheduling module into the toolbox is planned for the future.

7 Simulation Module

The simulation part is currently based on the `vgosDB` data format. The simulated delays consist of a deterministic part, according to the theoretical modeling of a single session analysis, and three stochastic components. These are simulated as baseline dependent noise, clock variations by power-law processes [9], and troposphere noise based on turbulence theory [10]. The variances for these processes can be chosen individually. The simulation was described in [2].

¹⁴ <ftp://gemini.gsfc.nasa.gov/pub/sked/catalogs/>

8 Conclusion and Future Work

The implementation of ivg::ASCOT is done in C++ and is thus highly flexible and expandable. Furthermore, using the Qt-library allows for a very intuitive and easy way to create graphical user interfaces. At the present stage of the development, typical VLBI parameters can be estimated in an independent solution, and basic time series analysis can be performed on residuals and estimates. Furthermore, global solutions can be used to estimate celestial and terrestrial reference frames, and even a combination of various analysis centers' input is possible.

Although not yet integrated, the scheduling part is based on the ivg::ASCOT libraries. This standalone scheduling program is currently used to schedule the INT2 sessions. However, porting the scheduling module into the toolbox is planned for the future.

Further developments will be primarily based on themes of PhD theses. Besides these scientific goals, it is planned to start the single session analysis at an earlier stage as is the case now. Thus, we will start with resolving ambiguities and calculating ionospheric corrections. Furthermore, the post-analysis tools will be enhanced, e.g., by implementing more thorough time series analysis.

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