Vienna Combination Software - VieCompy

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Abstract The Vienna Center for VLBI (Very Long Baseline Interferometry) presents a new state-of-the-art combination software called *VieCompy* written in Python. *VieCompy* is a stand-alone tool of the Vienna VLBI and Satellite Software (*VieVS*) and can be used to estimate global parameters, such as terrestrial and celestial reference frames based on normal equations. Currently, solely VLBI-only solutions can be derived, but we plan on continuously expanding the functionalities of *VieCompy*. In this work, the general concept of the software is presented and further development is discussed. The software will be made freely available in the future.

Keywords Global solution, *VieVS*, *VieCompy* software

1 Introduction

In general, there are few software packages which have been developed specifically for the combination of different space geodetic techniques, e.g., *CatRef*[1], developed at the Institut Géographique National (IGN) (Altamimi et al., 2002), *DOGS-CS*[2], developed at DGFI-TUM (Deutsches Geodätisches Forschungsinstitut) (Gerstl et al., 2004) and *KALREF*[3], developed at the Jet Propulsion Laboratory (JPL) (Abbondanza et al., 2017). With these software packages, it is possible to derive catalogs of station coordinates and velocities from a combination of all space-geodetic techniques, including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

Single-technique analysis programs provide the input to these inter-technique combination packages via solution independent exchange (SINEX) files. In the case of VLBI, beyond many others, *nuSolve*, developed at the NASA Goddard Space Flight Center (Bolotin et al., 2014) and *VieVS*[4], developed at the Vienna Center for VLBI (Very Long Baseline Interferometry) (Böhm et al., 2018) exist for this purpose. Besides the possibility of providing single-session solutions, some VLBI packages, such as the submodule *vie_glob* within *VieVS*, are capable of generating multi-session/global solutions to derive global parameters based on datum-free and unconstrained normal equation (NEQ) systems.

Standard geodetic VLBI sessions last 24 hours and are observed by subsets of a global network of antennas. By combining thousands of these sessions in a global least squares adjustment, very precise terrestrial reference frames (TRF) with catalogs of coordinates and their velocities, as well as celestial reference frames (CRF) with catalogs of source positions, can be determined. For this purpose, the NEQs of the respective sessions are stacked. By an inversion of the resulting global NEQ, the global parameters are determined. As already mentioned, thousands of VLBI sessions are combined in the process of determining a global reference frame, e.g., over 6700 sessions consisting of ap-

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[1] Combination and Analysis of Terrestrial Reference Frame

[2] DGFI Orbit and Geodetic parameter estimation Software - Combination and Solution

[3] Kalman filter for Terrestrial Reference Frame determination

[4] Vienna VLBI and Satellite Software

proximately 20 million observations are combined in the VIE2022 solution (Krásná et al., 2023).

Despite *vie_glob* being a well-developed tool, this module is part of the *VieVS* software and cannot be used independently, nor can it be easily extended to include other techniques. Therefore, at the Vienna Center for VLBI, we are currently working on a new state-of-the-art and stand-alone combination software, called *VieCompy*, which is currently capable of deriving a VLBI-only solution based on datum-free and unconstrained NEQ from SINEX files. This modern and flexible software package will enable computing inter-technique solutions in the future.

In the following, the concept and most essential functionalities of *VieCompy* are explained (Section 2). In Section 3 the current performance of the software is presented and in Section 4 further developments and ideas are discussed.

2 Concept

VieCompy is written in Python and is a stand-alone software under the umbrella of the chain of *VieVS* developments (Böhm et al., 2018). It can be operated by a text control file or by a modern graphical user interface (GUI) generated using the PyQt5 library. Both invoke the corresponding Python script and control, beyond other details, the input data and the parameterization of the global adjustment.

Fig. 1 *VieCompy* logo

The input are standard SINEX files, which contain unconstrained and datum-free NEQ. The software currently works for SINEX files of version 2.02 (IERS, 2006). First, information on all sessions is collected, leading to a high data volume and memory usage. The bookkeeping is of great importance so that it is known which elements are stored within the NEQ and where. For this purpose, Pandas DataFrames are used and provided with multiple indices (MultiIndex), stating the type of parameter and the reference epoch. In the next step, additional information can be added to the individual NEQ systems by expanding the NEQ by the corresponding rows and columns. This makes it possible to estimate so far unaccounted-for parameters, such as station or source velocities. The NEQ systems are reduced in the next step to decrease the high data volume. Therefore, based on the user input, parameters can be fixed, reduced or estimated. In the case of fixing parameters, the corresponding rows and columns are simply removed from all NEQ systems. By reducing parameters, in comparison to fixing parameters, the parameters can be implicitly estimated in a so-called backward solution. In the process of reduction, the NEQ is divided into two parts, global parameters (1) and reduced parameters (2) and special restitution equations (see Equation 1, Bloßfeld (2015)) are performed for every session i. Typically reduced parameters depend on a finite amount of time and do not profit from longer observing periods, e.g., clock parameters, zenith wet delays or tropospheric gradient parameters. By default, clock parameters are not included in standard SINEX files but may be of interest in the future.

$$\begin{aligned} N_r^i &= N_{11} - N_{12}N_{22}^{-1}N_{21} \\ b_r^i &= b_1 - N_{12}N_{22}^{-1}b_2 \end{aligned} \tag{1}$$

The remaining parameters are the global parameters that are considered constant over several sessions, today mainly source positions as well as station coordinates and their velocities. Subsequently, the reduced NEQ systems are merged into one global NEQ system. This process is called *stacking* or *Helmert blocking* (Helmert, 1872) and it describes the summation of common parameters (see Equation 2, with N being the number of sessions). Since, as mentioned earlier, Pandas MultiIndex DataFrames are used, it is ensured that when stacking, common parameters are added up correctly.

$$N = \sum_{i=1}^{N} N_r^i, \qquad b = \sum_{i=1}^{b} b_r^i \tag{2}$$

Before the solution can be utilized, exterior information about the parameters is necessary. Since VLBI observations are relative and, therefore, do not provide an absolute position or orientation, constraints concerning the geodetic datum must be applied to remedy the rank defect (Brockmann, 1997), making the NEQ invertible and, therefore, solvable.

In general, there are different methods of introducing a geodetic datum in VLBI analysis, including

- *Helmert rendering*, where constraints are forced to be fulfilled and
- *no-net-translation/no-net-rotation* (NNT/NNR) approaches, where formal errors for the constraints can be introduced.

For more details on the possibilities of datum definition and scaling, see Kern et al. (2023a,b,c,d). In *VieCompy*, the user can select between the different methods of datum definition and scaling and can define the formal errors in the NNT/NNR approach.

The most important step in the processing is the final inversion of this global NEQ system, which results in the determination of the global parameters (see Equation 3) and their variance information (see Equation 4, with s_0^2 being the a posterior variance of unit weight and C_{xx} the resulting covariance matrix).

$$x = N^{-1}b \tag{3}$$

$$C_{xx} = s_0^2 \cdot N^{-1} \tag{4}$$

As a standard, the software currently provides catalogs of station positions and velocities (TRF), source positions and, if selected, velocities (CRF). Estimates of session-wise reduced parameters, e.g., EOPs and tropospheric parameters, can be generated if the coefficients are carried over in the SINEX files and a backward solution is wanted. Furthermore, a set of plots showing the kinematics of stations and sources as well as the corresponding networks is provided.

3 Performance and validation

As mentioned before, thousands of VLBI sessions are typically combined in a global least squares adjustment making the matrices to be handled very numerous. Consequently, the process is computationally and memory expensive. For this reason, parallel computing was implemented in the following processing steps to improve the performance of *VieCompy*:

- reading of SINEX files,
- expansion of NEQ,
- application of constraints of parameters,
- reduction of NEQ,
- performing backward solutions.

Within *VieCompy*, the parallel processing is handled in a way that n processes are started, which are executed simultaneously. n represents the number of available logical cores on the executing device. This is applied to all of the steps listed above. The improvement in performance is dependent on the device's hardware. However, it can be said that the introduction of parallel computing has drastically reduced the processing time.

Besides that, since we plan to offer quarterly solutions soon, it is possible to save the stacked NEQ system from a previous solution and process and add only new NEQ information in the new solution. In this case, so-called pickle files are used to serialize the NEQ systems and thus reducing the computing time.

The results of *VieCompy* are validated by comparison with vie_glob. As already mentioned, in comparison to vie_glob, *VieCompy* is an independent program based on the NEQ of SINEX files and, therefore, not strictly coupled to a specific analysis package. Furthermore, performance optimization is a key element of *VieCompy* while its modular structure makes it easily extendable. In addition, many tests have already been implemented using the *pytest* framework to check the software and its individual functionalities automatically. This makes *VieCompy* a modern and flexible software package for the determination of global solutions.

4 Future plans

VieCompy is a software that is still under development. Currently, it can combine VLBI sessions for the determination of terrestrial and celestial reference frames on the NEQ level. We are continuously working on improving the performance and memory usage as well as implementing software tests that automatically check the code for bugs and correctness.

We also plan to introduce more functionalities in *VieCompy* in the near future, including the combination of VLBI with other space geodetic techniques, such as Satellite Laser Ranging (SLR) or data from ring lasers. Furthermore, the implementation of filter solutions, to ensure an optimal state estimation of the dynamical system Earth, as in Abbondanza et al. (2017), is one of the next major goals.

We plan on making *VieCompy* freely available on GitHub in the future.

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