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Vienna VLBI and Satellite Software (VieVS) for Geodesy and Astrometry

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Abstract

The Vienna VLBI and Satellite Software (VieVS) is state-of-the-art Very Long Baseline Interferometry (VLBI) analysis software for geodesy and astrometry. VieVS has been developed at Technische Universität Wien (TU Wien) since 2008, where it is used for research purposes and for teaching space geodetic techniques. In the past decade, it has been successfully applied on Very Long Baseline Interferometry (VLBI) observations for the determination of celestial and terrestrial reference frames as well as for the estimation of celestial pole offsets, universal Time (UT1-UTC), and polar motion based on least-squares adjustment. Furthermore, VieVS is equipped with tools for scheduling and simulating VLBI observations to extragalactic radio sources as well as to satellites and spacecraft, features which proved to be very useful for a variety of applications. VieVS is now available as version 3.0 and we do provide the software to all interested persons and institutions. A wiki with more information about VieVS is available at http://vievswiki.geo.tuwien.ac.at/.

Key words: methods: data analysis – astrometry – reference systems – time – geodesy – very long baseline interferometry

Online material: color figure

1. Introduction

In geodetic and astrometric Very Long Baseline Interferometry (VLBI), several software packages are available. The most prominent one is certainly Calc/Solve, which is developed and maintained by the NASA Goddard Space Flight Center and is used by a large number of groups and individuals worldwide. Further packages include (in alphabetical order without claim to completeness) c5++ (Hobiger et al. 2010), DOGS-RI (Schmid et al. 2014), GINS (Bourda et al. 2007), ivg::ASCOT (Artz et al. 2016), Occam (Titov et al. 2004), or VieVS (Böhm et al. 2012). The International VLBI Service for Geodesy and Astrometry (IVS) has organized two comparison campaigns (Plank et al. 2010; Klopotek et al. 2016) that found that the theoretical delays computed with the software packages and used in the parameter estimation process agree at the one millimeter level or better for most of the software packages including VieVS.

The development of the—at that time called—Vienna VLBI Software (VieVS; Böhm et al. 2012) was started in 2008 by the Department of Geodesy and Geoinformation (GEO) at Technische Universität Wien (TU Wien), Austria. Before developing VieVS, we used Occam for the analysis of VLBI observations. However, as Occam is written in Fortran and without a graphical user interface, it was rather difficult to get students involved in the development of VLBI software. Thus, we decided to start writing VLBI software in Matlab because the students at TU Wien are used to Matlab and can easily read and write Matlab code. Since 2008, there has been a long list of students who have used VieVS to write their Bachelor's, Master's, and PhD theses.

In Section 2, we provide an overview of the tools available in VieVS and summarize the research carried out in the field of VLBI analysis over the last 10 years. Highlights are summarized in Table 1. Section 3 deals with the plan to add new features to VieVS in the coming years.

2. VLBI for Geodesy and Astrometry

In geodetic VLBI, the so-called group delays that are determined as the rate of phase with frequency at X-band (8.4 GHz) and S-band (2.3 GHz) are primarily used. Geometrically, these group delays correspond to the differences in arrival times at the radio telescopes of radio waves emitted by quasars and can be determined in approximation as the scalar product of the baseline vector b between the stations and the

Table 1
Significant VieVS Events Since 2008 and Plans for the Future. For more
Details, We Refer to the Text

Year	Highlights in the Past 10 Years
2008	Start of VieVS with single session analysis
2010	First VieVS User Workshop (2010 September 7–9)
2013	First schedule for the International VLBI Service for Geodesy and Astrometry (IVS) with VieVS (session AUST10 on 2013 July 4)
2015	Contribution to the ITRF2014
2016	First correlation on the Vienna Scientific Cluster (session AUG022 on April 2, 2016)
2016	Scheduling and analysis of VLBI observations to satellites
2017	Contribution to the ICRF3

unit vector s_0 to the extragalactic source divided by the velocity of light c (Equation (1)):

$$\tau = -b \cdot s_0/c. \tag{1}$$

Actually, the delays at S-band are used to correct the delays at X-band for the ionospheric delays. With the current 3.0 version of VieVS, we start the analysis of VLBI observations with group delays at X-band as provided with the so-called NGS cards or the equivalent vgosDB files, which means that group delay ambiguities and ionosphere delays have been removed before (Schuh & Böhm 2013; Sovers et al. 1998). These group delays are then used to determine a variety of geodetic, geodynamic or astronomical parameters. It should be stressed here that VLBI is the only technique to realize the celestial reference system at radio wavelengths and to observe universal Time (UT1) as well as nutation in terms of celestial pole offsets.

VieVS includes various features which will be introduced in the following sections. In addition to the classical applications in terms of reference frames and Earth orientation parameters, VieVS is equipped with tools for scheduling and simulation of geodetic VLBI observations and it offers the possibility to investigate observations to satellites in terms of scheduling, simulation, and analysis.

2.1. Scheduling and Simulation

Scheduling is a critical part in geodetic VLBI because it defines the order and time of the observations to the quasars, thus determining the quality of the geodetic parameter estimation. Typically, there are thousands of possible next scans, which makes the optimization rather difficult and time consuming. The vast majority of geodetic VLBI sessions is scheduled with the software SKED, which is maintained and updated by NASA Goddard Space Flight Center (Gipson 2012). For astronomical VLBI sessions, software SCHED (Walker 2015) is often used. VieVS also features such a scheduling tool for the observation of quasars with VLBI radio telescopes (Sun et al. 2014). These tools have constantly been enhanced and improved over the last years, and VieVS is now used for, e.g.,

scheduling sessions with the Austral network in Australia plus Hartebeesthoek in South Africa, and Warkworth in New Zealand (Plank et al. 2017b). These sessions either have geodetic goals such as a precise terrestrial reference frame or astrometric goals such as observing new sources in the south. VieVS is used for scheduling Austral sessions about once a month. It should also be mentioned here that VieVS has special scheduling options like the source-based strategy or the star-mode (McCallum et al. 2017), and simulations have demonstrated that the performance of VieVS in terms of scheduling is similar to that of SKED (Sun et al. 2014).

Since early on, VieVS has also been equipped with a tool to carry out Monte Carlo simulations. Error sources to be simulated are tropospheric delays, clock errors, and instrumental white noise (Pany et al. 2011) as well as source structure (Shabala et al. 2015) (see Equation (2)).

$$\tau = \tau_0 + \tau_{trop} + \tau_{clock} + \tau_{noise} + \tau_{source}. \tag{2}$$

VieVS and the preceding simulation tools which were then implemented in the software contributed to the simulation studies for the VLBI Global Observing System (VGOS) (Petrachenko et al. 2009; Wresnik et al. 2009) and they were also used for assessing the influence of geophysical model errors on reference frames (e.g., Plank et al. 2013). Furthermore, VieVS scheduling and simulation tools have been used to emphasize the importance of particular VLBI locations, like O'Higgins in Antarctica (Klügel et al. 2015) or Hartebeesthoek in South Africa (Mayer et al. 2014).

2.2. Parameter Estimation

In geodetic VLBI, we do have many more observations (group delays) than unknown parameters. Consequently, we use least-squares adjustment approaches to estimate the parameters of interest (Schuh & Böhm 2013). Starting with the observation equations (Equation (3)):

$$(3)v = Ax - l, \tag{3}$$

where v denotes the vector of residuals to the observations, A the design matrix, x the vector of corrections to the a priori values of unknown parameters, and l the vector with observed minus computed observations, we finally estimate the parameter vector x as (Equation (4)):

$$x = N^{-1}A^T Pl \tag{4}$$

with the normal equation matrix $N = A^T PA$ and the weight matrix P. In VieVS, we typically neglect correlations between the observations and we add one centimeter squared to the formal uncertainty as provided by the correlator when determining the diagonal weight matrix. For test purposes, we down-weighted observations at low elevation angles and even applied correlations between observations within one scan (Krásná & Gipson 2018). Other groups use these approaches routinely, such as NASA Goddard Space Flight Center. One
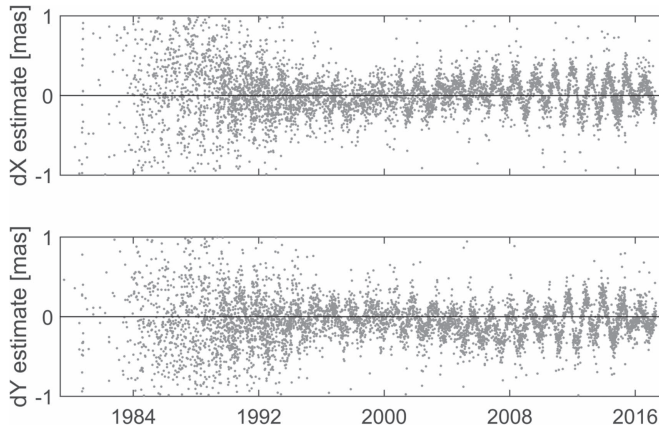
Figure 1. Celestial pole offsets as determined with VieVS. The periodic variation reflects Free Core Nutation.

Figure 2. Celestial reference frame as determined with VieVS in a global solution of nearly 6000 VLBI sessions along with the differences to the positions in ICRF2.
(A color version of this figure is available in the online journal.)

special feature of VieVS is that it estimates most of the geodetic parameters as piecewise linear offsets at integer hours (Schuh & Böhm 2013). This holds for Earth orientation parameters as well as for stochastic parameters such as troposphere and clock functions (Teke & Nilsson 2013). It also implies that we apply strong constraints between offsets if, e.g., constant Earth orientation parameters per session are to be provided.

Normal equation matrices from individual 24-hour sessions can then be stacked to derive so-called global solutions, which are typically used for the determination of terrestrial and celestial reference frames (e.g., Krásná et al. 2014). For the calculation of the computed (theoretical) delays, we strictly follow the Conventions of the International Earth Rotation and Reference Systems Service (IERS) (Petit & Luzum 2010) together with their electronic updates and special recommendations by the International VLBI Service for Geodesy and Astrometry (IVS) on the thermal expansion of radio telescopes as summarized by Nothnagel (2009).

Over the past decade, VieVS has been widely used for the analysis of VLBI observations, which holds for so-called 1-hour Intensive sessions (Teke et al. 2015), single 24-hour sessions, as well as for global VLBI solutions. Earth orientation parameters have been determined on a wide range of temporal scales and compared with estimates from other analysis software packages (e.g., Uunila et al. 2016). Girdiuk et al. (2016) and Madzak et al. (2016) determined high-resolution Earth rotation parameters for comparison with atmospheric and oceanic excitation, respectively. At the other end of the spectrum, Krásná et al. (2013a) determined Free Core Nutation parameters from a global VLBI solution in VieVS. Figure 1 illustrates celestial pole offsets as estimated with VieVS. Moreover, Krásná et al. (2013b) estimated frequency-dependent Love and Shida numbers and Krásná et al. (2015) assessed the influence of neglected station position variations on Earth
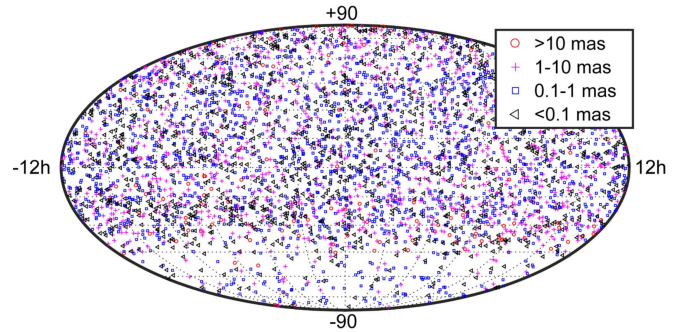
orientation parameters and reference frames. At a regional level, Krásná et al. (2013c) analyzed European VLBI sessions for tectonic studies.

It should also be mentioned here that a solution with VieVS (Böhm et al. 2016) was used in the combination process for the ITRF2014 (Altamimi et al. 2016) and that the Vienna VLBI group will contribute a solution for the upcoming realization of the International Celestial Reference System, the ICRF3 (Mayer et al. 2016, 2017). The VLBI combination for the ITRF2014 (Bachmann et al. 2016) and preliminary comparisons of ICRF3 prototype solutions (P. Charlot, personal communication) confirmed the high accuracy of the VieVS submissions, both in terms of coordinates and formal uncertainties. Larger standard deviations in Earth orientation parameters with respect to submissions by other groups as reported by some studies are believed to be due to the different representations (piecewise linear offsets at integer hours versus offset and rate at the mid of the session) causing issues in the comparison.

Figure 2 illustrates the distribution of more than 4000 sources on the sky as determined with VieVS along with their difference to the ICRF2 (Fey et al. 2015). However, some so-called special-handling sources have to be estimated session-wise. Exemplarily, Figure 3 depicts session-wise estimates of the source 0528+134.

2.3. VLBI Observations to Satellites

In recent years, we also focused on VLBI observations to satellites to improve the ties between kinematic and dynamic realizations of the celestial reference frame with VieVS. Plank et al. (2014) simulated VLBI observations to satellites of the Global Navigation Satellite Systems (GNSS) and assessed the impact on the terrestrial reference frame. Hellerschmied et al. (2017) improved the scheduling tools for VLBI observations to satellites which can now be used for GNSS satellites as well as low Earth orbiting (LEO) satellites. Recently, we used VieVS
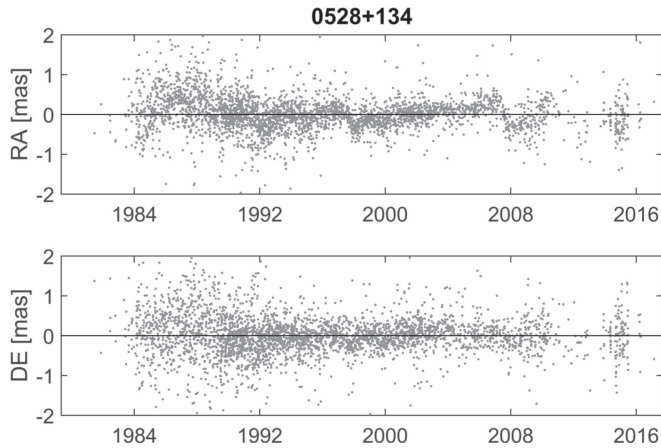
Figure 3. Session-wise estimates (upper panel: right ascension; lower panel: declination) with respect to mean values for the special-handling source 0528 +134 as estimated with VieVS.

Figure 4. High-level block diagram of VieVS. Boxes with solid lines illustrate modules already implemented, and boxes with dashed lines show modules under development. Gray-shaded boxes refer to products, gray arrows to observations. The combination module will also accept data (products, normal equations) from other techniques and software packages.

to schedule, model and analyze real VLBI observations to GNSS satellites (Plank et al. 2017a) and the Chinese APOD-A satellite (Sun et al. 2017), and found root-mean-square values at the decimeter level when analyzing satellite observations. These studies required the implementation of an adequate near-field delay model, which also served as a priori model in the correlation. In VieVS, we carry out an iterative solution of the light-time equation as described by Klioner (1991).

3. Plans for VieVS and Outlook

At GEO, there is also a research group focusing on satellite geodesy and GNSS in particular. Ongoing research projects deal with the determination of atmospheric parameters, the improvement of Precise Point Positioning (PPP) solutions, or the analysis of regional and global networks of GNSS stations. Those projects are mostly carried out with existing GNSS software packages like Bernese (Dach et al. 2015) and NAPEOS (Springer 2009), but an extensive list of in-house program code is also available. We plan to put those software activities under the umbrella of the Vienna VLBI and Satellite Software (VieVS). This has the advantage of simplifying the maintenance and development of the software, and it will strengthen the identity at GEO by labeling all modules as VieVS. Most of the source code will still be written in Matlab, but it is also possible to have Fortran or C++ code in VieVS. In any case, well-defined interfaces between the modules will be included.

One major new module in VieVS will be concerned with the analysis of Satellite Laser Ranging (SLR) observations. In the beginning, we will focus on the determination of station coordinates, but at a later stage the implementation of orbit determination tools will be considered as well. Interesting research options will be accessible by combining VLBI and
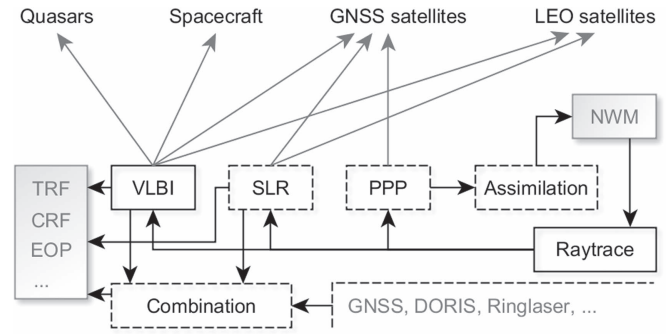
SLR solutions. To realize such a combination, we will develop a module that combines normal equations from VLBI and SLR analysis. Further, we will provide the possibility to add GNSS normal equations as derived with other software packages or normal equations from ring laser observations (Nilsson et al. 2012). However, we will not restrict the combination to normal equations but we will also consider filter approaches at the product level.

Hofmeister & Böhm (2017) developed a ray-tracing tool that will be integrated into VieVS as well. It generates tropospheric delays which can be applied in VLBI, GNSS, and SLR analysis. The module is available as Matlab and Fortran code, the latter being very important for large data sets because of computation time. There are well-defined formats for the ray-tracing output so that the delays can be easily used in the analysis of space geodetic techniques. A high-level block diagram of VieVS is illustrated in Figure 4.

Finally, we plan to close the gap between the correlator/fringe-fitting output and the VieVS modules. Currently, we make use of the Vienna Scientific Cluster 3 (Gruber et al. 2017) to run the software correlator DiFX (Deller et al. 2007) and the fringe-fitting process with fourfit/HOPS. In the near future, VieVS will be able to read this output directly and perform the ambiguity resolution and ionosphere correction without using third-party software (compare Table 2).

4. Summary

The Department of Geodesy and Geoinformation (GEO) at Technische Universität Wien, Austria, is developing software for the analysis of space geodetic observations with a special emphasis on VLBI for geodesy and astrometry. This Vienna VLBI and Satellite Software (VieVS) has proved to be of the highest quality and fully competitive when scheduling VLBI observations or analyzing VLBI observations for the determination of Earth orientation parameters as well as

Table 2
VLBI Data Flow and Capabilities of VieVS

Scheduling	VieVS can schedule VLBI observations to quasars and satellites.
Correlation	We use DiFX on the Vienna Scientific Cluster.
Fringe-fitting	We use fourfit/HOPS and PIMA; additionally, we plan to look into developing our own fringe-fitting tools as part of VieVS.
Ambiguity resolution, ionosphere correction, and data editing	We are using NuSolve (Bolotin et al. 2014) for those tasks; however, we will develop our own tools as part of VieVS.
Analysis of single sessions	VieVS
Global solutions	VieVS

celestial and terrestrial reference frames. At the same time, VieVS is perfectly suitable for easy model testing. We do provide a documentation of VieVS at http://vievswiki.geo.tuwien.ac.at/ and we have held VieVS User Workshops each year since 2010.

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