Scheduling of VLBI observations to satellites with the Vienna VLBI Software (VieVS)

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Abstract The observation of satellites with VLBI is an auspicious approach, providing a variety of new possibilities. Promising applications can be found, among others, in the field of inter-technique frame ties. Although several test observations to GNSS satellites have been carried out in recent years, this approach is still far away from being applied routinely. Difficulties already start during observation planning, with the standard geodetic scheduling software not being prepared to include satellites as observation targets in the required control files. The new satellite scheduling module of the Vienna VLBI Software (Böhm et al., 2012) offers a solution to this. It allows the user to prepare schedules for observations of selected satellites, also in combination with standard observations to natural radio sources. The schedule files in the current VEX format created this way provide the possibility to conduct actual VLBI satellite experiments. The next step is to evaluate suitable scheduling strategies for satellite observations, which will allow to implement an automatic source selection approach. The development of a convenient scheduling software in the form of the new VieVS module is important to support further research and development in this field.

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1 Introduction

Observations of anthropogenic space objects with radio telescopes is not new for the VLBI in general. There have been numerous of those observations in the last decades, mainly for the navigation of (deep) space missions, e.g. carried out by the NASA Deep Space Network (e.g. Border, 2009). However, the observation of spacecrafts, in particular of Earth-orbiting satellites, is new for the geodetic VLBI system. The basic idea is to apply standard VLBI data acquisition and analysis schemes to direct observations of satellite signals, similar to those used for operational observations of natural radio sources (mostly quasars). This will offer a variety of new possibilities for the geodetic community, where probably the most promising ones can be found in the field of inter-technique ties, see e.g. Plank et al. (2014).

For successful VLBI data acquisition, suitable observation plans, referred to as schedules, are required to define the timing of a VLBI session and to configure the receiver equipment. The scheduling of geodetic VLBI sessions is a critical task and is usually done by dedicated software, such as SKED (Gipson, 2012), or VIE_SCHED (Sun et al., 2014), the standard scheduling module in VieVS. In case of VLBI satellite observations the problem was that those commonly used geodetic scheduling programs did not support satellites as radio sources routinely. Hence, lots of manual interactions were needed for previous experiments, to carefully prepare the required observation plans and the related interchange files. To close this gap a dedicated Satellite Scheduling Module was developed for VieVS (Hellerschmied et al., 2015), which enables the cre-

ation of realistic schedules for satellite observation for upcoming test and research campaigns in a simple and convenient way. The observation plans are saved in a standardized file format and can be applied to control real observations.

2 VLBI satellite observations

2.1 Basic observables

The choice of the basic observables in the data analysis affects how the data have to be taken, both in frequency setup and in the sequence of scans. In geodesy typically measurements of signal delays derived from phase slopes of wide frequency ranges are used. The available bandwidth of satellite signals is small compared to quasar signals. On the other hand, the signal strength is usually much higher, which is assumed to compensate the negative effects of the narrow bandwidth on the accuracy of the derived delay observables.

Alternatively, phase referencing could be used between satellite and a nearby target, e.g. a well defined natural radio source of known position. This scheme has been used for most astronomical applications, as well as for near-field VLBI observations of space probes, e.g. of the ESA Venus Express Spacecraft (Duev et al., 2012). A big complication for this approach for Earth orbiting satellites emerges due to the very short distance between target and observer: A quasar that is close to a satellite seen from one site is likely to be far from this satellite as seen from another site.

2.2 Combined schedules

The combination of satellite and quasar scans in one session and a common treatment in the data analysis offers various interesting possibilities, such as:

- Determine satellite positions directly in the CRF
- Reveal local-tie discrepancies between the VLBI frame and reference frames of other techniques, e.g. as shown for VLBI and GNSS in the simulation study by Plank et al. (2014)
- Establish a direct link between the geometric VLBI reference frame and the geocenter (Dickey, 2010)

However, there are severe observation restrictions on the station level, mainly due to limited receiver capabilities. Standard geodetic VLBI is done routinely in the S- and X-band, while satellite signals are not restricted to those bands. GNSS satellites, which are particularly interesting for VLBI observations, transmit radio signals in the L-band, which is generally not observable with the standard geodetic antenna equipment without changes in the hardware. Only a few antennas provide the possibility to combine S/X-band observations and L-band observations, either by automatically switching the receiver (e.g. Medicina[1]), which has the drawback that those adaptions take some time and may change internal signal delays, or by using dedicated S/X/L-band receivers as developed at the station Wettzell by Kodet et al. (2014).

2.3 Future scheduling strategies
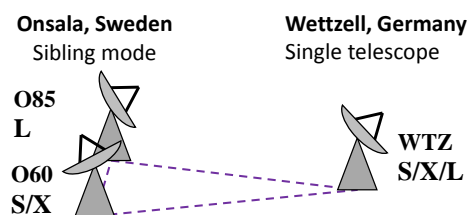
Fig. 1 Possible constellation for combined S/X/L-band observations. Wettzell is able to observe all bands. In Onsala sibling antennas are used to cover all three frequency bands.

One major task for the near future is the implementation of an automatic source-selection approach for satellites and combined sessions, respectively. Current geodetic scheduling software implement automatic source selection approaches, which usually optimize the sky coverage at the stations. This is required to determine accurate tropospheric corrections and to beat down atmospheric errors.

However, there are still several open questions: One question is how to combine satellite and quasar scans reasonably within one session (in terms of scan sequence, ratio between satellite and quasar scans, spatial source distribution, etc.) to improve the desired target estimates. Another important point is how to han-

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[1] http://www.med.ira.inaf.it/ManualeMedicina/

dle station-dependent restrictions in the observable frequency bands, as discussed in Sec. 2.2. One possibility is to take advantage of twin or sibling telescopes: One telescope for satellites, e.g. in L-band, and the other one for classical S/X-band observations, as outlined in Fig. 1 for the baseline Onsala-Wettzell.

3 VieVS Satellite Scheduling Module

The Satellite Scheduling Module is integrated into the Graphical User Interface (GUI) of VieVS. In addition to the function range of the standard scheduling module VIE_SCHED it provides the following features:

Orbit prediction: Satellite positions and velocities are required for two tasks: (a) For the observation planning to check the conditions for a valid scan (see Sec. 3.2) and to determine whether a satellite is observable at a certain epoch. (b) For the calculation of the tracking data which are included in the final schedule files to enable a stepwise satellite tracking (see Sec. 3.3). The applied orbit determination approach has to provide the possibility to predict satellite positions at least a few days to the future with sufficient accuracy, because the scheduling is usually done several days before the actual sessions are carried out. In VieVS the orbit determination is based on Two-Line Element (TLE) datasets. The great advantage of TLE data is their wide availability for thousands of space objects on a daily basis and free of charge[2]. The calculations are based on analytical Simplified General Perturbation models (SGP; Hoots and Roehrich, 1980), without the requirement of CPU-intensive interpolations. The accuracy of those orbit predictions is not sufficient to be used for the correlation. Therefore, the satellite positions have to be obtained from other sources, e.g. from GNSS final orbits provided by the IGS.

Interactive user interface: The scheduling is controlled via a text-based user interface. Several interactive plots visualize the current satellite-station constellation, observation restrictions and summarize the available observation times of

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[2] For more information visit: `http://www.celestrak.com/NORAD/elements/`

potential targets. Useful auxiliary information are also provided, e.g. cable wrap positions, etc.

Satellite scans: Satellite scans can be added scan by scan, just by selecting the target. The scan start time is calculated automatically, but the on-source has to be defined manually.

Combined schedules: Quasar and satellite scans can be mixed in one schedule, where blocks of quasars scans can be added automatically using the station-based scheduling strategy of VIE_SCHED (Sun et al., 2014). Individual station networks can be defined for both observation types, including antennas in twin/sibling mode.

3.1 Program overview and workflow

A program overview is outlined in Fig. 2:

1. **Input data:** On program start, different kinds of input data are loaded. Catalog files provide all required information about VLBI stations, e.g. coordinates, equipment and antenna parameters. Configuration files are used to define the receiver configuration for specific observation scenarios and TLE data are needed for orbit predictions.

2. **VieVS GUI:** The basic observation setup can be defined in the GUI. The user selects the station network, session start time and duration, and further observation parameters, e.g. the cut-off elevation. Via mouse-click the internal TLE library can be updated automatically over a web service. Furthermore, a pre-selection of satellites has to be made.

3. **User interface:** After setting all required parameters, the program calculates the available observation periods for all selected satellites and provides this information to the user in terms of text and graphics. Via the provided interface, the user is able to compile an observation plan by assembling satellite and quasar scans manually in the desired order. After selecting a target source, the program calculates the required slew times and suggests a scan start time automatically. For quasar scans, also the optimal scan duration (on-source time) is calculated. For satellites the determination of the on-source time is still a subject of research, because several required parameters (e.g. flux density, receiver efficiency, etc.) are still unknown. There is also the possibility to combine satellite
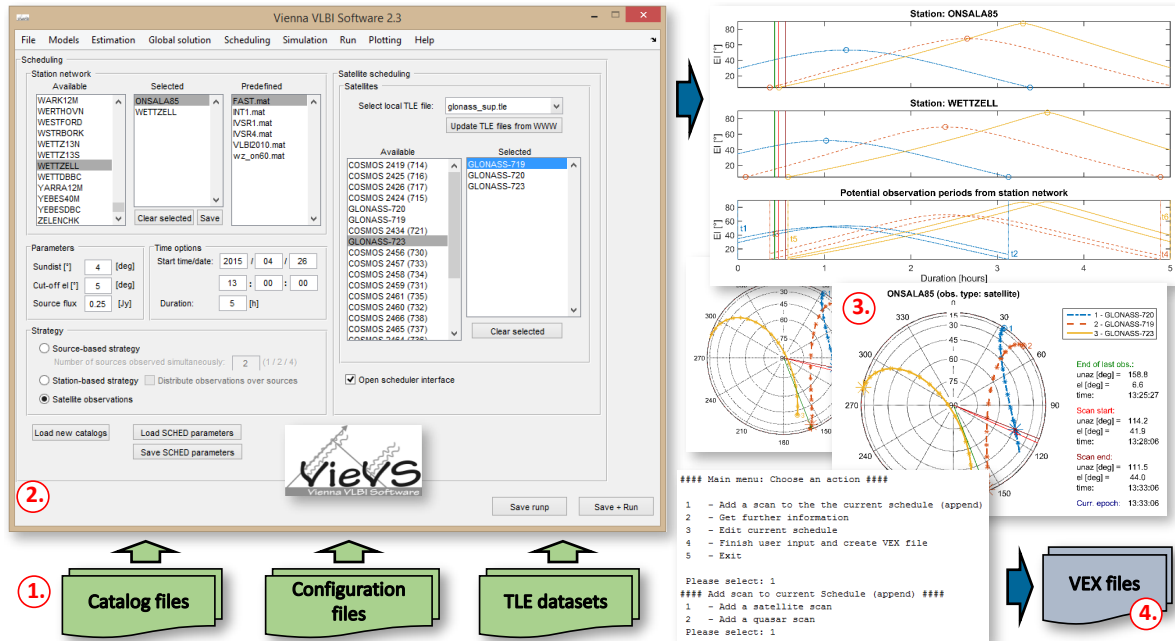
Fig. 2 Overview of the VieVS Satellite Scheduling Module: (1.) Input data, (2.) GUI, (3.) user interface and (4.) output.

scans in sequence with classical geodetic schedules of quasar scans, computed by the station-based scheduling approach of VIE_SCHED (Sun et al., 2014).

4. **VEX files:** The final observation plans are saved as VEX-formatted files (see Sec. 3.3).

3.2 Observation conditions

To determine whether an observation target is observable at a certain epoch, several visibility conditions and limitations in the antenna hardware are considered:

Common visibility: A satellite has to be visible simultaneously from all antennas of the defined station network. Therefore, the visibility is examined separately for each site, considering the defined cut-off elevation and a horizon mask, if available. By combining these data, the common visibility from the network is examined. Although it would be required for large (up to global) station networks, sub-netting is not supported so far. For delay time calculations a target has to be visible simultaneously from at least two stations forming one baseline. However, single station observations,

e.g. for signal acquisition tests, can also be scheduled.

Slew rates: Contrary to quasars, satellites can move quite fast relative to the Earth's surface, depending on their orbit height. Hence, it has to be ensured, that the antenna slew rates are sufficiently high, so that the antennas are able to keep track of the satellite during data acquisition.

Axis limits and cable wrap: Axis limits of individual antennas are checked. Furthermore, the cable wrap of AzEl-mounted antennas has to be tracked to calculate slew times between consecutive scans unambiguously.

Sun distance: A certain distance between the Sun and the observation target has to be kept to prevent signal degradation.

3.3 Schedule files

The final observation plans are saved in VEX-formatted schedule files. VEX (Whitney et al., 2002) is a standard file format for VLBI schedules. Those files comprise all required information to carry out a VLBI session. Additionally to the scan sequence, all setup

parameters for the receiver equipment are defined there, e.g. sample rates, frequencies and bandwidths.

To enable satellite tracking without the requirement of dedicated satellite tracking modes, a so-called *stepwise tracking* (e.g. Hellerschmied et al., 2015) is implemented in the issued VEX files. Satellite orbits are fragmented and approximated by discrete positions in the VEX files, defined by topocentric Ra/Dec similarly to the source definition of quasars. Satellites are tracked by repositioning the antennas in a defined time interval to the defined tracking points. Individual VEX files are generated for each station, because the topocentric satellite positions differ between sites.

The testing period for a revised VEX format (VEX 2.0) already started in December 2014[3]. This is quite important for VLBI satellite tracking, because the new format will provide the possibility to include TLE orbit data directly to the control files. In combination with dedicated satellite tracking features of the VLBI Field System this will enable continuous and smooth tracking (Himwich and Gipson, 2013).

4 Summary and outlook

The VieVS Satellite Scheduling Module provides a flexible tool for the scheduling of real VLBI satellite observations, also in combination with classical quasars scans. The final observation plans are saved in VEX-formatted schedule files, which are able to control real experiments by applying a stepwise tracking approach for satellites. This module was initially applied for successful test observations of GLONASS satellites in January 2014 on the baseline Onsala-Wettzell (Haas et al., 2015).

The implementation of a suitable scheduling optimization approach, which is a prerequisite for an automatic selection of satellites, requires further research. Therefore, it is planned to combine the simulation tools for satellites (Plank et al., 2014) with the new scheduling module in VieVS, to investigate scheduling strategies for satellites based on realistic schedules.

[3] `https://safe.nrao.edu/wiki/bin/view/VLBA/Vex2`

References

Böhm J, Böhm S, Nilsson T, Pany A, Plank L, Spicakova H, Teke K, Schuh H (2012) The new Vienna VLBI software. In: S. Kenyon, M. C. Pacino, U. Marti (eds.), *Proc. IAG Scientific Assembly 2009*, IAG Symposia Series 136, 1007–1011,

Border J S (2009) Innovations in delta differential one - way range: from Viking to Mars Science Laboratory. In: *Proc. 21st Int. Sym. Space Flight Dynamics*, Toulouse, France

Dickey J M (2010) How and Why do VLBI on GPS. In: D. Behrend and K. Baver (eds.), IVS 2010 General Meeting Proc., NASA/CP 2010-215864, 65–59.

Duev D A, Molera Calvés G, Pogrebenko S V, Gurvits L I, Cimó G, Bocanegra Bahamon T (2012) Spacecraft VLBI and Doppler tracking: algorithms and implementation. *Astron Astrophys*, 541:A43+

Gipson J (2012) Sked - VLBI Scheduling Software. NASA Goddard Space Flight Center, `ftp://gemini.gsfc.nasa.gov/pub/sked/sked_Manual_v2012May09.pdf`

Haas R, Hobiger T, Hellerschmied A, Neidhardt A, Kodet J (2015) GLONASS-VLBI: Onsala-Wettzell test observations. In: R. Haas, F. Colomer (eds.), *Proc. 22nd EVGA Working Meeting*, 107–111.

Hellerschmied A, Böhm J, Neidhardt A, Kodet J, Haas R, Plank L (2015) Scheduling VLBI Observations to Satellites with VieVS. In: C. Rizos and P. Willis (eds.), *Proc. IAG Commission 1 Symposium 2014: Reference Frames for Applications in Geosciences (REFAG2014)*, Springer Berlin Heidelberg, IAG Symposia, DOI 10.1007/1345_2015_183, accepted.

Himwich E, Gipson J (2013) GSFC Technology Development Center Report. In: K. D. Baver, D. Behrend, K. Armstrong (eds.) *IVS 2012 Annual Report*, NASA/TP-2013-217511, 280–282.

Hoots F, Roehrich R (1980) Spacetrack Report No.3: Models for Propagation of NORAD Element Sets. Tech. rep., US Airforce Aerospace Defense Command, Colorado Springs, CO.

Kodet J, Schreiber K, Plötz C, Neidhardt A, Kronschnabl G, Haas R, Molera Calvés G, Pogrebenko S, Rothacher M, Maennel B, Plank L, Hellerschmied A (2014) Co-locations of Space Geodetic Techniques on Ground and in Space. In: D. Behrend, K. D. Baver, K. L. Armstrong (eds.) *IVS 2014 General Meeting Proc.*, Science Press (Beijing), 446–450.

Plank L, Böhm J, Schuh H (2014) Precise station positions from VLBI observations to satellites: a simulation study. *J Geod*, 88(7), 659–673.

Sun J, Böhm J, Nilsson T, Krásná H, Böhm S, Schuh H (2014) New VLBI2010 scheduling strategies and implications on the terrestrial reference frames. *J Geod*, 88(5), 449–461.

Whitney A, Lonsdale C, Himwich E, Vandenberg N, van Langevelde H, Mujunen A, Walker C (2002) VEX File Definition/Example, Rev. 1.5b1. `http://www.vlbi.org/vex/docs/vex`