Observing Satellites with VLBI Radio Telescopes
– Practical Realization at Wettzell –

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Abstract A concept of an operational path for VLBI satellite observations from scheduling to actual observations is introduced in this report. It is based on a recently developed satellite scheduling module for the Vienna VLBI Software (VieVS) in connection with dedicated satellite tracking functions of the NASA Field System (FS) and the station specific realizations. This concept has been exemplarily realized with the radio telescope Wettzell.

Keywords VieVS, satellite observations, scheduling

1 Introduction

Satellite observations with VLBI is a promising topic and has been vividly discussed in the community for the last few years. Although several experiments were carried out successfully [10], a clear strategy for realizing such observations operationally has not been shown by now.

The difficulties already start with the observation planning, because standard VLBI scheduling programs are not able to routinely schedule satellites as targets. Furthermore, the standard data formats used for VLBI schedule files do not provide the possibility of including information on satellite orbits in a suitable way. Although the most recent version of the NASA FS [13] provides dedicated functions for satellite tracking with VLBI antennas, it does not yet support the generation of local control files with DRUDG [11], including the necessary commands. For those reasons, previous satellite observations meant a large expenditure compared to classical geodetic VLBI observations of quasars. Experiments had to be done with hand-written schedules and numerous manual interactions were necessary at the stations.

In order to overcome those deficiencies, a joint initiative in cooperation with the Geodetic Observatory Wettzell was started to investigate options for an operational path to implement VLBI satellite observations.

2 Tracking Satellites with VLBI Radio Antennas

Standard VLBI antennas do not provide dedicated functions for the tracking of satellites. Therefore, in previous experiments, the antennas were steered by using a step-wise approach [8, 9, 10]. Sequences of celestial positions in terms of topocentric right ascension (RA) and declination (DEC) angles were commanded consecutively, separated by a defined time interval of, e.g., 15 seconds, to track the satellite on its orbit. The great advantage of this approach is that it is feasible with every VLBI antenna, if the slewing rate is fast enough and if it is able to process celestial coordinates. No additional dedicated satellite tracking software is requested.

The drawback is, however, that due to the step-wise repositioning, it is not possible to keep the satellite ex-

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actly centered within the antenna beam all the time during an observation. According to Tornatore et al. [9], this may produce some glitches in the resulting data of the residuals with a period equal to the duration of the guidance interval. Hence it would be preferable to track satellites in a continuous fashion.

Some kind of orbit information is needed at the station during an observation to calculate the position of the currently observed satellite and accurate pointing data to control the antenna continuously. NORAD Two Line Elements (TLE, [5]) provide that ability. They are freely available over the Internet for a vast number of spacecrafts and facilitate a precise enough orbit determination by dedicated analytical models.

The way in which the orbit data, such as TLE, has to be prepared, processed, and formatted to satisfy the demands of satellite tracking at the location of the telescope depends on the requirements of the local Antenna Control Units (ACU) and is therefore strictly station specific. When the ACU of a dedicated VLBI antenna does not provide the ability to process the satellite orbit data directly, software is needed to prepare that information as required. SATTRACK [7], a module for the FS, provides the capability of doing these translations. Furthermore, FS versions 9.11.2 and higher are able to process TLE data [4]. Both programs provide new FS commands intended for satellite tracking. They convert TLE data to discrete satellite positions in terms of RA/DEC or azimuth/elevation.

3 Scheduling of VLBI Satellite Observations

The setup of a VLBI experiment for the entire station network is defined in a dedicated schedule file. A commonly used file format is VEX 1.5b [14].

Prior to a VLBI experiment, the program DRUDG [11] is used at all participating stations to extract locally necessary information from the VEX file and to generate a local control file in the Standard Notification for Astronomical Procedures (SNAP) format. Such SNAP files consist of sequences of FS commands (SNAP commands) in order to set up the local station configuration and to perform the observations as scheduled. Although the FS already has some features implemented for the realization of satellite tracking, neither the current releases of the VEX format nor the current version of DRUDG provide the feasibility of including satellites in the appropriate way (the same way as radio sources). Therefore local workarounds are necessary.

To have software available for the planning of VLBI satellite sessions, VieVS [2] was updated with a Satellite Scheduling Module. The program leads the user through an interactive scheduling process. Initially it calculates positions of all selected satellites, e.g. the GLONASS constellation, on the basis of TLE data and checks whether they have shared visibility from the particular station network for the chosen date and time. After checking of further conditions, such as observation restrictions due to limited antenna slew rates, etc., a list of observable satellites is presented, and the user is asked to assemble a sequence of desired sources. Automated source selection is not yet included. Finally a VEX file is generated, containing all required data to run the scheduled observations. Due to the inadequate satellite support of the current VEX format, the satellites are still defined as step-wise stationary sources (like quasars) in terms of topocentric RA and DEC. Topocentric indicates that RA/DEC satellite positions depend on the geographic location of the observing station and therefore have to be defined separately for each site in the schedule. Using these schedule files, it is possible to track satellites "step-wise" and, with the following station adaptations, also continuously.

4 Satellite Tracking at Wettzell

There are three VLBI radio telescopes at the Geodetic Observatory Wettzell: the 20-m Radio Telescope Wettzell (RTW) and the twin telescope consisting of two 13.2-m antennas. After a hardware update in 2013, each of them is equipped with an identical ACU from Vertex Antennentechnik GmbH and is able to operate in a *Two Line Track Mode* and capable of processing TLE data directly for satellite tracking purposes [12]. The ACU satellite tracking capability has the advantage that the antenna movement is precisely adjusted to the internally predicted satellite movement, without the detour of calculating discrete satellite positions in the FS.

The satellite tracking procedure is illustrated in Figure 1. DRUDGing a VEX file issued by VieVS generates a SNAP file (SNP_s), defining each satellite scan as a sequence of SNAP commands, (*source=<sourcename><RA><DEC><epoch>*), which point the antenna to specified celestial positions. To enable the continuous tracking, a perl script (*SNAP File Translator*) was implemented to translate these SNAP files: it simply replaces the source-command sequence for each scan by a single satellite SNAP command. Although the new satellite tracking functions of the FS were already activated for the twin telescope, they could not be used for satellite experiments with the RTW, because an older FS version (9.10.4) was installed. For that reason a new SNAP command (*antenna=tle,<tle_filename>*) was implemented in the station specific part of the FS. Both the "satellite" and the "antenna=tle" command read the TLE data either from the shared memory of the FS or from a separate TLE file and send them to the ACU. There the tracking points are calculated and the mode is switched to the Two Line Track, which starts the continuous orbit track.

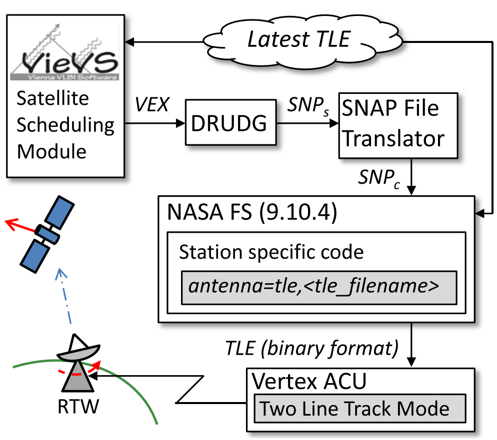

Fig. 1 Satellite Tracking Procedure for the Radio Telescope Wettzell (RTW). The latest TLE data sets are obtained from a Web-service before an experiment. A perl script (SNAP File Translator) is used to convert SNAP files intended for step-wise tracking (SNP$_s$) to enable continuous tracking (SNP$_c$).

5 Satellite Observation Experiments

Several VLBI observations of L1 signals of the GLONASS satellites were carried out in January 2014 to validate the proper functionality of the newly implemented satellite tracking features at Wettzell and the VieVS Satellite Scheduling Module in general.

5.1 Experiment Description

Two sessions were carried out on January 16, 2014 (G140116a and G140116b), and another two were carried out on January 21, 2014 (G140121a and G140121b) on the baseline Wettzell–Onsala. Each of them had a duration of one hour and scheduled several GLONASS satellites consecutively.

For all sessions, the scheduling and further on the creation of VEX files was performed with the new VieVS Satellite Scheduling Module. A detailed listing of the selected GLONASS satellites, the related observation intervals for each scan, and the emitted frequencies for all four sessions can be found in Tables 1 and 2.

Table 1 Observation setup from 16 January 2014.

Session Name	Glonass Number	Scan Period [UT]	L1 Carrier Frequ. [MHz]
G140116a	743	12:30 – 12:45	1605.3750
	723	12:50 – 13:05	1602.0000
	730	13:10 – 13:30	1602.5625
G140116b	743	14:00 – 14:15	1605.3750
	723	14:20 – 14:35	1602.0000
	730	14:40 – 15:00	1602.5625

At Wettzell, all sessions were carried out by the 20-m RTW. The RTW's front end receiver was basically designed for observations in the S- and X-band domain, as is common for geodetic VLBI. When trying to observe GLONASS L1-band signals (1592–1609 MHz) with the existing S-band receiver system, these signals were blocked due to a narrow S-band band pass filter (2210–2350 MHz). To enable the reception of L1 signals with the existing antenna hardware, the S-band front end system of the RTW was upgraded and split to create a new L1 receiver module [6]. This enables the acquisition of L1-band in addition to S/X-band without changing the receiver hardware. At the first experiment (G140116a), the antenna was guided, using a step-wise approach with a re-positioning interval of 15 seconds to test if the scheduling was principally functional. In the other three sessions, the satellites were tracked continuously by means of the new FS functions.

Table 2 Observation setup from 21 January 2014.

Session Name	Glonass Number	Scan Period [UT]	L1 Carrier Frequ. [MHz]
G140121a	743	13:30 - 13:35	1605.3750
	732	13:37 - 13:43	1603.6875
	743	13:44 – 13:49	1605.3750
	732	13:51 – 13:56	1603.6875
	743	13:59 – 14:04	1605.3750
	735	14:08 – 14:13	1603.1250
	735	14:14 – 14:19	1603.1250
	732	14:25 – 14:30	1603.6875
G140121b	735	15:00 – 15:04	1603.1250
	735	15:05 - 15:09	1603.1250
	735	15:10 – 15:14	1603.1250
	746	15:20 –15:24	1604.2500
	746	15:25 – 15:29	1604.2500
	746	15:30 – 15:34	1604.2500
	723	15:45 – 15:49	1602.0000
	723	15:50 – 15:54	1602.0000
	723	15:55 – 16:00	1602.0000

Onsala's 25-m radio telescope (ONSALA85) used its L-band front end receiver. This qualifies it to receive strong L1 signals, but acquisition of S/X-band signals is not possible without changing the receiver. Because Onsala's SATTRACK module was not installed when the experiments were carried out, all satellites were tracked step-wise there with a 15 second re-positioning interval, controlled by the VieVS schedules.

5.2 Observation Results

The DiFX software [3] was used to correlate the acquired data. The correlation was done with 0.25 seconds of integration time, and the results were fringe-fitted with the Astronomical Image Processing System software (AIPS, [1]). Continuous phases and strong amplitudes were found for all satellites, indicating that the described concepts for satellite observations worked correctly at both stations. The fringe plot (amplitude and phase) for GLONASS-732 is shown exemplarily in Figure 2.

6 Summary and Outlook

The VieVS Satellite Scheduling Module provides a flexible tool for scheduling real VLBI satellite observations, even for large station networks and arbitrary satellites. It generates VEX files able to perform satellite tracking directly in a step-wise fashion. For the future it would be important to extend the current VieVS module with further functionalities, such as the possibility of combining satellite observations with classical observations to quasars or providing automated source selection, based on a dedicated scheduling optimization approach.

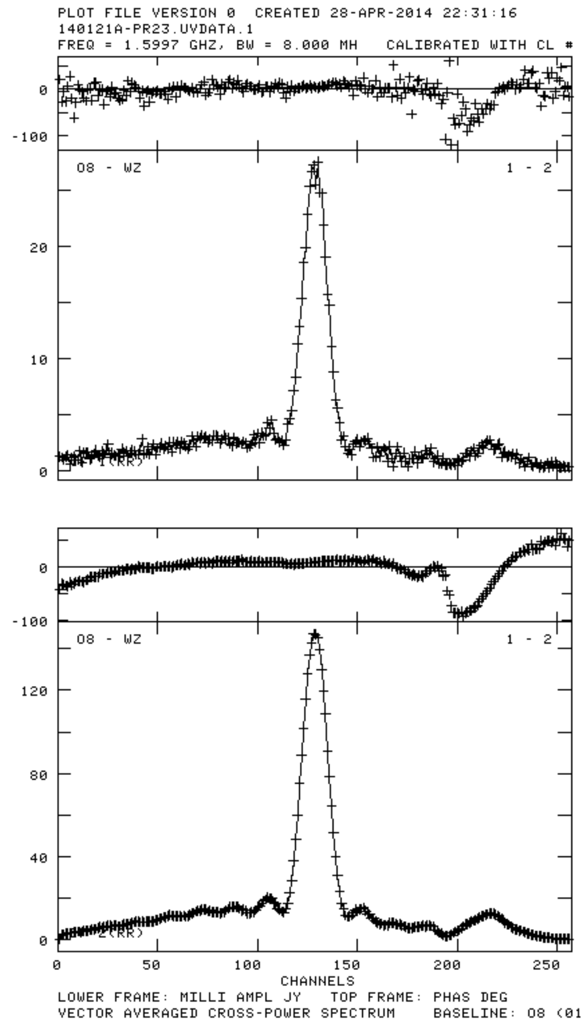

Fig. 2 Fringe plots for GLONASS-732. Data acquired during the G140121a session (2^{nd} scan).

Fully operational application and process automation of VLBI satellite observations, comparable to the traditional geodetic VLBI observation of quasars, is presently restricted due to limitations in the schedule file format (VEX) and generation of local control files (SNAP files) with DRUDG. Although the upcoming release of VEX 2.0 will provide possibilities to define satellites as radio sources in terms of TLE data appropriately (personal communication with E. Himwich), currently the best option seems to be to define satellite orbits by sequences of celestial coordinates in the schedule. This directly allows step-wise satellite tracking with all suitable VLBI antennas. Despite there being different ways to realize continuous tracking (SATTRACK, FS, ACU), it still depends on local implementations and antenna features. Because the current version of DRUDG does not support dedicated satellite commands, a way has to be found to include the satellite SNAP commands in the control files. At Wettzell, this was done by modifying the SNAP files with a perl script which can also be shared with other stations.

Based on several satellite tracking experiments on the baseline Wettzell–Onsala, two things could be validated so far: first, that the schedule files (VEX) prepared with VieVS were applied successfully to control the satellite observations and second, that satellite tracking with both approaches, step-wise and continuous, worked properly at the involved stations.

The developments in satellite tracking and scheduling allow VLBI satellite observations in an easy and nearly automated manner. This is an important step to promote further developments regarding satellite observations with VLBI, such as investigations related to link budget, signal attenuation, correlation of satellite signals, etc., and finally the co-location of different space geodetic techniques.

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