

# First Results of the FAST-S/X Sessions with New VGOS Antennas

Alexander Neidhardt<sup>1</sup>, Pablo de Vicente<sup>2</sup>, Alessandra Bertarini<sup>3,7</sup>, Thomas Artz<sup>3</sup>, Sebastian Halsig<sup>3</sup>, Dmitry Ivanov<sup>4</sup>, Alexey Melnikov<sup>4</sup>, Johannes Böhm<sup>5</sup>, Andreas Hellerschmied<sup>5</sup>, David Mayer<sup>5</sup>, Christian Plötz<sup>6</sup>, Gerhard Kronschnabl<sup>6</sup>, Axel Nothnagel<sup>3</sup>, Sergei Kurdubov<sup>4</sup>, Andrey Mikhailov<sup>4</sup>, Dmitry Marshalov<sup>4</sup>, Iliia Bezrukov<sup>4</sup>, Yu. Bondarenko<sup>4</sup>

**Abstract** During the VTC meeting in Ponta Delgada, Portugal, it was decided to form a group with the goal of testing the fast slewing mode of the VGOS antennas on intercontinental baselines. The goal is to observe S/X-schedules regularly using fast slewing modes of the antennas. Two sessions, FAST02 and FAST03, were scheduled with VieVS at the Vienna University of Technology, employing the new VGOS antennas at Yebes in Spain, Wettzell in Germany, and Zelenchukskaya and Badary in Russia. FAST02 was a 24-hour session observed in DDC mode. FAST03 was a six-hour session to test the PFB mode. The correlation was done both in Bonn, where also the main geodetic analysis was made, and at the IAA in Russia. Unfortunately, FAST03 was not successful due to incompatible frequency setups. In this paper, we report on the first results of the FAST02 session.

**Keywords** FAST, S/X observations, VGOS antennas

## 1 Introduction

The first international 24-hour long session, FAST02, was observed on December 16/17, 2015 using the fast slewing modes of the new VGOS antennas with a standard S/X-frequency setup. The goal was to demon-

strate and test the capabilities of scheduling, running, correlating, and analyzing sessions in the new modes. While the VGOS tests directly focus on broadband experiments, the FAST sessions should demonstrate which improvements for standard setups can be made by increasing the number of observations within 24 hours. While FAST02 used a standard frequency setup, FAST03 tested the polyphase filterbank mode with 16x32 MHz continuous channels in combination with the direct sampling mode at the Russian sites. While FAST02 provided usable results, except for some existing issues, FAST03 could not be correlated due to the missing overlap of frequencies observed.

## 2 Scheduling of FAST Sessions

The FAST sessions were scheduled with VIE.SCHED [9], the scheduling module of the Vienna VLBI Software (VieVS) [1]. VIE.SCHED automatically generates geodetic VLBI schedules with an optimized sky coverage at each station. On-source times are determined to meet the defined target SNR (15 dB and 20 dB for S- and X-band respectively), considering source fluxes, antenna sensitivities, and the recorded data rates. Slew times are calculated according to the antenna specifications.

We chose to stay close to the standard setting of S/X observations. Basically, the GEO-SX mode was used with increased data rates of 1 Gbps and 2 Gbps for FAST02 (DDC mode) and FAST03 (PFB mode), respectively. Badary and Zelenchukskaya used data rates of 6 Gbps and 4 Gbps for FAST02 and FAST03, respectively. Due to constraints and a very high sampling rate at the Russian stations, a special relaxed

1. FESG Wettzell, Germany
2. Observatorio de Yebes-IGN, Spain
3. IGG Bonn, Germany
4. Institute of Applied Astronomy RAS, Russia
5. Technische Universität Wien, Austria
6. BKG Wettzell, Germany
7. MPIfR Bonn, Germany

mode (only every 4<sup>th</sup> scan was observed) was implemented for ZELEN13M (Zv) and BADAR13M (Bv). The minimum scan length was set to 20 seconds, and sub-netting was enabled in order to get a reasonable sky coverage at all sites.

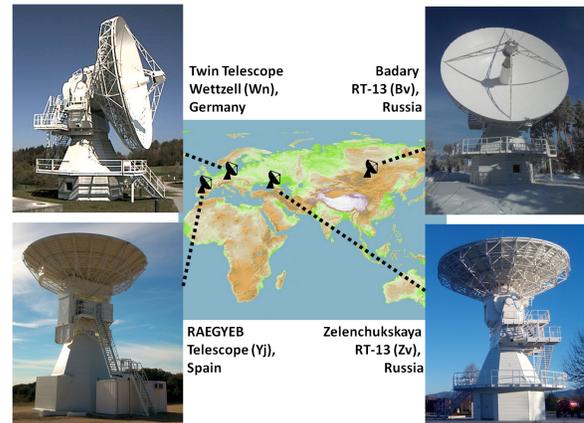
A summary of the schedule can be found in Table 1. With this setup, WETTZ13N (Wn) and RAE-GYEB (Yj) get about 70 scans/hour which is an increase of about a factor of 3 compared to normal IVS-R1 and IVS-R4 sessions. Another apparent fact is that about 30% of the time is used for calibration. In order to get the most scans/hour this limiting factor has to be decreased by revising the calibration procedures. However, this was not done for this schedule and is subject to future investigations.

**Table 1** Schedule summary for FAST02 and FAST03. With the fast VGOS antennas a remarkably large number of observations was reached, with an average of 70 and 73 scans/hour at Wn and Yj respectively (Russian antennas only participated in every fourth scan).

	FAST02				FAST03			
Session start	2015-12-16 13:00 UT				2015-12-21 9:00 UT			
Duration [h]	24				6			
Site statistics	Wn	Yj	Bv	Zv	Wn	Yj	Bv	Zv
Obs. time [%]	42	43	12	11	42	42	11	10
Cal. time [%]	31	31	8	8	32	32	8	8
Slew time [%]	19	25	13	14	19	26	13	14
Idle time [%]	8	1	67	67	7	0	67	67
Scans total	1658	1658	413	415	510	510	126	128
Scans/hour	<b>70</b>	<b>70</b>	18	18	<b>73</b>	<b>73</b>	19	19
Avg. scan [sec]	22	23	25	24	21	21	21	21

### 3 Observation Network

A network of the antennas at Badary (Bv), Wettzell (Wn), Yebes (Yj), and Zelenchukskaya (Zv) was used. All antennas are VGOS-compliant and use 13.2-m dishes with ring-focus design. For the FAST-sessions they were at least temporarily equipped with S/X/Ka-band feeds and receivers. While Yj uses six down-converted intermediate frequency bands (IF) with two polarizations, the other antennas support eight bands from an up-down-converter, for example, to offer four bands in both polarizations. The European antennas used a DBBC2 and a Mark 5B+ for digitization and recording backend for digital down



**Fig. 1** The observation network used for FAST02 and FAST03.

conversion (FAST02) or polyphase filter bank mode (FAST03). The Russian antennas used the proprietary Broadband Acquisition System (BRAS) [5, 6, 7] which implements direct sampling conversion and the Data Recording System (DRS) for high speed recording. Both systems are developed in Russia.

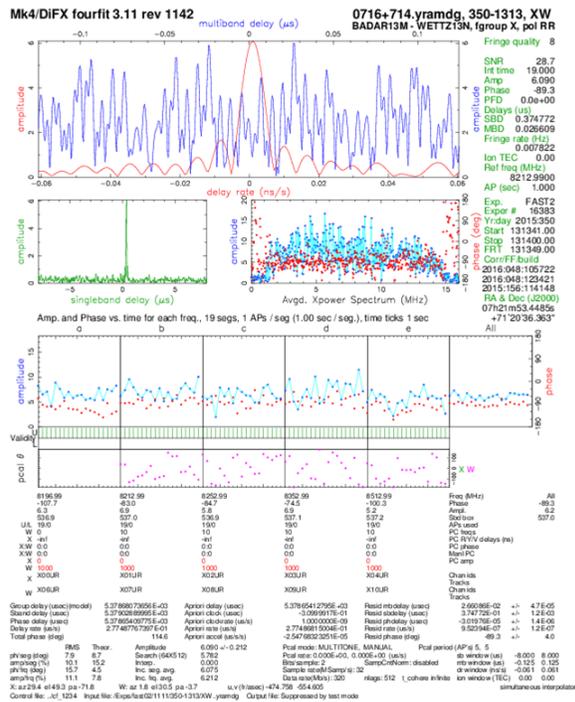
Badary and Zelenchukskaya radio telescopes observed every fourth scan of the 24-hour FAST02 experiment due to limited disk capacity. The reason is that the current version of the DRS software cannot automatically switch to a free disk pool during a running session. Therefore, this could have been changed manually by the operator, using a patched software but to avoid potential operator mistakes, we decided to observe without manual switching.

## 4 Correlation

The correlation was successfully done at Bonn, Germany and at the IAA in Russia to do extended investigations into different aspects.

### 4.1 Correlation at the Bonn Correlator, Germany

FAST02 was correlated in Bonn using the DiFX ([3]) software correlator. To correlate this experiment, “zoom band mode” was used to deal with the different backend setups: the Russian antennas recorded the data



**Fig. 2** Baseline Bv-Wn (zoom band). In this case only five X-band channels are seen because of the splitting of Bv data into three files, of which only one was used for the correlation.

using direct sampling (3 x 512 MHz channels), whilst Yebe and Wettzell used 16 x 16 MHz-wide channels. DiFX was instructed to extract and cross-correlate only the part of the bands which were common to all four stations. Because the Russian antennas wrote the data into three different files (one per IF output), three processes of correlation would have been required. We only performed one pass, hence we correlated only five X-band channels (see Figure 2).

**4.2 Correlation by the IAA, Russia**

Correlation was also performed at the IAA RAS with DiFX 2.4.0 on the new blade-server hybrid cluster together with a new GPU-based correlator [4]. Because of the mixed bandwidth setup (Wn and Yj with 16 MHz-wide channels; Bv and Zv with 512 MHz), and also shifted sky frequencies by 10 kHz at Wn and Yj, it was necessary to use the *zoom band* mode of DiFX. It allows extraction of exact frequency ranges from spectra for the correlation. One method is to set

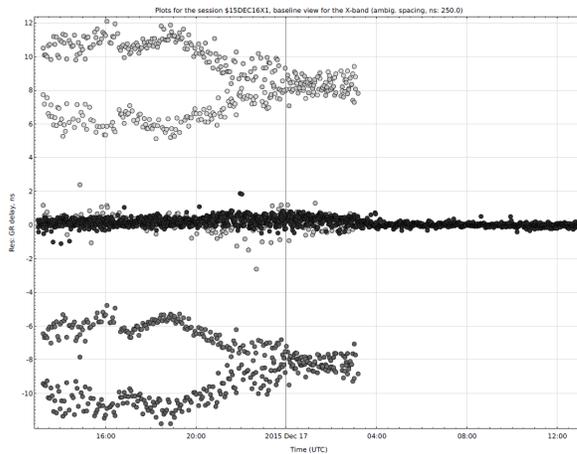
10.24 MHz bandwidths of every zoom band channel to get power of two spectral points in correlated data used with HOPS (first time suggested by the Chinese RU0197 fringe test). Another method is to shift the LO by 10 kHz and put proper values into the VEX file for the Bv and Zv antennas (suggested by W. Brisken). Both methods were applied, and fringes were obtained. Additionally, analysis data were used for a second correlation method. The data of the Russian antennas from three individual 512 MHz-wide channels were merged into a single VDIF file, and all 16 frequency channels were correlated in one pass. We also performed correlation of the Bv-Zv baseline only with 512 MHz-wide channels and an independent correlation of three groups of 16 MHz-wide channels: two in X-band and one in S-band. Post-processing was done with the PIMA software [8] without adaption of phase calibration (pcal).

**5 Analysis**

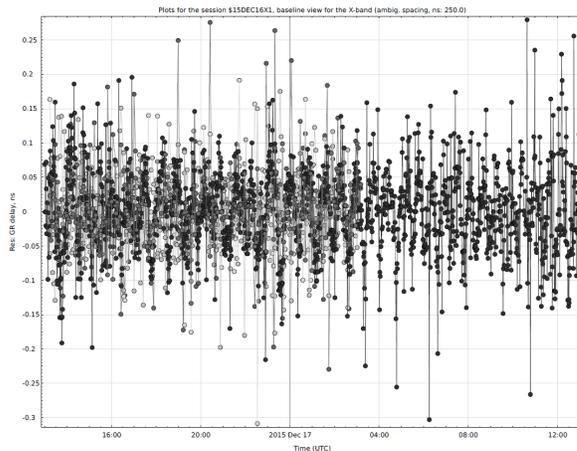
**5.1 Analysis by the IGG Bonn, Germany**

The data processing has been done with vSolve [2]. This includes the resolution of ambiguities and the calculation of the ionospheric contribution. In the least-square adjustment, clocks (reference clock: Wettzell) and zenith wet delays were estimated in the form of 60-minute continuous piece-wise linear functions (CPWLF) and gradients as daily CPWLF. The corresponding residuals are depicted in Figure 3. Significant offsets can be seen between Wettzell/Yebes and Badary/Zelenchukskaya, which are currently unexplained. Further investigations are in progress to find the reasons for these inconsistencies. Most probably this is due to inconsistencies of the station setups.

To overcome this issue, we estimated baseline clock offsets for the baselines Yebe-Badary and Yebe-Zelenchukskaya and ended up with weighted root mean squared residuals at the level of legacy VLBI sessions, i.e., 57 ps. As can be seen in Figure 4, there is a saw-like structure in the residuals for all baselines with Yebe. This slightly degrades the solution. However, this feature can be explained by the behavior of the air conditioning system.



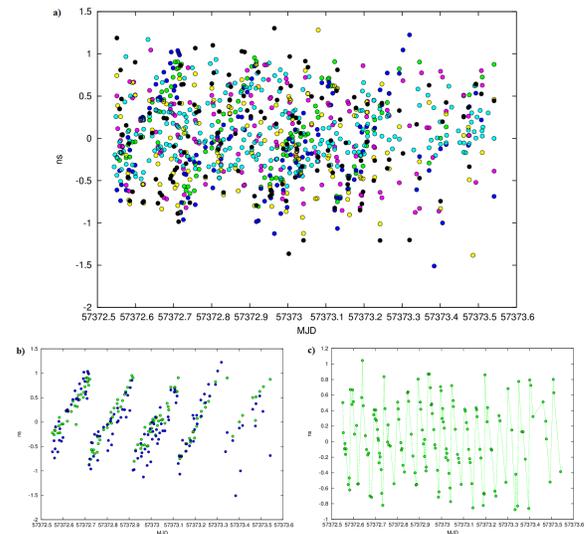
**Fig. 3** Post-fit residuals for all baselines. Residuals around zero belong to Wetzell-Yebes (black) and Badary-Zelenchukskaya (gray).



**Fig. 4** Post-fit residuals when estimating baseline clock offsets for all baselines, especially the residuals for the Wetzell-Yebes baseline (black), which represent the spurious saw-like variations at Yebes due to the air conditioning system.

## 5.2 Analysis by the IAA, Russia

The analysis was also done with the “Quasar” software suite (see Figure 5). The top panel a) of Figure 5 looks rather noisy, but there are no significant triangle closures. The baselines with Badary (panel b) of Figure 5: WnBv and YjBv) allow the assumption of several clock breaks. However, ZvBv (panel c) of Figure 5) does not show such peculiarities, but on the contrary there are strong saw-like patterns of clock irregularities. The data from WnZv and YjZv do not show anything unusual.



**Fig. 5** Intermediary solution: a) residual plot for baselines WnBv (blue), YjBv (green), BvZv (violet), YjWn (gray), YjZv (yellow), WnZv (black), b) focus on baselines WnBv (blue) and YjBv (green), and c) focus on baseline ZvBv.

As a result, the triangle disclosures are about 0.5 ns in magnitude revealing a saw-like pattern, which have different periodicities for different baseline combinations.

## 6 Conclusion and Outlook

The scheduling and observation of the first FAST sessions were a first step using VGOS antennas for fast-slewing experiments. FAST02 delivered results using existing formats and recording systems. The correlation ran smoothly within ten hours. We had high SNRs and a detection rate of 99% because in only one percent of the scans telescopes were late on source. This demonstrates that the network is able to observe fast-slewing experiments. The analysis used the S/X-legacy mode which is comparable to all other IVS experiments. There was a higher temporal resolution, but there is also the need to investigate 17 ns triangle misclosures, which might be caused by different station setups and by a problem with the cycling of the air conditioning system at Yebes, which influenced the analysis results and needs to be eliminated.

The data analysis was successful with WRMS residuals at the level of legacy VLBI sessions. Unfor-

tunately, there is a spurious signal in the residuals due to the behavior of the air conditioning system at Yebees, which degrades the solution. Thus, estimating zenith wet delays with a higher temporal resolution than one hour has no physical meaning. However, due to the huge amount of observations, it would be possible to go down below ten minutes, which represents the success and opportunities of our observing mode.

After having gained experience from the two FAST campaigns, where we demonstrated the possibility of scheduling, observing, correlating, and analyzing the fast slewing mode, we can now follow-up with better designed observations. Furthermore, we would like to enlarge our array to more VGOS antennas that are equipped with S/X-receiving systems. We plan to improve and smooth the processing, by using a common setup and a standardized way of observation. An important result obtained from these campaigns is that shorter scan lengths are possible: ten seconds might be achieved while keeping the good performance.

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