Onsala Space Observatory – IVS Technology Development Center Activities during 2021–2022

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Abstract We give a brief overview on the technical development related to geodetic VLBI done during 2021 and 2022 at the Onsala Space Observatory.

1 General Information

The technical development work for geodetic VLBI at the Onsala Space Observatory (OSO) was dedicated to the Onsala twin telescopes (OTT) and the Onsala 20-m telescope (On), see Figure 1. The main activities are summarized as follows and discussed in detail in the subsequent sections:

- Focal adjustment of the OTT
- Flux density monitoring of quasars with the OTT
- Testing new e-transfer software
- Testing 32 and 64 Gbps recording with the OTT
- Fringes up to 15 GHz with the OTT
- An assessment of using future VGOS receivers for radiometric corrections of the signal delay due to atmospheric water vapor.

Fig. 1 The three telescopes at Onsala used for IVS observations: Ow (left), Oe (middle), On (right).

2 Focal Adjustment of the OTT

As already reported in [1], an adjustment of the receiver position in the eastern OTT (Oe) was done using a motorized focal-finder developed in-house. This work was started in 2020 and an optimized position for the receiver was determined for Oe. The focal-finder equipment had to be left on Oe during the Covid-19 pandemic and could only be taken down in March 2022, leaving the Oe receiver at the +20 mm position. Unfortunately, there is a suspicion that the focal-finder itself was not as stable as expected and introduced small elevation-dependent tilt movements of the receiver during observations, which were detected during the analysis of the ONTIE sessions [2]. It was thus decided to remove the focal-finder in March 2022 from Oe and to not use it for a similar work on the western OTT (Ow). For Ow the optimization work was done instead using fixed distance pieces, so-called shims. On July 11, 2022, the preliminary best receiver position was determined to be +15 mm and has been used since then in all VGOS observations.

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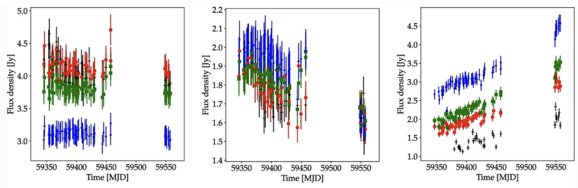
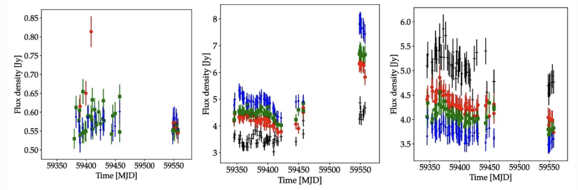
3 Flux Density Monitoring of Quasars with the OTT

During 2021 and 2022 we used the OTT to observe a small sample of quasars to verify the system temperature measurement systems now installed on the telescope control systems. We found that the electronics and calibration tables used to monitor system temperatures for the Onsala twin telescopes are working as expected within the nominal 10% uncertainty. With minor improvements to the model of antenna gain vs. elevation, and corrections for backend systematics, flux densities of ∼500 mJy-sources could in the future be monitored to within a few percent in the 3–15-GHz band. Example light curves are shown in Figure 2. For more details on this flux monitoring project, we refer to [3]. Once the full international VGOS network is capable of routinely monitoring system temperatures during observations, the astronomical community may get regular broadband flux density monitoring (and full-polarization mapping) of hundreds of sources "for free" during geodetic VLBI observations.



(a) 0552+398 (b) 1144+402 (c) 1156+295



(d) 1617+229 (e) OJ287 (f) 3C418

Fig. 2 Multi-frequency light curves of six sources observed in the FM-sessions [3]. Flux densities in the four VGOS bands 1, 2, 3, and 4 are shown with black crosses, red circles, green squares, and blue dots respectively. Note that the vertical scale is different for the different sources.

4 Testing New e-Transfer Software

Geodetic VLBI observations produce voltage data which need to be copied from the stations to the correlator before the correlation and subsequent geodetic analysis can take place. Especially with the new VGOS observations, the data volumes can be significant—typically ∼24 TB for a 24-hour session with the current bandwidth and scan times. While some other stations send data as physical shipment of hard drives, Onsala transfers all data electronically via the Internet, also called *e-shipping*. Special e-shipping software has been developed for this purpose, within the astronomy and geodesy VLBI communities, with the two major packages in use today being tsunamid/tsunami (server/client) and jive5ab/m5copy (server/client). While these work, they have limitations and issues which are increasingly severe when dealing with the large data sets from VGOS antennas. In particular, because transfers may take several days and nights, it is desired to minimize user input and supervision and to simplify fast recovery in case transfers are aborted before completion.

A new software, simply called "etransfer", was developed by M. Verkouter at JIVE. This consists of a server/client pair called etd/etc, and it has a number of improvements compared to existing software packages. In particular, the overhead time used to establish the connection for sending many files (important for Onsala VGOS data which are recorded in eight parallel files per scan) is minimal (the jive5ab/m5copy overhead here is significant), and there is a fast and reliable option to *resume* broken transfers (not available in tsunami). The only current drawback with etc/etd is that it cannot read directly from VBS file systems, and hence data have to first be mounted using the tool `vbs_fs`, but direct VBS reading may come in the future.

An example of m5copy transfer of 6-TB EU-VGOS data from Onsala to VIEN correlator can be seen in Figure 3. With m5copy, the large files are transferred with the maximum available bandwidth of 1.3 Gbps, while the smaller files suffer significant overhead and the effective transfer rate is only 657 Mbps. The resulting average speed is only 762 Mbps. With etd/etc, the maximum 1.3 Gbps is achieved for all files.

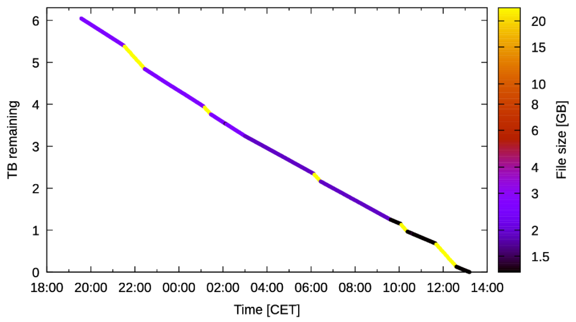


Fig. 3 Example of m5copy transfer of 6 TB EU-VGOS data from Onsala to VIEN correlator. (Image credit: F. Jaron at VIEN correlator.)

5 Testing 32- and 64-Gbps Recording with the OTT

Current VGOS observations with OTT use 8 Gbps bandwidth (some S/X still use 128 Mbps). More bandwidth means better signal-to-noise ratios for geodetic delay measurements (for the same observing time), and possibly shorter scan times (for the same scan SNR), i.e., more possible scans, which lead to better measurements of the geodetic parameters for, e.g., Earth orientation.

While the current 8-Gbps limit is in place for practical reasons (data transfer times to correlators, correlation time, etc.) the OTT hardware in principle supports higher data rates. We carried out test observations with a 32-Gbps data rate to test and verify the OTT hardware capabilities. We found that while our recording machines (flexbuffs) can handle up to 50 Gbps for longer periods of time, the network topology was limited to 32 Gbps. Changing the network, we managed to record 64 Gbps for 60 seconds using RAM buffers, but sustained recording for longer periods needs changes in our flexbuff setup.

Also, the current backend firmware (DBBC3 firmware version 124) only supports 8 Gbps, so for this test we used a preliminary version 125 which supports higher bit rates. With this, we successfully recorded data at 32 Gbps. We correlated these data and found fringes, proving that the full chain works. But we found that the v125 firmware was not fully stable. We now await the next v126 firmware which should enable more flexible DBBC3 configurations with higher bit rates in a stable way.

6 Fringes up to 15 GHz with the OTT

Going to higher (than normal VGOS, i.e., > 11 GHz) frequencies is desirable because it will improve geodetic delay measurements (larger bandwidth equals better constraints), open frequency bands with less RFI, and allow for different sources and/or source positions (e.g., core-shift effects) to be studied in more detail. While the OTT are in principle ready to receive frequencies up to 15 GHz, the cable patching of the signals coming from the telescope to the backend limits the upper frequency to 11.4 GHz.

But, by changing the cable connections we can use the 11.4–15.2-GHz band with existing hardware and investigate the sensitivity (SEFD) and search for fringes up to 15 GHz. Preliminary SEFD measurements on Cas A for the eastern OTT antenna (Oe) are shown in Figure 4. Fringes for the uppermost BBCs towards the bright source 0059+581 (a common VGOS fringe-finder source) are shown with the HOPS fourfit software in Figure 5.

We conclude that OTT can observe up to 15 GHz with existing equipment but currently needs cables to be moved from the standard VGOS setup. Preliminary SEFD measurements report 3000–4000 Jy in the 14–15-GHz band. Fringes were found in both linear polarizations on the OTT baseline towards 0059+581

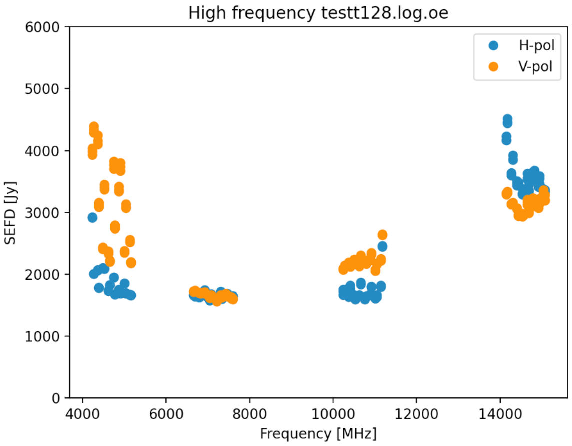
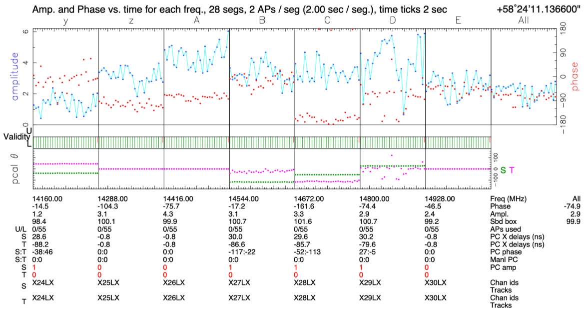


Fig. 4 Preliminary SEFD measurements up to 15 GHz using the eastern OTT antenna towards Cas A. We note that there was a minor Field System bug in ONOFF for BBCs wider than 32 MHz (these were done with 128 MHz during the 32 Gbps test), which was fixed after these figures were made. It could alter the frequencies slightly but not impact the results in a significant way.



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     14160.00   14288.00   14416.00   14544.00   14672.00   14800.00   14928.00   Freq (MHz)           All
     -14.5      -104.3     -75.7      -17.2      -161.6     -74.4      -46.5      Phase              -74.9
     1.2        3.1        4.3        3.1        3.3        2.9        2.4        Ampl.                2.9
     98.4       100.1      99.9       100.7      101.6      100.7      99.2       Sbd box             99.9
U/L  0/55       0/55       0/55       0/55       0/55       0/55       0/55       APs used
  S  28.6       -0.8       -0.8       30.0       29.6       30.2       -0.8       PC X delays (ns)
  T  -88.2      -0.8       -0.8       -86.6      -85.7      -79.6      -0.8       PC X delays (ns)
S:T  -38:46     0:0        0:0        -117:-22   -52:-113   27:-5      0:0        PC phase
S:T  0:0        0:0        0:0        0:0        0:0        0:0        0:0        Manl PC
  S  1          0          0          1          1          1          0          PC amp
  T  0          0          0          0          0          0          0
  S  X24LX      X25LX      X26LX      X27LX      X28LX      X29LX      X30LX      Chan ids
                                                                                  Tracks
  T  X24LX      X25LX      X26LX      X27LX      X28LX      X29LX      X30LX      Chan ids
                                                                                  Tracks
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Fig. 5 HOPS fourfit plot showing the upper eight BBCs used in the high-frequency test with fringes up to 15 GHz towards source 0059+581.

up to 15 GHz. But phase-cal signals are likely too weak at these frequencies and need additional work, possibly using equalizers to allow boosting the level at high frequencies while attenuating the level at lower frequencies.

7 Future VGOS Receivers for Calibration of the Wet Delay

An important motivation for the design of VGOS was to have many observations, at different elevation angles, per unit time, in order to infer accurate estimates of the wet propagation delay. Microwave radiometers, often referred to as Water Vapor Radiometers (WVR), have been a complementary technique and used to provide independent wet delays for the VLBI data analyses [4, 5]. The main drawback of using a WVR for wet delay calibration in VLBI is that the method breaks down during rain and when large drops of liquid water are present in the observed air volume. During conditions when no clouds contain water droplets the WVR method will work well observing one frequency only. But this is not always true for many geodesy VLBI sites, so the standard design is to use two frequencies in order to estimate the two unknowns: the amount of water vapor (the wet propagation delay) and the amount of liquid water in the form of cloud droplets. Because the WVR method cannot provide independent wet delays during all weather conditions, its main use has been to validate the wet delay estimates from the VLBI analyses at specific time periods.

Rather than having a standalone microwave radiometer we have, through simulations, evaluated the possibility of using radiometric data from the VLBI receiver in the VGOS telescopes [6]. An advantage is that the water-vapor emission sensed by the radiometer originates from the same atmospheric volume that delays the VLBI signal. This is of specific importance when validating estimated horizontal gradients.

The simulated sky brightness temperatures and the wet delays were calculated from the ERA-Interim analysis of European Centre for Medium Range Weather Forecasts (ECMWF) for the Onsala site. We added a root-mean-square (rms) receiver noise in the range from 0.1 K to 1.0 K. With an rms noise of 1 K, and observations evenly spread between elevation angles from 10° to 90° we obtained an rms error of the estimated equivalent Zenith Wet Delay (ZWD) of the order of 3 mm for a one frequency algorithm, used under cloud free conditions, and 4 mm for a two frequency algorithm, used during conditions with clouds containing water droplets. An important conclusion from the simulations was that one of the frequencies observed must be close to the water vapor emission line at 22 GHz and at least above 20 GHz.

Figure 6 summarizes the expected error in the equivalent ZWD for a WVR observing at two frequencies in the range 14–24 GHz. The optimum frequency pair, in the sense that it offers the lowest expected error, is indicated by a pair of circles. Note that the reason for the small errors at six air masses ($\approx$ 10° elevation angle) is that the errors are presented in the equivalent ZWD.

Of course, just as for the case of a standalone WVR, these simulated results exclude rainy conditions when the method does not work. The ZWD errors are typically reduced by a factor of 3 when the receiver rms error is reduced from 1.0 K to 0.1 K. This implies that the receiver's measurements of the sky brightness temperature are likely to be the main error source. Therefore, we have high priority to carry out further analyses related to the receiver performance.

8 Outlook and Future Plans

Our plan for the upcoming two years is to continue optimizing the OTT systems for VGOS operations.

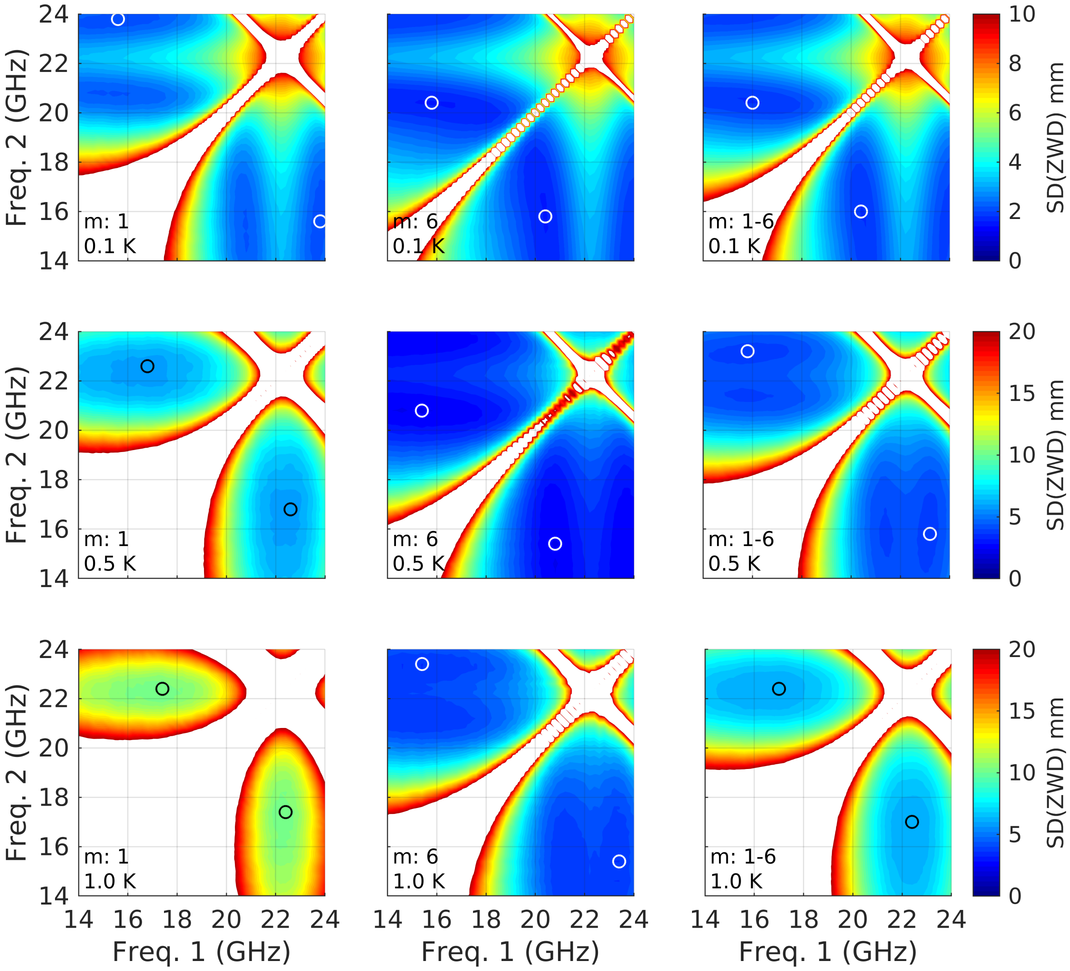

Fig. 6 Simulations of the expected ZWD rms error (standard deviation) for the two-frequency algorithm for one air mass (left column), six air masses (middle column), and one to six air masses (right column). The receiver noise is 0.1 K (top row), 0.5 K (middle row), and 1.0 K (bottom row). The white areas correspond to rms errors larger than the upper limit of the scale to the right, and the circles mark the lowest rms error obtained for the optimum frequency pair, from [6].

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