Onsala Space Observatory – IVS Technology Development Center Activities during 2015–2016

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Abstract We give a brief overview of the technical development related to geodetic VLBI done during 2015 and 2016 at the Onsala Space Observatory with emphasis on details of the design and tests of the signal chain for the Onsala Twin Telescopes project.

1 General Information

The technical development work for geodetic VLBI at the Onsala Space Observatory (OSO) was entirely dedicated to the Onsala Twin Telescopes (OTT) project. It included the design, assembly, testing, and installation of the OTT signal chain. The main activities can be summarized as follows and are discussed in more detail in the subsequent sections:

- construction of cryogenic receiver and selection of feeds.
- design and construction of the signal chain.
- time and frequency distribution system.

The telescopes were ordered in late 2014 from MT Mechatronics [1]. During 2015 the necessary infrastructure work was done at OSO to prepare for the installation of the telescopes. Two concrete towers were constructed to provide very stable long-term foundations for the telescopes. The towers are located 75 m apart from each other. The construction work was finished in early spring of 2016. The infrastructure work performed during 2015 and 2016 included also installation platforms, road work, electricity, and fiber and computer network.

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Fig. 1 Photo of the OTT taken on 15 August 2016 during the lift of the azimuth cabin on to the concrete tower of the northern telescope. The two reflectors and the azimuth cabin of the southern telescope are still on the ground. The telescope towers have no cladding yet.

The telescopes were delivered to OSO in June 2016 and the assembly and installation was carried out during the summer and autumn of 2016. The photo presented in Figure 1 was taken during the lift of the azimuth cabin on top of the concrete tower of the northern telescope. The two reflectors and the azimuth cabin of the southern telescope are still on the ground. The telescopes are equipped with axis-symmetric ring focus, dual-reflector systems with primary and secondary reflectors of 13.2 m and 1.55 m in diameter, respectively. The site acceptance test for the OTT took place at the end of November 2016.

2 Construction of Cryogenic Receivers and Selection of Feeds

The cryogenic receivers integrate the broadband feeds and the first stage amplifiers at cryogenic temperatures to provide ultimate sensitivity. The receiver design was driven by two requirements: 1) to fit into the feed cone on the telescopes and 2) to make the interior and the volume dedicated for the feed installation flexible enough to accommodate different types of feeds. Figure 2 shows the two OTT cryostats during the assembly in the OSO Electronics Laboratory in August 2016. The feed selection was dictated by frequency range, sensitivity, and polarization properties.

After consultation with the IVS VGOS Technical Committee (VTC) and taking into consideration the local RFI situation at OSO as well as the requirements for keeping compatibility with the legacy S/X system, we decided to use two different feeds for the two OTT telescopes. One receiving system will be equipped with a 3–18 GHz Quad-Ridged Feed Horn (QRFH) [2] and the other with an Eleven Feed for the 2–14 GHz range [3]. The mechanical design of the vacuum window and the infrared window was done to make it suitable for both the Eleven feed and the QRFH. The two systems are exchangeable so that either of the telescopes can be equipped with the QRFH or Eleven-feed receiver system.

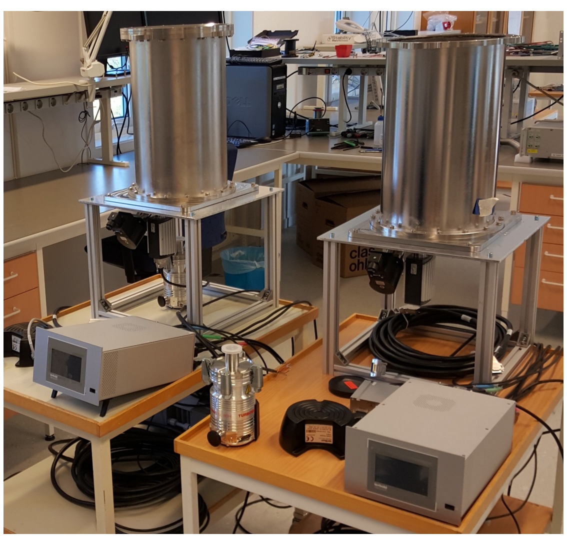

Fig. 2 The two cryostats for the OTT during the assembly in the OSO Electronics Laboratory.

Fig. 3 The interior of the two OTT cryogenic receivers with QRFH (left) and Eleven-Feed (right).

Special care in the cryostat design was taken in order to provide good mechanical references between the feed mechanical position and the interface to the telescope. This will ensure that the phase center of the feed will be well aligned with the focal point of the reflector system. For support of the receiver we used glass-fiber pipes with lateral openings to access the cryostat interior and mount components. The feed is mounted on a plate bolted to the glass-fiber support and connected with flexible copper braids to the cold head to transfer the heat and at the same time to prevent transfer of mechanical vibrations from the cold head to the feed. Pictures of the interior of the cryostats are shown in Figure 3. The first stage Low Noise Amplifiers (LNA) for the two receivers were purchased from Low Noise Factory [4]. The signals from the feed are fed first to directional couplers for inserting noise calibration signals and then passed to the LNAs.

The purchase of the QRFH was agreed with Sander Weinreb at Caltech Institute of Technology. A contractual agreement was set up between OSO and Caltech to scale up the existing 2–14 GHz Caltech QRFH design and to optimize the performance to provide optimal efficiency for 3–18 GHz for the MT Mechatronics ring focus reflector system. The optimization was carried out using CST Microwave studio [5]. The goal was to obtain 60% efficiency over 90% of the 3–18 GHz frequency range at a fixed focus position of the feed. Two feeds were purchased with the provision that the cryostat with the Eleven feed could be upgraded with QRFH at a later stage. The feeds were received in August 2016 and the beam patterns were measured in the beam measurement range at the Antenna Group, Department of Signals and Systems, Chalmers University of Technology. The aperture efficiency calculated from measured QRFH beam patterns is presented in Figure 4. It is below the expected 60% over large parts of the band. However, as it will be discussed later in this section, the sensitivity obtained from the measured equivalent noise temperature is nonetheless expected to be well within the VGOS specifications.

The integration of the QRFH was accomplished in November 2016 and the equivalent receiver noise was tested at the newly build Y-factor measurement facility at the OSO Electronics Laboratory using the sky as cold load and an absorber at ambient temperature as hot load. The results are presented in Figure 5. The careful design of the cryostat opening that does not truncate the beam, the efficient cooling of the feed, and especially the use of an amplifier with very low equivalent noise temperature made it possible to reach excellent receiver noise. The equivalent receiver noise is in the order of 10 K for approximately half of the receiver band. The increase in receiver noise at the low part of the band is due to a mismatch between the feed impedance and the input impedance of the LNA.

In order to accurately estimate the overall system sensitivity, the spillover noise contribution after the reflector system has to be estimated accurately. The estimation of the overall on-sky sensitivity of the QRFH was done using a GRASP system simulator [7], where the field patterns were analyzed in the reflector geometry using GRASP [6]. The sensitivity for a large range of telescope elevation angles was simulated with the system simulator using measured QRFH data and the receiver noise test results presented in Figure 5 to estimate the equivalent system noise. The simulated system sensitivity for the reflector looking at zenith is presented in Figure 6. The VGOS sensitivity specification is set in [8] as 2,000 Jy over all elevation angles. Our analysis showed that the sensitivity of the QRFH receiver is well below the specification for the whole range of elevation angles between ten degrees and zenith.

For the integration of the Eleven feed we decided to use a passive feeding network in front of the LNAs, thus decreasing the number of amplifiers from eight

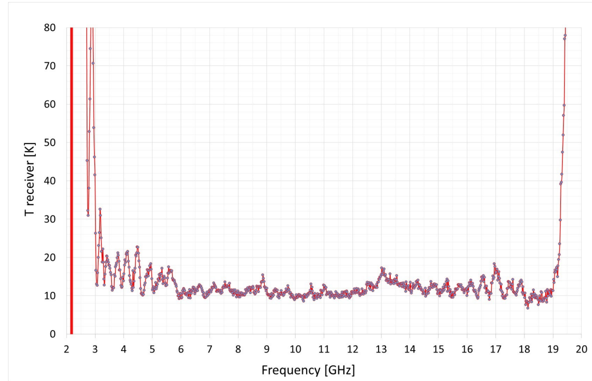

Fig. 5 Results from the Y-factor measurements of the QRFH receiver.

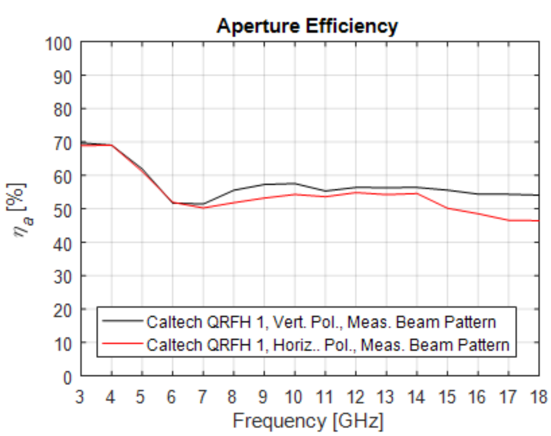

Fig. 4 Aperture efficiency of the 3–18 GHz Caltech QRFH calculated from measured beam patterns.

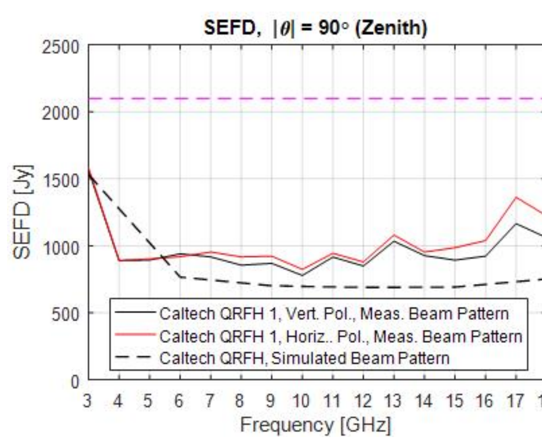

Fig. 6 Simulated SEFD using measured QRFH beam patterns and Y-factor test results.

(four LNAs per polarization) to two (one LNA per polarization). Tests were done in December 2015 and the measured equivalent receiver noise was in the order of 25 K. We did the same analysis as described in the previous paragraph to estimate the expected sensitivity and the results showed that this system will achieve SEFDs below 2,000 Jy.

3 Signal Chain

As the OTT telescopes are placed approximately 800 meters from the H-maser in the 20-m antenna building, we had to decide how to transfer frequency and RF signals, and where to locate the backends. Three possible placements for the backend systems were discussed: 1) in the towers of the telescopes, 2) in the 25-m control room, and 3) in the 20-m control room. After careful consideration of advantages and disadvantages for each of these alternatives we decided to place the backends of type DBBC3 [9] in the 20-m control room and to transfer the frequency from the existing H-maser in the 20-m building to the OTT. For the distribution of the RF as well as frequency we decided to use Radio Frequency over Fiber (RFoF) links. The installation of all fiber links was made taking into account very good thermal insulation. The fibers are placed at least 80 cm below surface, where possible, and insulated with thick foam everywhere else. The type of fiber cable used is LS Cable LSGS-06-OC0190-02 G.652D single mode fiber. This cable type was selected because of its excellent thermal coefficient of delay.

The term “Signal Chain”, as used in this report, covers the entire active and passive RF circuitry used to amplify the astronomical signals received by the telescope, to couple noise and phase calibration into the system, to provide a link over optical fiber cable over a distance of almost one kilometer, and also to split the whole frequency band into sub-bands that are fed into the digital backend system. It consists of four functional units, interconnected in the following order: cryogenic receiver, RF front-end, RFoF link, and RF backend.

The functionality of the cryogenic receiver as part of the signal chain is to capture the signals from the telescope via the feed horn, couple phase and noise calibration, and provide low noise amplification. The RF front-end unit provides second stage amplification. To avoid potential problems with the dynamic range of the RFoF link as well as to mitigate possible saturation of the amplifiers in the signal chain due to strong RFI signals, we decided to split the RF-band at the output of the receiver into two sub-bands and use two RFoF links for the Low and High sub-bands of each polarization. This functionality is also provided from the RF front-end. The RFoF links were purchased from RF Optics [10]. In the control room the optical signals are down-converted to RF. At the output of the optical receivers for the Low and High sub-bands we installed filter banks to form four IF channels that are passed to the DBBC3. Several options for the filter banks were discussed. The goal was to design a system that will provide full VGOS operations in the future and at the same time be compatible with the present Haystack system to allow VLBI sessions as early as possible. At present time (end of 2016) Haystack is using 512-MHz bandwidth around center frequencies of 3.3, 5.5, 6.6, and 10.5 GHz. After discussions with Jim Lovell and Gino Tuccari [11] we adopted the IF bands as listed in Table 1.

Table 1 Filter bands for four channels fed to the digital backend.

Band	Bandwidth (−20 dB) [GHz]	Pass-band [GHz]	LO [GHz]	IF [GHz]
1	1.8– 4.1	2.0–3.8	–	2.0–3.8
2	3.7–7.7	3.8–7.6	7.7	0.1–3.9
3	7.5–11.5	7.6–11.4	7.5	0.1–3.9
4	11.3–15.3	11.4–15.2	11.3	0.1–3.9

4 Frequency Distribution

As described in the previous section we decided to distribute frequency over a RFoF link from the H-maser at the 20 m to the OTT. The complexity of finding the best technical solution was additionally complicated because of the selection of the strategy for integrating the Cable Delay Measurement System (CDMS). We considered two alternative solutions for transferring time and frequency: a) actively compensated link from Menlo Systems, model RFCD1500, and b) using Cable Delay Measurement System (CDMS) from MIT Haystack [12]. After some experiments and considering the project time line we decided for the CDMS with ground units and RFoF transmitters both installed at the H-maser in the control room of the 20 m and RFoF receiver and antenna units installed at the receiver in each of the telescopes. The distribution of the 5-MHz frequency uses WDM (wavelength division multiplexing) fiberoptical transceivers and a two-way fiber between the CDMS units.

5 Current Status and Future Plans

In December 2016, the receiver with QRFH was installed in the northern telescope. The photo shown in Figure 7 was taken in the elevation cabin with the receiver installed on the trolley that provides transportation to the operational position in the telescope's focal plane. The signal chain was verified by sweeping a continuous wave signal via the directional coupler in front of the LNA and monitoring the response on a spectrum analyzer in the 20-m control room.

The plan for 2017 is to bring the OTT into full network operation and to participate in the CONT17 session in the autumn of 2017. During the spring of 2017 we will proceed with the scientific commissioning of the OTT infrastructure. The first step will be to perform comprehensive tests of the receiver and signal chain doing SEFD measurements, pointing, beam maps, and optimizing of the illumination of the subreflector. The next step will be to verify the performance of the CDMS checking long-term stability when the telescopes are in motion over a wide range of day and night temperature variations. The third step of the scientific commissioning is bringing into operation the two DBBC3 units that will be delivered in February.

We also plan to establish a new GNSS reference installation in the vicinity of the OTT. The antenna will be mounted on a slightly higher location (the site and antenna cable are already prepared) and the ground below should be covered with electromagnetic absorber material in order to minimize multi-path reflections. Furthermore, we plan to establish a network for local survey and monitoring of the OTT.

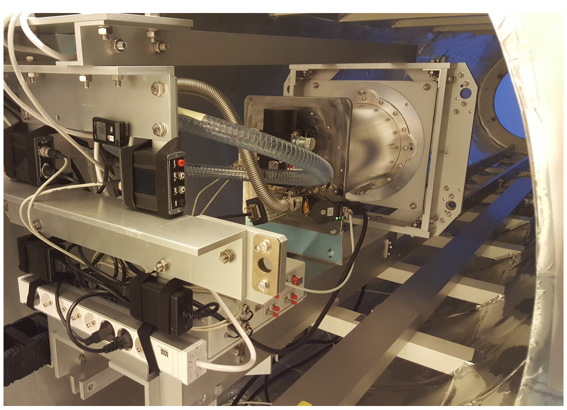

Fig. 7 Receiver with QRFH installed in the northern telescope.

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