Design, Implementation and Tests of the Signal Chain for the Twin Telescopes at Onsala Space Observatory

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Abstract We give an overview on the design, realisation and tests of the signal chain for the twin telescopes at Onsala Space Observatory. The choice of feed and frequency band was dictated by the requirement for keeping compatibility with the S-band system and existing reference frame established from the observations performed for decades with the OSO 20 m and in the same time creating system that will be flexible for adding new frequency bands above 14 GHz. We describe the design details and test results for the two developed systems: a cryogenic front-end with 3–18 GHz Quad-Ridged Feed Horn (QRFH), installed on the northern telescope and a cryogenic front-end with Eleven Feed for the 2–14 GHz range, installed on the southern telescope. We present the criteria and the selection process related to evaluation of key system components as for example the feed, LNA and RFoF link. We give also details on the design of the signal chain, including RF signal distribution to the back-end, noise and phase calibration and the system for monitoring and control of the RF chain.

Keywords VGOS, QRFH, Eleven Feed, RFoF, Signal Chain, RF Chain

1 Introduction

The Onsala Space Observatory (OSO) was involved in VLBI since the first experiments in 1968. The diverse advanced equipment acquired during the years as well as the longest time series in the VLBI database makes OSO to be an unique fundamental space geodetic site. In order to meet the new VGOS standards, activities for purchase of VGOS-compatible telescopes and equipment started as early as 2011. The contract for the delivery and installation of a twin pair of antennas was awarded to MT Mechatronics (MTM) (MTM, 2015) and the construction of the signal chain was decided to be accomplished by the Electronics Laboratory at OSO. A general overview on the Onsala twin telescope project is given in Elgered et al. (2017). Here we present the main activities related to the design and construction of the signal chain.

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2 System overview

The Onsala twin telescopes (OTT) are located approximately 800 meters from the 20 m antenna building which hosts the control room for the 20 m and the 25 m antennas as well as two H-masers. We were faced with a problem of how to decide on the transfer of frequency standard and RF signals and also to make decision for the location of the back-ends. Three possible placements for the back-end system were discussed: a) the towers of the telescopes, b) the 25 m antenna building (located 50 m from the OTT), and c) the 20 m antenna control room. After careful consideration of advantages and disadvantages for each of these alternatives we decided to place the back-ends in the 20 m antenna control room and transfer the time and frequency standards from the existing maser in the 20 m antenna building to the OTT. For the distribution of the RF as well as time and frequency standards we decided to use RF over Fiber (RFoF) links.

In the OTT project we define the signal chain as the system that captures the EM signal from the antenna reflector system and provides amplification, filtering subband division and transportation to the back-end, and also supplies noise and phase calibration signals. Part of the signal chain are also the components providing control and monitoring of the active elements and monitoring of the RF signals. Fig. 1 depicts a context diagram of the signal chain. The RF chain is a sub-system of the

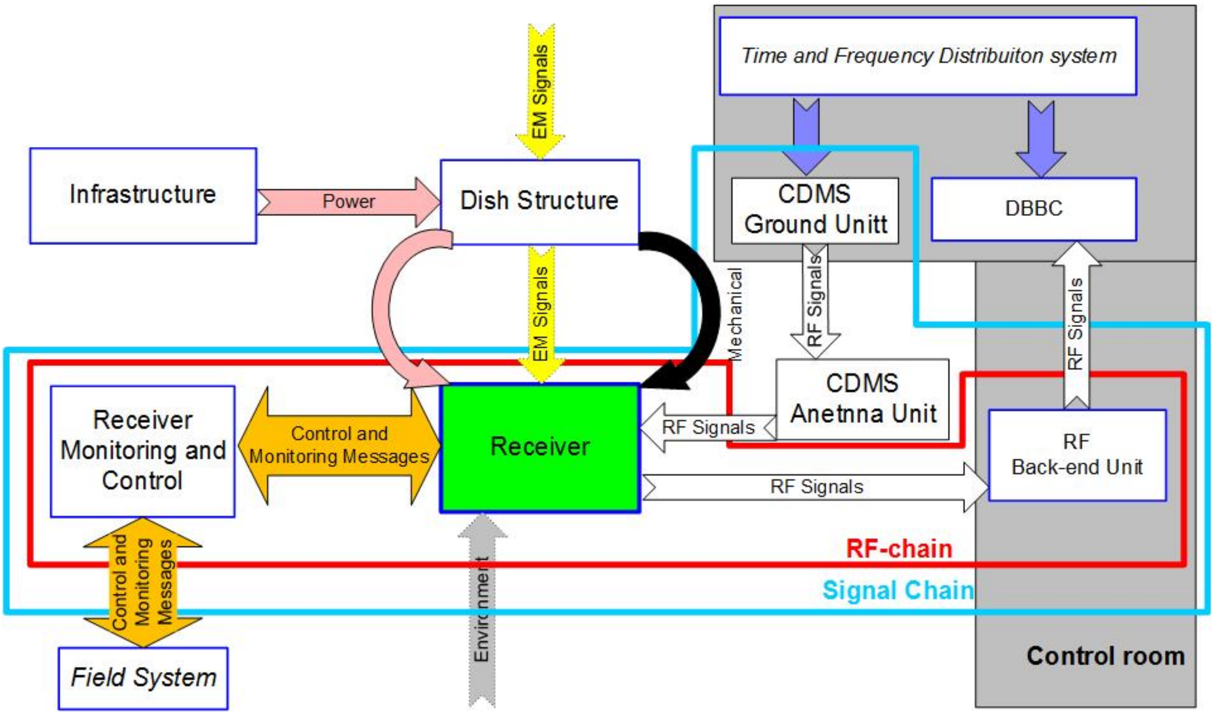

Fig. 1: Signal chain - context diagram.

signal chain that converts the EM signals received from the telescope and delivers them to the back-end. The RF chain consists of four functional units, interconnected in the following order: cryogenic receiver, RF front-end, RFoF link and RF back-end. The receiver that houses the feed and the cryogenic LNAs is located inside the elevation cabin and interfaces mechanically and optically to the antenna reflector. The RF signals are transported via RFoF link to the control room located in the 20 m antenna building. The RF Back-end unit provides amplification, filtering and sub-band division and supplies the signals to the Digital Base Band Converter (DBBC). The time and frequency distribution system uses reference signals from the H-maser which is also located at the 20 m antenna control building. 5 MHz and 1 pps are supplied to the DBBC and the ground unit of the Cable Delay Measurement System (CDMS) that is located in the same temperature-stabilised room as the H-maser.

The work on the signal chain started in 2015 with definition of the various sub-systems and selection of suppliers for the key components as for example feed, RFoF and CDMS. The detailed design of the cryostat, RF distribution and control system was carried out at the Electronics Laboratory at Onsala and was accomplished by the spring of 2016. The procurement, assembly and test of all locally designed sub-systems was finished and tested in the lab by the end of 2016. In January 2017 the first receiver was installed and tested on the north telescope followed by installation and tests with the second receiver on south telescope in April 2017.

3 Selection of feeds

The MTM antennas are equipped with axis-symmetric ring focus dual reflector systems. The diameter of the primary and secondary reflectors are 13.2 m and 1.55 m, respectively. This antenna geometry requires a feed with wide illumination angle. The feed selection was dictated by a few factors: frequency range, sensitivity and polarisation properties. After considering some input from the IVS working group and also taking in to account the local RFI situation at OSO, as well as the requirements for keeping compatibility with the S-band system and

Fig. 2: The interior of the two cryogenic receivers.

existing reference frame established from the observations performed for decades with the OSO 20 m telescope, we decided to have two different type of feeds covering different frequency bands for the OTT. It was decided that one of the telescopes will be equipped with 3–18 GHz Quad-Ridged Feed Horn (QRFH) (Akgiray et al., 2013) and the other one with an Eleven Feed for the 2–4 GHz range (Yang et al., 2011).

The purchase of the QRFH was agreed with Sander Winereb at California Institute of Technology (Caltech). A contractual agreement was set up between OSO and Caltech to scale up in frequency the existing 2–14 GHz QRFH design and optimize the performance to provide optimal efficiency for the 3–18 GHz for the MT Mechatronics ring focus reflector system. The optimisation was carried out using CST Microwave studio (CST, 2016). 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. Details on the feed analysis are given in Flygare et al. (2017).

4 Construction of the cryogenic receivers

The cryogenic receiver is the first component of the signal chain. The function of the cryogenic receiver as part of the signal chain is to capture the signals from the antenna via the feed horn, couple phase and noise calibration, and provide low noise amplification. Therefore, the receiver integrates the broad band feed and the first stage amplifier at cryogenic temperature to provide ultimate sensitivity for receiving sky signals. The receiver design was driven by the requirements to allow exchange of different type of feeds. Pictures of the two cryostats are shown in Fig. 2. 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 antenna. This will secure that the phase centre of the feed will be well aligned with the focal point of the reflector system. For the support of the receiver we used glass-fiber pipes with openings on the side to access the cryostat interior and mount components. The feed is mounted on an aluminum plate bolted to the glas-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. The heat load due to infrared radiation is minimised using Multi-Layer Insulation based on aluminum foil wrapped around the heat shields. The optical interface of the feed towards the sub-reflector is provided by an infrared window that minimises the heat load towards the 20 K stage and a vacuum window providing the hermetical sealing. The infrared window is constructed from thin teflon sheets separated by plastic mesh. The vacuum window is a self-supported Mylar film clamped with O-ring. The mechanical design of the vacuum window and infrared window was made suitable for both Eleven feed and QRFH. The signal from the feed is fed first to a directional coupler for inserting noise calibration signal and then passed to the LNA. The first stage gain Low Noise Amplifiers (LNA) for the two receivers were purchased from Low Noise Factory (LNF, 2016).

5 RF front-end and back-end units

The RF front-end unit is the component following the cryogenic receiver. To avoid potential problems with the dynamic range of the RF oF link as well as to mitigate possible saturation of the amplifiers in the signal chain from strong RFI signals we decided to split the RF-band at the output of the receiver to two sub-bands and use two RFoF links for the Low and High sub-bands of each polarisation. Thus the function of the RF front-end unit is to provide additional amplification of the RF signal and also to divide the signal to two sub-bands.

The RFoF links were purchased from RF Optics (RF Optics, 2016). The installation of all fibers was made taking in to account very good thermal insulation. They are placed at least 0.8 m below the surface, where possible, and insulated with thick foam everywhere else. The fibre cable used is LS Cable LSGS-06-OC0190-02 G.652D single mode fiber. This cable type was selected because its excellent thermal coefficient of delay.

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 have installed filter bank for forming four IF channels that are passed to the DBBC. Several options for the filter banks were discussed. The goal was to design system that will provide full VGOS operations in the future and at the same time to be compatible 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 discussion with Jim Lovell and Gino Tuccari (Lovell et al., 2016) we adopted the IF bands as listed in Table 1.

The OTT equipment located in the 20 m control room is shown in Fig. 3. The RFoF receivers supplies signals to the RF back-end unit which splits the RF to four sub-bands and feed them to the DBBC. There is additional functionalities providing the possibility to mon-

Table 1: Filter bands for four channels fed to the DBBC.

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

itor the spectra of the RF signal as well to analyse the phase calibration signal for each of the four sub-bands.

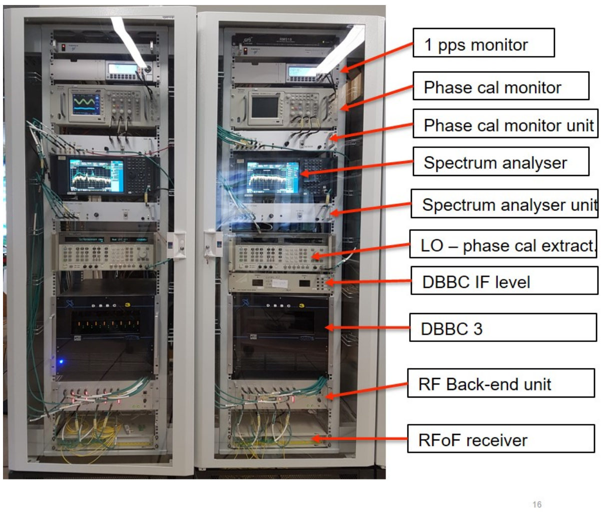

Fig. 3: The OTT equipment in the control room of the 20 m building. The left cabinet is for OTT-S, the right for OTT-N.

6 Phase and Cable delay measurement

As described in the previous section we decided to distribute the time and frequency normal over RFoF link from the H-maser at the 20 m to the two telescopes. The complexity of finding the best technical solution was additionally complicated because of the selection of strategy for integrating Cable Delay Measurement System (CDMS). We considered two alternative solutions for transferring the time and frequency normal: a) actively compensated link from Menlo Systems (model RFCD1500), and b) using the CDMS from MIT Haystack (CDMS, 2016). After some experiments and considering the project time line we decide to go for the CDMS with ground and RFoF transmitter both unit installed at the H-maser in the control room of the 20 m and RFoF receiver and antenna unit installed at the receiver in each of the antennas.

7 Test Results

The integration of the QRFH was accomplished in November 2016 and the equivalent receiver noise was tested using Y-factor method with the sky as cold load and absorber at ambient temperature as hot load. The testing was done at the newly build Y-factor measurement facility at the Electronics Laboratory at OSO. The results are shown in Fig. 4. The careful design of the cryostat opening that does not truncate the beam, the efficient cooling of the feed and especially the use of amplifier with very low equivalent noise temperature made possible to reach excellent receiver noise. As seen in the figure the equivalent receiver noise is in the order of 10 K for approximately the half of the receiver band. The rise in receiver noise at the low part of the band is due to mismatch between the feed impedance and the input impedance of the LNA. For the integration of the Eleven feed we decided to use passive feeding network in front of the LNAs thus decreasing the number of amplifiers from eight (four per polarisation) to two (one LNA per polarisation). Due to the usage of this feeding network the receiver noise of the receiver with the Eleven feed is higher than the QRFH.

In order to accurately estimate the overall system sensitivity, one needs to accurately estimate the spill over noise contribution after the reflector system. The estimation of the overall on-sky sensitivity of QRFH was done using a GRASP system simulator (Ivashina et al., 2011). The sensitivity for range of antenna elevation angles was performed with the system simulator using measured QRFH and Eleven feed data and using the receiver noise test results from Fig. 4 to estimate the equivalent system noise. Fig. 5 depicts the simulated system sensitivity for QRFH for zenith angle. The VGOS sensitivity specification is set in Petrachenko et al. (2009) as 2000 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

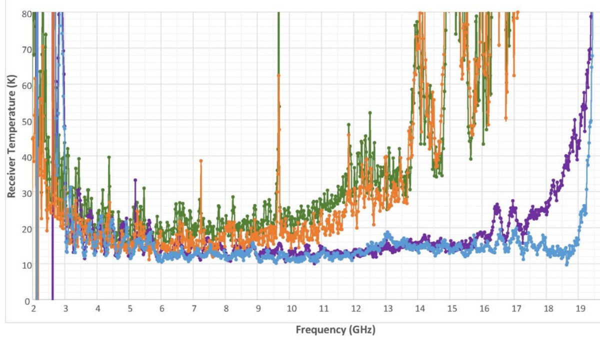

Fig. 4: Y-factor tests of the receivers with the Eleven feed (orange and green) and the QRFH (light and dark blue).

elevation angles. We did the same analysis of the sensitivity of the receiver with the Eleven feed and the results showed that the system will achieve SEFD below 2000 Jy. Details on the feed analysis are given in Flygare et al. (2017).

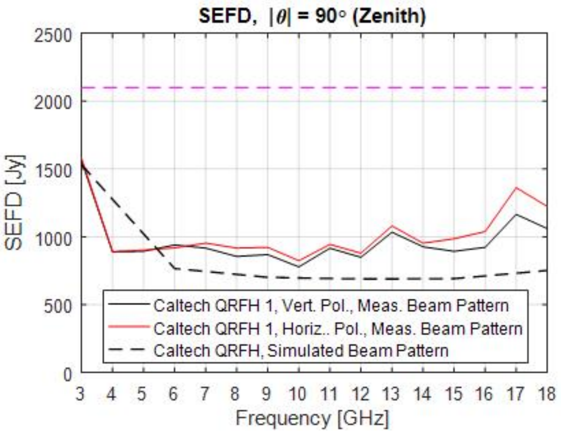

Fig. 5: Calculated SEFD using measured QRFH beam patterns and Y-factor test results.

8 Conclusions and Future Plans

We have successfully designed, built and tested signal chain for the OTT. Two receivers were constructed, one with QRFH and one with Eleven feed. The plan to bring the OTT in full network operation and participate in the CONT17 session in the autumn of 2017.

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