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Integration of the BRAND receiver analog front-end in the Effelsberg radio telescope

P. Rahimi[1], A. L. Roy[1], C. Kasemann[1], U. Bach[1], O. Polch[1], M. Wunderlich[1], S. Dornbusch[1], G. Tuccari[2,1], W. Alef[1,3], and H. Rottmann[1]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[2] INAF, Via Piero Gobetti 101, I-40129 Bologna, Italy
[3] Reichert GmbH, Hittorfstr. 26, D-53129 Bonn, Germany

Abstract. The BRAND receiver is a new system, intended mainly for the EVN, that covers the remarkably broad contiguous frequency range of 1.5 GHz to 15.5 GHz. It includes all required components of the entire signal path from the cryogenic frontend, feed, amplifiers, hybrids, a 56 Gsps sampler, with digital transmission on fibre to the VLBI backend and is intended for VLBI and single-dish work. This band coverage offers flexibility for redshifted spectral lines, sensitivity and frequency agility in the EVN.

Here we present the integration tests recently carried out and initial commissioning of the BRAND components into a prototype system installed in the Effelsberg 100 m telescope. This work is part of the master thesis programme of the first author, which continues the development from the RadioNet BRAND-EVN project. The work presented is based on technical tests on the cryogenic-, IF-, and data-acquisition system in Bonn and Effelsberg. On-sky tests include single dish spectroscopy and VLBI resulting in a 1.5 to 12 GHz bandwidth spectrum of the W3 molecular cloud, and in a VLBI experiment with fringes on all baselines. We have made the first on-sky measurements with the latest and broadest-band member in the family of broad-band receivers at Effelsberg (C/X with fractional bandwidth of 80 %, UBB with 130 % and BRAND with 165 %). Cross scans and Moon observations have resulted in a T_{sys} of around 90 K, which is higher than expected and will be investigated and improved. From the spectrum of the W3 cloud, 57 radio recombination lines were detected, and from a VLBI session between four EVN stations strong fringes were detected. This has allowed us to assess the real-world performance in various scenarios, e.g. astronomical as well as geodetic VLBI and single-dish applications and should help inform the decision-making about future EVN capabilities.

1. Introduction

The BRAND (BRoad bAND) receiver is part of the RadioNet Joint Research Activity (JRA) development for a broad-band radio astronomical receiver with digitization closely integrated with the receiver front-end. It offers a bandwidth of 1.5 to 15.5 GHz with direct sampling and requires no down conversion. This broad bandwidth has the advantage of wide instantaneous frequency availability and reduced need for receiver changes during EVN VLBI sessions. Further, direct sampling at the receiver saves the need for an analog IF transmission system, which is complex and challenging to maintain, especially at Effelsberg with its long cable runs and flexible receiver suite. These features make the receiver desirable for integration in the Effelsberg 100 m radio telescope, other EVN stations, or VGOS.

The receiver front-end includes three main analog and one digital component, which are accompanied by power and control panels. The analog components are the Dewar, the analog processing module, and the noise source. The digital component is the BRAND digital board with its high-performance four-quadrant 56 Gsps 8 bit sampler and four FPGAs for digital band-pass filtering and packetization. These developments have been made by teams in Sweden, Spain, Germany, Netherlands and Italy over the past years. The digital signal is then transported through fibre to the back-end, where it can be processed with a choice of back-end systems or recorded.

Over the course of 6 months from January to June 2024, within a master thesis programme, the first ever sky-test and integration of the analog front-end of the BRAND receiver in Effelsberg radio telescope has been successfully carried out.

2. Observation setup

To prepare the receiver for integration at the Effelsberg telescope, we tested each component in the chain individually, characterizing its gain, passband, compression point, and noise floor. We then set up the receiver in the parking lot at Effelsberg station to gain experience with the system on sky and we performed the first hot-cold test of the analog front-end (for results see Sec 3). These tests gave us confidence the system was ready to be brought to the primary focus of the telescope.

Our observational setup differed from the intended final architecture (see et al.) in that we used a DBBC3 digitizer in the back-end room connected with the receiver frontend over an analog RF-over-fibre transmission system, instead of integrating the BRAND digitizer in the receiver package. This was due to the BRAND digital board not being ready at the time, as well as it lacking a proper shielding box to protect the front end from the internally generated RFI while letting out the dissipated heat. Our experimental setup is shown in Figure 1.

Although this setup was an interim solution, it allowed us to run the first observation. But it did bring serious limitations with it, and was not as easy as were the BRAND digitizer in place. This is due to the following three factors.

1. The RF-over-fibre system went into compression at the relatively low RF power level of -3 dBm or, if we reduced the signal level, it was operating too close to its noise floor and would contribute excess noise. This made the adjustment of the signal levels tricky, especially in the presence of RFI, and the RF-over-fibre caused intermodulation of the RFI.
2. The frequency plan for the downconversion was complicated and required multiple filters and re-patching by hand during observing to scan through the band. The bandwidth of 1.5 to 15.5 GHz was divided into 1.5 to 14 GHz (wide band) and 14 to 15.5 GHz (narrow band) after the analog processing module. The bandwidth was further reduced through pre-filtering (4 GHz bandpass) and was downconverted to $0-4$ GHz (post-conversion filter). To cover the whole 1.5 to 14 GHz of bandwidth, a number of specific filters were needed and we changed them during observation to change frequency. In our case we could cover 1.5 to 12 GHz in 4 GHz pieces.
3. The spectrometer in Effelsberg has only 2.5 GHz bandwidth. This means not only the filter had to be changed but the LO of the downconverter had to be changed sequentially to upper- or lower-sideband conversion to cover the 1.5 to 12 GHz full bandwidth.

With this setup, we have done pointing, focus and ON/OFF scans on known calibrators and the Moon. We have recorded the full spectrum of the W3 main cloud from 1.5 to 12 GHz, in which many radio recombination lines (RRL) were detectable, and in W3(OH) we detected the OH and methanol maser lines. The first ever VLBI test with BRAND analog front-end has been also done with the same setup, using the DBBC3 in place of the FFT spectrometer, and this also yielded the first estimate of the polarization purity.

3. First observation results

During two available observation nights at the Effelsberg radio telescope, the first technical tests and configuration settings have been carried out. After a few corrections, the results are as follows.

1. RFI assessment: The RFI observed in the parking lot and in zenith in the primary focus (see Figure 2) are less than shown in the survey from 2017 at Effelsberg (see Tercero [2017]).
2. Pointing scans: To obtain the system and calibration temperatures, we performed cross-scans over a few primary calibrators whose flux densities are known, such as 3C 286, NGC 7027, and Cas A, which yielded T_{sys} values of about 100 K and calibration source temperature of 100 K to 240 K (see Kraus [2007]). The system temperature obtained here is roughly in agreement with the system temperature calculated from the hot-cold test in the parking lot, where we used the sky as the cold load and absorber over the horn as the warm load, and obtained $T_{\mathrm{sys}} = 120\,\mathrm{K}$ (see Burke et al. [2019]). The cross scans also showed the primary beam shape to be symmetric and have low sidelobe levels and the width was consistent with a dish edge taper of -14 dB, showing the dish illumination pattern is close to optimal as for other Effelsberg receivers (see Figure 3).
3. Focus scans: By adjusting the receiver package in the axial direction towards and away from the dish while observing a source, one can find the optimum focal position. During this focussing procedure the focus mechanism downward limit was reached before the focus peak was reached at some frequencies, due to the Dewar being mounted a bit too high in the receiver box. This caused the observation results to be made while about 20 mm to 30 mm out of focus.
4. Moon scan: To obtain another system temperature measurement that was less sensitive to the focus error, we pointed the telescope on and off the Moon. The Moon served as an "absorber" with a temperature of roughly 250 K (see Köppen [2020]) against the sky. This resulted in a system temperature of 80 K to 90 K (see Kraus [2007]).
5. Full spectrum of W3 cloud: The full spectrum of W3 main cloud has been recorded in bands of 1.5 to 4 GHz, 4 to 6.5 GHz, 5.5 to 8 GHz, 8 to 10.5 GHz and 9.5 to 12 GHz, which we stitched together in a contiguous spectrum in Figure 4. We detected many radio recombination lines, and also OH and 6.7 GHz methanol maser lines in the spectrum of W3(OH).
6. VLBI observation: With the BRAND receiver in Effelsberg, we repeated an EVN NME session at 4.85 GHz with three other EVN stations in Yebes, Medicina, and Onsala to compare the results of VLBI observation with the standard receiver. Strong and stable fringes were found on all baselines, but with a number of data quality issues. Only one baseline, namely Effelsberg - Yebes, had strong fringes in both circular polarisations LL and RR for the duration of the test observation. Onsala had one polarization channel defective, and Medicina produced fringes for only the last 40 minutes of 3 hours and then with very different SNR in LL and RR. Our analysis therefore concentrated on the Effelsberg - Yebes baseline, an example of which is shown in Figure 6.

   The BRAND receiver produced circular polarization with cross-talk of 10 % on the baseline. The BRAND receiver uses an analog hybrid junction polarsation converter made by Yebes and it worked quite well for

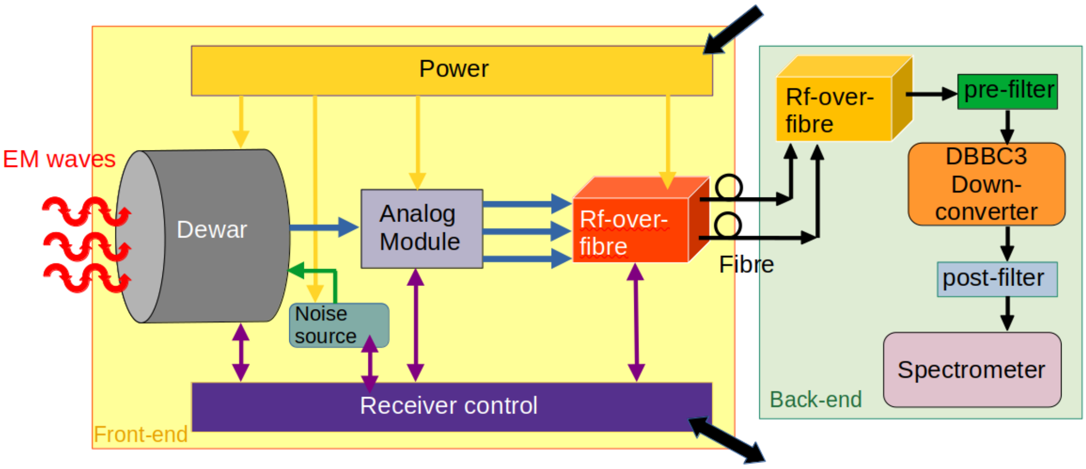
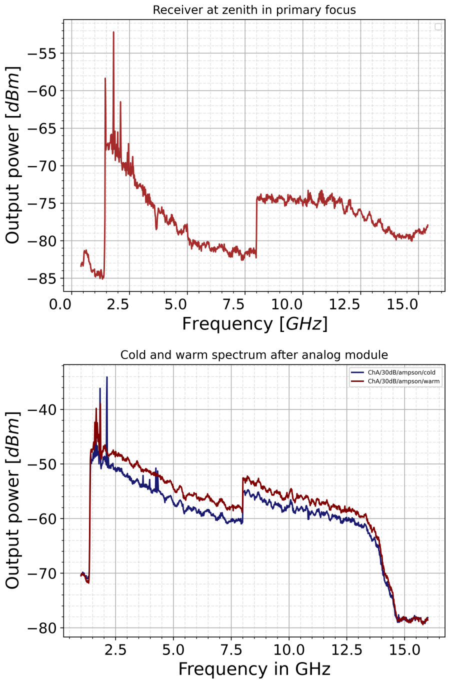


Fig. 1. Experimental setup used for the observation at Effelsberg. The RF-over-fibre module does not digitize the signal but only transfers the analog radio signal from the front-end to the back-end, where its optical receiver is mounted and outputs the electrical signal on coaxial cable. This is followed by analog downconversion and bandpass filtering and input to the existing FFT spectrometer or DBBC3 at Effelsberg for the tests.



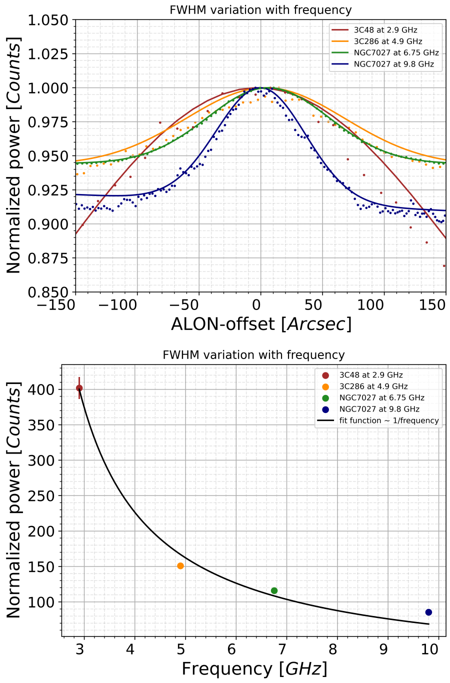


Fig. 2. RFI assessment in the parking lot and the sky. The step in the middle of the spectrum is due to the settings we used on the spectrum analyzer. Lines at 1.5, 1.8, 2.1 and 2.6 are LTE (mobile phone) frequencies LTE.

Fig. 3. Top: Primary beam shape measured from cross scans. Bottom: The primary beam FWHM dependence over frequency follows a 1/f relation quite accurately as expected.

the frequency range of the test. We could not determined whether the high cross-talk (more than 5 %) was contributed by the Yebes receiver or the BRAND receiver or both as we had only one baseline. It should be noted that the main polarisation solver in AIPS uses a linearised approach which works properly only in the low cross-talk domain of less than about 5 %.

It is advantageous to have the analog polarisation converter in place in the receiver as this is much easier than converting native linear to circular polarization after correlation. By producing circular polarization, we collect significantly more signal in the parallel hands of polarisation, which eases the fringe search and error analysis of the data at the correlator. These advantages offset the drawback is that the hybrid might add some extra noise before the LNA.

The SNRs achieved in this test will be compared to the regular NME observation conducted a week prior.

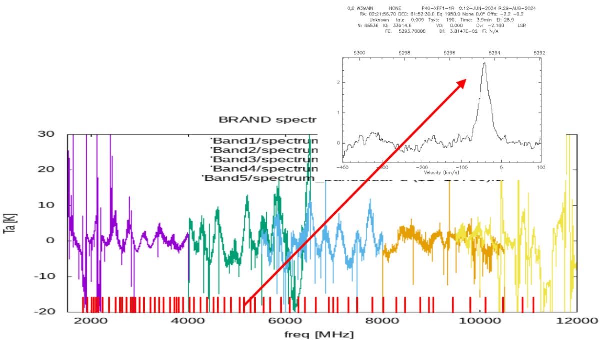


Fig. 4. 1.5 to 12 GHz spectrum of W3 main cloud with detected RRLs marked in red, observed with the analog front-end of BRAND. An example of a RRL is shown on the side, with peak set at -50 km/s

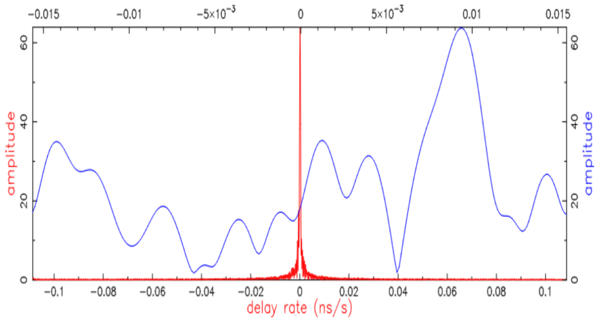


Fig. 5. An example of VLBI fringes detected between the Effeslberg and Medicina stations with SNR of 4602 and an integration time of 540 s with LL polarization.

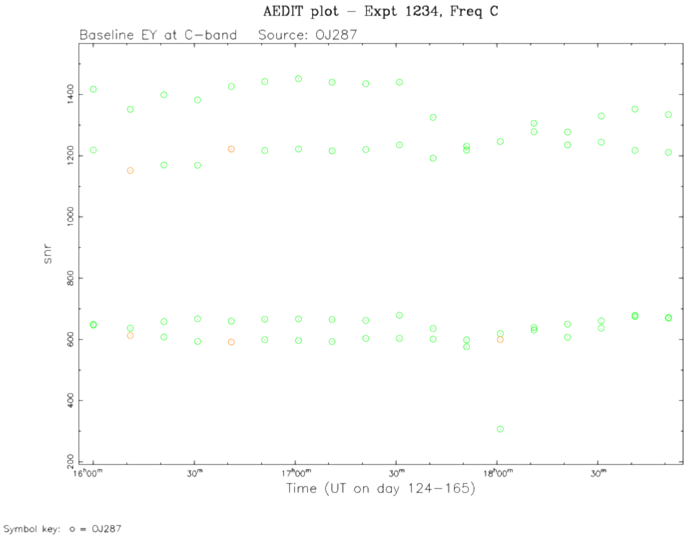


Fig. 6. The VLBI fringe SNR vs time between the Effelsberg and Yebes stations. The cross-hand amplitudes are 10 times lower than the parallel hands, indicating the BRAND receiver at Effelsberg was circularly polarized with leakage of 10 % or lower.

4. Future perspectives

After recognizing the integration challenges of the system, preparing a shielding box for the BRAND digital board, and fixing the focus problem are the next steps to be taken on the commissioning of the receiver.

We expect a significant improvement when we can use the BRAND digital frontend for digitising and processing the data. This step should improve the system temperature and thus allow for instance wide-band pulsar, VLBI and spectral observations.

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