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CHARACTERIZATION AND INITIAL RESULTS WITH EMBRACE

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Abstract. EMBRACE is a prototype instrument using an array of nearly 5000 densely-packed antenna elements creating a fully sampled, unblocked aperture. This technology is proposed for the Square Kilometre Array and has the potential to provide an extremely large field of view making it the ideal survey instrument. We describe the system, its flexibility, and early results from the prototype.

Keywords: Square Kilometre Array, SKA, aperture array, EMBRACE

1 Introduction

The Square Kilometre Array (SKA) Dewdney *et al.* (2009) will be the largest radio astronomy facility ever built with more than 10 times the equivalent collecting area of currently available facilities. The SKA will primarily be a survey instrument with exquisite sensitivity and an extensive field of view providing an unprecedented mapping speed. This capability will enormously advance our understanding in fundamental physics including gravitation, the formation of the first stars, the origin of magnetic fields, and it will give us a new look at the Universe in the time domain with a survey of transient phenomena.

A revolution in radio receiving technology is underway with the development of densely packed phased arrays. This technology can provide an exceptionally large field of view, while at the same time sampling the sky with high angular resolution. The Nançay radio observatory is a major partner in the development of dense phased arrays for radio astronomy, working closely with The Netherlands Foundation for Radio Astronomy (ASTRON). The joint project is called EMBRACE (Electronic MultiBeam Radio Astronomy ConcEpt). Two EMBRACE prototypes have been built. One at Westerbork in The Netherlands, and one at Nançay. These prototypes are currently being characterized and tested at the two sites. Conclusions from the EMBRACE testing will directly feed into the SKA and will have a decisive impact on whether or not dense array technology is used for the SKA.

The date for selection of technology for the SKA is 2016. If dense arrays are not selected for the SKA, then the SKA will have a much reduced mapping speed compared to what has come to be expected by the astronomical community. It is therefore of crucial strategic importance that work on EMBRACE succeeds in showing the viability of dense arrays for radio astronomy.

EMBRACE has been operational since 2011, and a number of tests have been carried out over the past two years. Much of the work for the first year has been focused on low-level testing and debugging of the system, especially related to the control software, data acquisition, and phase calibration algorithms. Other tests of basic functionality include pointing at sources and tracking the movement of sources in the sky, compensating for the Earth's rotation. Higher level engineering measurements are also being carried out. These aim to quantify the performance of the system by calculating parameters such as the system temperature, and the beam profile.

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2 EMBRACE System Description

EMBRACE is a SKA Pathfinder for the mid frequencies. Two EMBRACE stations were built, largely financed by the European Commision Framework Program 6 project SKADS. EMBRACE is the first large-scale demonstrator of the dense aperture array technology for radio astronomy.

EMBRACE@Nançay is a phased-array of 4608 densely packed antenna elements (64 tiles of 72 elements each). For mechanical, and electromagnetic performance reasons, EMBRACE@Nançay has, in fact, 9216 antenna elements, but only one polarization (4608 elements) have fully populated signal chains. For more details on EMBRACE architecture see Kant *et al.* (2010, 2011)

2.1 Hierarchical Analogue Beam Forming

EMBRACE@Nançay uses a hierarchy of four levels of analog beamforming leading to 16 inputs to the LOFAR backend system for digital beamforming. The first beamforming is of 4 Vivaldi elements done on the integrated circuit "beamformer chip" developed at Nançay (Bosse *et al.* 2010). The output of 3 beamformer chips is summed together on a "hexboard" and 6 hexboards make a tile. At Nançay, we have one further analog summing stage with 4 tiles making a tileset. This final stage is done on the Control and Down Conversion (CDC) card in the shielded container. The cables running from individual tiles to the CDC cards are 15 m in length, and there are phase perturbations between the various connectors and length of cable leading from each tile. This is calibrated out using an algorithm implemented in the Local Control Unit. The output of the tilesets is fed into a LOFAR-type RCU and RSP system for digital beamforming (Picard *et al.* 2010).

2.2 Beamformer Chip

At the heart of EMBRACE is the integrated analog circuit called the Beamformer Chip which was developed at Nançay. This chip applies the phase shifts necessary to four antenna elements to achieve pointing in the desired direction. The beamformer chip forms two independent beams for each set of four antenna elements. Over 4000 chips were produced for the EMBRACE stations at Westerbork and Nançay (Bosse *et al.* 2010).

3 EMBRACE Monitoring and Control Software

The Monitoring and Control software for EMBRACE was developed at Nançay, and continues to be improved. An extensive Python package library on the SCU (Station Control Unit) computer gives scripting functionality for users to easily setup observation scripts for various targets and types of observation. Integrated statistics data are acquired from the LCU (Local Control Unit) and saved into FITS files. Raw data (beamlets) are captured from LCU Ethernet 1Gbps outputs and saved into binary files (Renaud *et al.* 2011).

4 Results

4.1 Beam parameters

Figure 1 shows a drift scan of Cas-A. This is effectively a measurement of the EMBRACE@Nançay main lobe since Cas-A is small enough to be considered a point source for EMBRACE@Nançay. The main lobe is Gaussian, and the FWHM of 1.47 deg at 1176 MHZ is the expected value.

We typically cannot determine noise temperatures and instrument efficiencies as separate quantities. For example, to determine the $T_{\rm sys}$, we'd need to fill the entire beam pattern with a uniformly radiating blackbody with a well known physical temperature such as an absorber. Conversely, the main beam efficiency cannot be determined without calibrating the intensity scale with a $T_{\rm sys}$ value. The same goes for the area efficiency which is the ratio of measured power over the incident field power entering the geometrical cross section of the instrument. What we can do is either assume a reasonable value for an efficiency and then use sources with either well-known brighnesses and geometries or with well known source fluxes.

The Sun is used as a reference source using simple frequency interpolation based on "quiet Sun" measurements. At this time, approaching a solar 11-year maximum, the values we get for $T_{\rm sys}$ should be considered lower limits. At meter frequencies – where the solar flux originates mostly in the corona – the flux may vary by factors of 10 or more. The variation is much less severe around 1200 MHz but there is no way to know

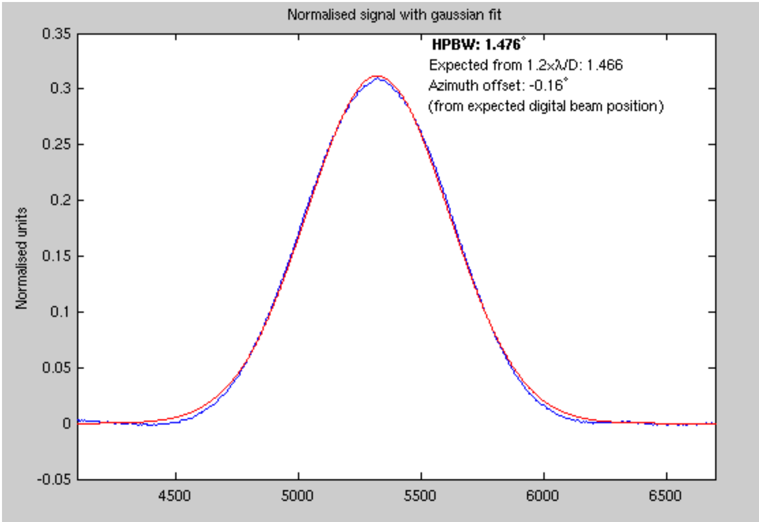

Fig. 1. Drift scan of Cas-A showing the expected shape of the beam main lobe.

by exactly how much since the Sun is poorly monitored in the lower L-band. Even at frequencies as high as 2.8 GHz, the day-to-day variation can be as high as 25%.

The Sun with its ~0.5° extension is nearly a point source and we can ignore the main beam gain variation over the source. For a measurement with raw uncalibrated measurements x (on-source) and y (off-source), we may assume that these values are proportional to detected noise and source powers.

$$\frac{T_{\rm sys}}{\eta_{\rm A}} = \frac{S \times A}{k} \frac{y}{x-y} \tag{4.1}$$

where A is the geometrical area and $\eta_{\rm A}$ is an efficiency of how much of the availble power the instrument surface is able to pick up. The Sun temperature was taken to be $\sim$ 90000 K at 1176 MHz. For a tileset, $A = 4.5$ m^2, and assuming that $\eta_{\rm A}$ is equal to 70% gives a $T_{\rm sys}$ of $\sim$ 120 K.

4.2 Intrinsic Power Variation

Long duration observations performing tracking across the sky show an apparent power variation as a function of pointing direction. Numerous repeated observations have shown that this power variation is intrinsic to the instrument, and is completely independent of source strength in the beam. A 10 hour tracking observation of Cas-A showing a power variation was repeated many times, including following the same azimuth-elevation track but shifted in time such that Cas-A was not in the beam (i.e. tracking empty sky at the same declination but different right-ascension of Cas-A). The power variation is not a function of the source strength in the beam, as demonstrated by GPS satellite tracking which does not show the power variation increasing with the much stronger GPS carrier strength compared to Cas-A.

Two remedies have been implemented, the first of which uses a classic ON-OFF type observing, but with the multi-beam capability of EMBRACE, the ON and OFF beams can be measured simultaneously. The pointing configuration is shown in Figure 2. The power variation is thus reduced by several orders of magnitude.

The second remedy takes advantage of the imaging capability of EMBRACE and also further demonstrates that the power variation is entirely an intrinsic system artefact. The power variation can be eliminated by subtracting an array correlation matrix (ACM) measured at an empty sky position. This corrector ACM is subtracted from the subsequent ACM produced at each integration. The corrector ACM is a constant and need only be measured once, and then applied to all subsequent observations.

4.3 Astronomical Observations

A number of astronomical observations have been done successfully, in addition to the drift scan of Cas-A shown in Fig. 1.

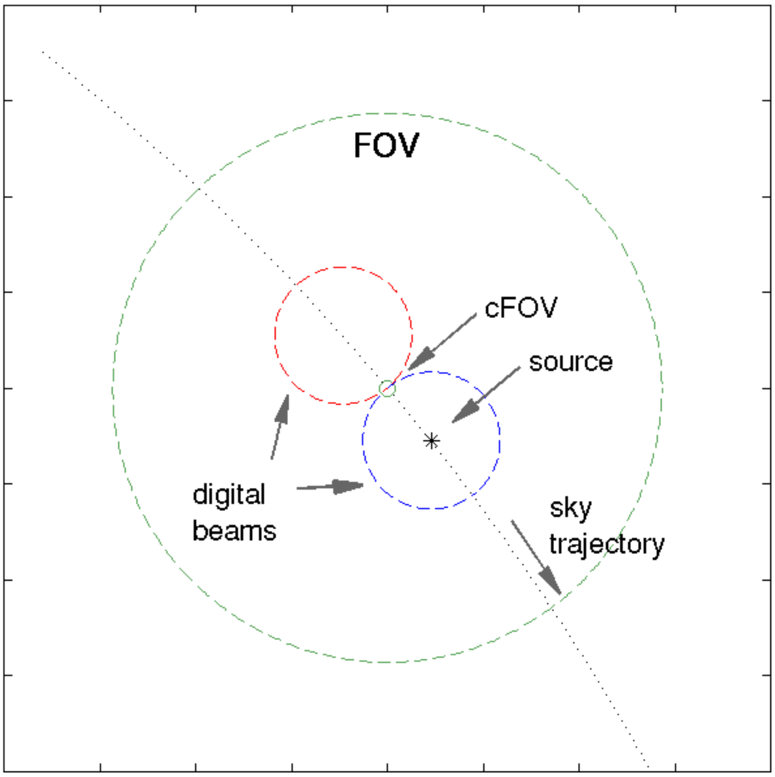

Fig. 2. The pointing strategy for tracking a source points at ON and OFF source positions simultaneously. The OFF position is along the trajectory of the source across the sky.

Figure 3 demonstrates over 9 hours of tracking the pulsar B0329+54. The pulse is clearly detected after several minutes, and the array continues tracking measuring continuously the pulsar, except where RFI has been filtered at 21500 seconds. The array was configured with a bandwidth of 12 MHz (62 beamlets) centred at 1176.45MHz. The array was phased-up using the GPS BIIF-2 satellite, and the phase parameters were applied for the observation of B0329+54. The high data rate output from the RSP boards is read by a data acquisition system running the Oxford ARTEMIS pulsar processing software (Serylak et al. 2013; Armour et al. 2012).

Figure 4 shows a drift scan of the Sun using the multibeam capability of EMBRACE@Nançay. Six beams were pointed on the sky along the trajectory of the Sun, including three partially overlapping beams. The result shows the Sun entering and exiting each beam as expected, and the off-pointed beams are 3 dB down from the peak, as expected.

Figure 5 shows the spectroscopic capability of EMBRACE@Nançay. This is a spectrum of the galaxy M33 after a one hour integration using the ON-OFF pointing strategy as shown in Fig. 2.

5 Future Developments

EMBRACE@Nançay continues to be tested with the goal of verifying its long term stability, and improving the calibration. EMBRACE@Nançay is also being used as a testbed for developments of RFI mitigation algorithms, and a new Data Model.

Future hardware developments include the further integration of functionality on-chip with the goal of reducing power consumption and improving performance. A dual polarization tile is also under development for a future, large scale, demonstrator.

6 Conclusions

EMBRACE@Nançay is a demonstrator of a new technology for radio astronomy. We have demonstrated its capability as a radio astronomy instrument, including astronomical observations of pulsars and spectroscopic

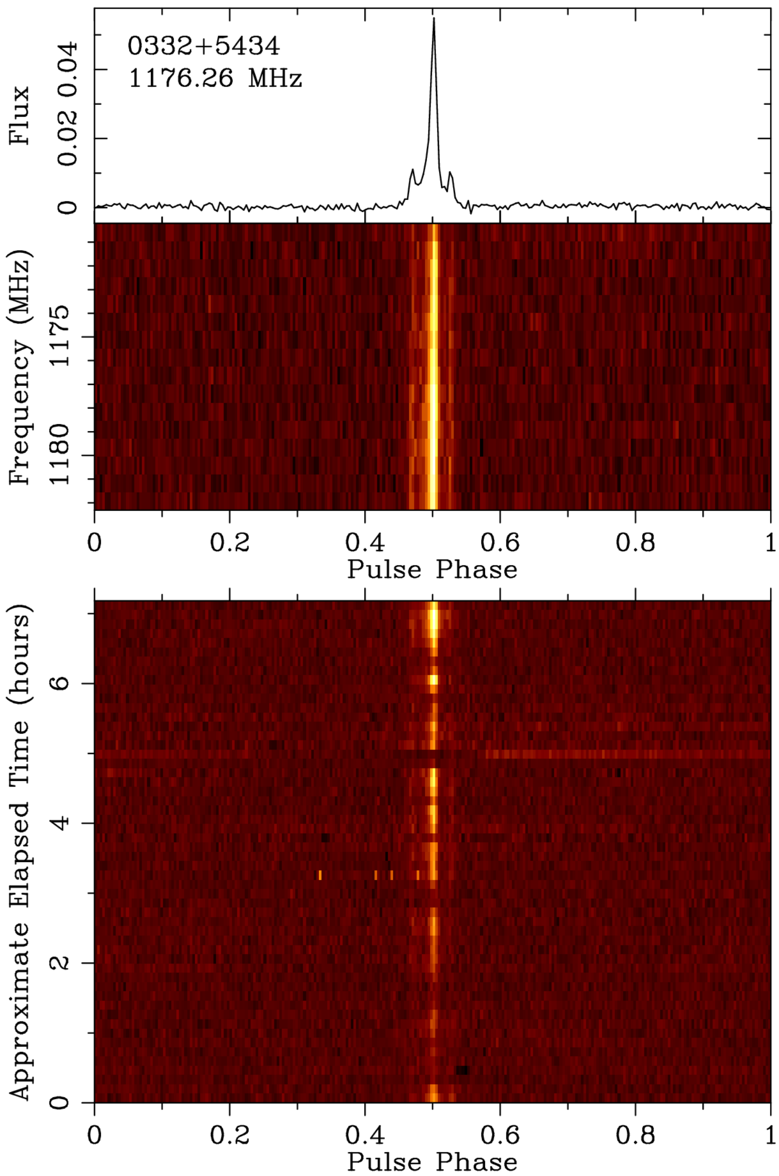

Fig. 3. Pulsar B0329+54 was detected after several minutes as shown in this dynamic plot folded at the pulsar period of 715 msec.

observations of galaxies. We have also demonstrated its multibeam capability. Dense aperture array technology is a viable solution for the SKA, offering the benefit of an enormous field of view and flexibility making it the most rapid astronomical survey machine.

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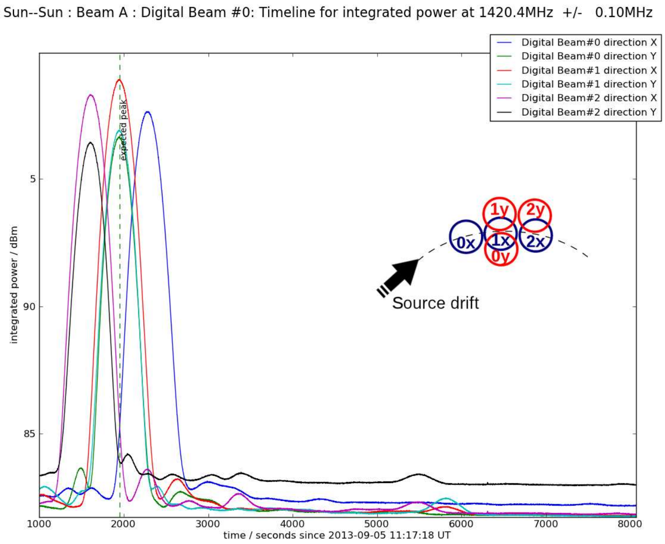

Fig. 4. This drift scan of the Sun used 6 beams of EMBRACE@Nançay pointing along the trajectory of the Sun across the sky (inset top right).

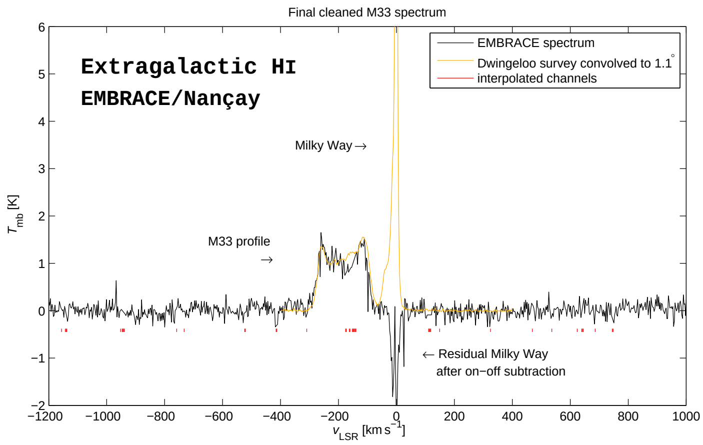

Fig. 5. EMBRACE@Nançay detected the galaxy M33 after a one hour integration using the ON-OFF pointing strategy described in the text.

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