On sky characterization of the BAORadio wide band digital backend

Search for H I emission in Abell85, Abell1205 and Abell2440 galaxy clusters

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Abstract We have observed regions of three galaxy clusters at \( z \sim [0.06 \div 0.09] \) (Abell85, Abell1205, Abell2440) with the Nançay radiotelescope (NRT) to search for 21 cm emission and to fully characterize the FPGA based BAORadio digital backend. We have tested the new BAORadio data acquisition system by observing sources in parallel with the NRT standard correlator (ACRT) back-end over several months. BAORadio enables wide band instantaneous observation of the [1250, 1500] MHz frequency range, as well as the use of powerful RFI mitigation methods thanks to its fine time sampling. A number of questions related to instrument stability, data processing and calibration are discussed. We have obtained the radiometer curves over the integration time range \([0.01, 10000]\) seconds and we show that sensitivities of few mJy over most of the wide frequency band can be reached with the NRT. It is clearly shown that in blind line search, which is the context of H I intensity mapping for Baryon Acoustic Oscillations, the new acquisition system and processing pipeline...
outperforms the standard one. We report a positive detection of 21 cm emission at 3σ-level from galaxies in the outer region of Abell85 at ≃ 1352 MHz (14400 km/s) corresponding to a line strength of ≃ 0.8 Jy km/s. We also observe an excess power around ≃ 1318 MHz (21600 km/s), although at lower statistical significance, compatible with emission from Abell1205 galaxies. Detected radio line emissions have been cross matched with optical catalogs and we have derived hydrogen mass estimates.

**Keywords** Radio telescopes and instrumentation · L-band digital backend for interferometry · Wide band RFI mitigation · Extragalactic H I · Galaxy clusters

1 Introduction

A complete analog and digital electronic system (BAORadio), for acquisition and processing of radio signals was designed, built by Irfu1 and LAL,2 in 2007–2009. The system commissioning, tests and qualification was carried out in 2009–2010 at the Nançay radio observatory3 in collaboration with Observatoire de Paris staff. This development, intended for large bandwidth radio interferometers in GHz domain, has been achieved within the BAORadio4 project, in the context of 21 cm intensity mapping for BAO (Baryon Acoustic Oscillations) detection and Dark Energy science [1, 3, 10, 24]. The system has also been deployed at the CRT (Cylindrical Radio Telescope) prototype at CMU (Pittsburgh) in interferometric mode with up to 32 antennae [6]. It is also being used in the PAON-4 interferometer, which is a wide band transit type radio-interferometer featuring four 5 m diameter antennae. PAON-4 has been deployed at Nançay at the end of 2014 and is designed as a test bed for 3D intensity mapping.

To quantitatively qualify the performance and capabilities of BAORadio in terms of RFI filtering, sensitivity, and wide band blind H I search, the authors have used the Nançay Radio Telescope (NRT), equipped with the BAORadio digital back-end and a dedicated data processing pipeline to search for 21 cm emission in three nearby galaxy clusters with 0.05 ≲ z ≲ 0.10 (Abell85, Abell1205, Abell2440), during a 11-month period, from March 2011 to January 2012.

Our primary goal in this program was the full and long term characterization of the BAORadio system. However, target selection was guided by the question of galaxy formation and evolution, and the effect of the environment on this processes, with a more ambitious program in mind, following these pilot observations. Major efforts have been and are devoted to radio surveys to observe H I mass distribution properties

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1 Institut de recherche sur les lois fondamentales de l’Univers.
2 Laboratoire de l’Accélérateur Linéaire.
3 The Nançay Radioastronomy Station is part of the Observatoire de Paris and is operated by the Ministère de l’Éducation Nationale and Institut des Sciences de l’Univers of the Centre National de la Recherche Scientifique.
4 http://groups.lal.in2p3.fr/bao21cm/.
in the local universe, and its evolution with the redshift or with the environment, such as the HIPASS [20], the ALFALFA [17] surveys or the NIBLES survey at Nançay [34].

The Arecibo Galaxy Environment Survey (AGES) [4], which uses the ALFA (Arecibo L-band Feed Array) has been specifically designed to probe $H_I$ distribution dependence in different environment, in particular in the Virgo cluster [30, 31].

After the description of the instrument setup, observation modes and list of observed targets in the next section, the data processing pipeline, RFI cleaning and calibration procedures are presented in Section 3. Section 4 is devoted to the discussion of the results obtained in term of the reached sensitivities, and to the comparison with previous extragalactic $H_I$ observations using the NRT [21, 25, 32]. The obtained spectra and identified line emissions toward the different targets are then presented. The cross identification with optical catalogs, using the NED$^5$ and SDSS$^6$ databases, as well as measured 21 cm line emission parameters are discussed in Section 5.

2 Instrument setup and observations

2.1 NRT optical system, receiver and standard correlator (ACRT)

The NRT is a transit instrument of the Kraus/Ohio State design, and consists of two mirrors, one movable and one fixed. The tiltable primary mirror of $40 \times 200$ m (east-west) is made up of ten flat panels (each 40 m high and 20 m long); the fixed spherical secondary mirror is 300 m long and 35 m high and is located at 460 m to the South (radius: 560 m) of the primary. 280 m North of the spherical mirror, there is a focal chariot moving along a curved railroad track which contains a compact dual-reflector Gregorian feed system [16, 28, 33], with two wide band conical corrugated horns, equipped with orthomode transducers, orthogonal linear polarization antennas and low-noise amplifiers, cooled to $\approx 20$ K.

All celestial objects with declination greater than $-39^\circ$ may be observed, and the west-to-east motion of the focal chariot allows for about one hour observation for a zero-degree declination source. The tracking time increases in proportion to the secant of the declination ($\propto 1/\cos \delta$).

Two receivers allow a continuous coverage of the band 1.1–3.5 GHz with optimized characteristics for 21 cm $H_I$ line observations and each corrugated horn can be rotated by $\pm 90^\circ$. Up to two linear and two circular polarizations can be recorded simultaneously. The digital correlator (ACRT) bandwidth can be set from 195.3 kHz to 50 MHz and has 8192 frequency channels split into 2 to 8 banks. Auto- and cross-correlation modes are available, and up to 4 independent frequency bands and/or polarization may be recorded simultaneously. Continuum measurements can be performed through 8 dedicated channels using the correlator’s setup (frequency, bandwidth and polarization).

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$^5$http://ned.ipac.caltech.edu.  
$^6$http://www.sdss3.org/index.php.
The $^{1}$H observations with the NRT are characterized by a half-power beam width (HPBW) of 3.7 arcmin in the East-West (right ascension) direction and 22 arcmin in North-South (declination), at $\sim$ 1420 MHz (21 cm line). The point-source efficiency is 1.4 K/Jy at zero declination $\delta = 0^\circ$ and the system temperature is about $T_{\text{sys}} \simeq 35$ K.7

We have used the following two observation modes for the program discussed here:

- The right ascension “Drift Scan” mode for which the focal chariot remains stationary during each cycle, and radio sources pass through the beam during 180 s acquisition periods or phases. We used this mode only for the observations of the calibration source 3C161.
- “Total power (position-switching) mode” using consecutive cycles, each consisting of pairs of 40 s ON- and 40 s OFF-source integration phases, with same chariot position on the rail to have same ground noise contribution in ON- and OFF-source spectra. At the beginning of each acquisition phase, two 3-sec pulses from a noise diode (DAB) are injected at horn level to perform a relative calibration.

2.2 BAORadio digital back-end

In this article we focus on some important features of the BAORadio system, a more complete technical description and its performance can be found in [2, 9].

One important difference between BAORadio and ACRT systems resides in the fact that the first one is embedded inside the NRT chariot as close as possible to the analog receiver, whereas for the second one the analog signals are transferred through about 150 m of cables from the chariot to the control building.

The BAORadio sampling board can sample up 4 analog inputs at 500 Msample/s with 8 bits dynamic range. It can optionally convert the wave forms into frequency components through an Fast Fourier Transform (FFT) implemented on the FPGA. Alternatively, for this article a firmware (RAW) which can perform waveform digitization has been used. Then, the FFT has been calculated offline. Other digital systems with similar features such as the CASPER/ROACH or UNIBOARD have also been developed [23].

To cope with the data rate system limitations, the acquisition rate was limited to 8000 digitization frames of 16 kSamples (32 $\mu$s) per second, leading an useful fraction of time ON-sky of 25 %. This acquisition rate produced a total data flow dumped to disk of about 300 MByte/s (about one TByte/hour) for the two polarization signals. After offline FFT, we obtained 8192 complex coefficients per frame (nicknamed a BRPaquet), corresponding to 30.5 kHz frequency resolution ($\simeq$ 6.5 km/s) on the entire frequency band $[1250, 1500]$ MHz for the two polarizations. The complete data set from all the observations have been archived at the IN2P3 computing center using the Irods system.8

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7http://www.nrt.obspm.fr/nrt/obs/NRT_tech_info.html, http://en.wikipedia.org/wiki/Nancay_radio_telescope.
8http://cc.in2p3.fr/IRODS.
2.3 Observed targets

Some $\text{H}_\text{I}$ emission observation has been reported [7] for Abell85, but our search of such a signal has to be considered as a pathfinder in the general context of “blind search” as for BAO intensity mapping. In this context, a comparison between the BAORadio system and the NRT standard auto-correlator (ACRT) is reported. The observations of the three clusters reported here represent the first stage of a more ambitious program described in the introduction, but they already provide valuable indications about the feasibility of the $\text{H}_\text{I}$ intensity mapping.

The targets observed are outer regions of Abell1205 and Abell85, and the center region of Abell2440, three clusters in the redshift range $z \simeq 0.05 - 0.10$ (Table 1). The two first have been observed much longer that the last one, so we will only report on the radiometric curve for Abell2440, and not on $\text{H}_\text{I}$ search. The calibration sources 3C161 and NGC4383 were also included in the observation program (Table 1). The observation modes have been “total power (position-switching) mode” for the Abell clusters and NGC4383, and “drift scan” for 3C161.

– Abell85 is a rich cluster located at $z \simeq 0.055$ and has been extensively studied in optical [14, 27] and in X-rays [15, 19, 29]. This cluster has also been studied in 21 cm, using VLA and observation of $\text{H}_\text{I}$ emission of some of the blue galaxies in the outer region has been reported [7]. However, no detail or figures quantifying the emission strength or velocity/redshift from these galaxies can be found in the literature [8]. The map of the optically identified galaxies around our target position that have spectroscopic redshift estimates is shown in Fig. 1, with the ON and OFF NRT beam HPBW (Half Power Beam Width) footprints.

– The Abell1205 has not been as extensively studied; the optically selected galaxy distribution around the observed Abell1205 targets is shown in Fig. 2.

3 Data analysis

Two data processing pipelines have been setup to handle data from the BAORadio system and the standard NRT correlator (ACRT) system, both of which have similar stages. An overview of the BAORadio pipeline is presented in the next section, followed by the calibration procedure description.

3.1 BAORadio data reduction pipeline

We describe in this section the data reduction of the observations obtained with the “total power (position-switching) mode”.

1. FFT and fiducial time.

   After FFT computation, each digitization frame (BRpaquet) and hence each spectrum is time-tagged with 8 ns precision by the ADC-board firmware. Since each ON and OFF phase starts with a DAB (noise diode) pulse (see Section 3.3) and ends with a NRT chariot positioning movement, few seconds are needed for
Table 1  Observation data for H I cluster sources (Abell) and the calibration sources 3C161 and NGC4383

| Source         | RA          | Dec         | $v_{obs}$ (MHz) | Obs. period      | $T_{exp}$ (s) |
|----------------|-------------|-------------|-----------------|------------------|---------------|
| Abell85        | 00$^h$43$^m$16.99$^s$ | $-9^\circ09'46.99''$ | 1346.3          | Apr.-Oct. 2011   | 4882          |
| Abell1205      | 11$^h$15$^m$08.37$^s$ | $+2^\circ33'01.39''$ | 1320.8          | Mar. 11-Jan. 12  | 6277          |
| Abell2440      | 22$^h$24$^m$33.30$^s$ | $+0^\circ53'18.59''$ | 1302.4          | Mar. 11-Jun. 11  | 1725          |
| 3C161          | 06$^h$24$^m$43.09$^s$ | $-5^\circ51'14.00''$ | 1420.4          | 9$^h$ Dec. 2011  |               |
| NGC4383        | 12$^h$25$^m$25.5$^s$ | $+16^\circ28'12''$  | 1412.5          | 22$^{nd}$ Oct. 2011 |  |

RA and Dec refer to J2000 epoch, $v_{obs}$ is the central observation frequency in ACRT band, $T_{exp}$ is the total effective exposure, taking into account the fraction of useful time for the BAORadio system.

system stabilization before data can be considered as reliable. Therefore we used only 30-sec data over the 40-sec available per ON and OFF phase of a cycle.

2. RFI filtering.

Outside the radio protected band [1400,1427] MHz, many terrestrial signals pollute the surveyed frequency band [1250,1500] MHz at Nançay. We have used the very fine time sampling of the BAORadio system ($\lesssim$ 0.1ms), to implement an RFI mitigation method for fast intermittent signals, such as radar pulses, using median filtering over time, for each frequency component. Figure 3 shows for instance a time-frequency map, corresponding to $\simeq$ 86 s observations of Abell85, with 0.6 s time resolution and $\simeq$ 30.5 kHz frequency resolution. A number of intermittent and permanent RFI signals are clearly visible. We have applied our RFI cleaning method independently to each polarization signal.

3. Rejection of noisy observations.

The RFI cleaned spectra are then used to compute average spectra for each (noise diode DAB, ON, OFF) phase of each cycle, and for each polarization signal $p_0$, $p_1$. These cycle/cycle spectra are then used to produce average spectra over different coarser time scales, per run (observations during a given day), or over the whole period. We also discarded noisy observations, affected by the Sun transits for instance, and a small fraction of the data affected by electronic instabilities. We find that the BAORadio system associated with the NRT has been quite stable and reliable, compared with the ACRT. We have been able to keep more than 95 % of the whole data sets for all Abell clusters for the final analysis, compared to 40–60 % for standard NRT ACRT data.

4. Correction to the Local Standard of Rest (LSR) frame.

Each observation run has been doppler shifted to take into account the motion of the Sun with respect to nearby stars, to obtain spectra in the LSR reference frame (correction $\lesssim$ 140 kHz).

5. Computation of the overall frequency response $g(\nu)$.

The frequency response $g(\nu)$ represents the NRT optics and the BAORadio electronic chain frequency response, although the variations are mainly due to the analog electronic filter shape. We define a normalized frequency response $g(\nu)$ using the filtered and smoothed measured spectrum $P(\nu)$, which is dominantly due to thermal noise. We have developed two analysis methods, starting
Fig. 1 Distribution of galaxies in the redshift range $0.02 < z < 0.1$ around the NRT ON/OFF beam positions near Abell85 cluster in the (RA, DEC) plane. Color scale represents the galaxy redshifts, the NRT ON and OFF beam spots (HPBW contour) are represented as solid and dashed ovals from the same set of cycle/cycle spectra, based on the frequency response determination $g(\nu)$, and adapted for two calibration techniques, using either 3C161 radio source or the Milky Way 1420 MHz line.

Method (a): For each cycle, a frequency response function $g(\nu)_{\text{cycle}}$ is computed from the smoothed, median filtered OFF-source spectrum $g(\nu)_{\text{cycle}} = P_{\text{cycle}}^{\text{Off}, \text{filt}}$. The signal toward a given target is then obtained by averaging, over all cycles, the difference of ON-source and OFF-source spectra, normalized by the frequency response i.e.

$$
\langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle = \left\langle \frac{P_{\text{On}}_{\text{cycle}} - P_{\text{Off}}_{\text{cycle}}}{g(\nu)_{\text{cycle}}} \right\rangle_{\text{cycles}}.
$$

This is done independently for each polarization.

Method (b): Average ON-source and OFF-source spectra are computed for each run (all cycles for a given day), and are used to compute a frequency response for each run, for the ON-source and OFF-source spectra separately $g_{\text{run}}^{\text{On}}(\nu)$ and $g_{\text{run}}^{\text{Off}}(\nu)$. Before averaging on a run, the average per cycle is first
filtered with a sliding median filter over a window of 15 MHz wide, and then modeled as a spline curve with 4 MHz step. The smoothed spline frequency responses $g_{\text{run/off}}^{\text{On/Off}}(v)$ are free from RFI. The signal toward each observed ON-source and OFF-source is then given by:

$$\langle \text{On} / g_{\text{run}}^{\text{On}} \rangle = \langle P_{\text{run}}^{\text{On}}(v) / g_{\text{run}}^{\text{On}}(v) \rangle_{\text{runs}}$$

$$\langle \text{Off} / g_{\text{run}}^{\text{Off}} \rangle = \langle P_{\text{run}}^{\text{Off}}(v) / g_{\text{run}}^{\text{Off}}(v) \rangle_{\text{runs}}$$

This is also done independently for each polarization.

6. Radiometric calibration.

The average spectra obtained in the previous step are not expressed in physical units, but in r.a.u (Relative Arbitrary Unit). The conversion factor into physical units, brightness temperature (Kelvin) or source intensity (Jansky) is determined using the 3C161 continuous source for the (method a) $\langle (\text{On} - \text{Off}) / g_{\text{cycle}} \rangle$ spectrum and using the Milky Way 1420 MHz line for the (method b) $\langle \text{On} / g_{\text{run}}^{\text{On}} \rangle$ spectrum. The calibration procedure is described in Section 3.3.

We obtain fully compatible spectra with both methods (a) and (b).
Fig. 3 Time-frequency map of $\simeq 86$ s observations of Abell85 for one polarization showing intermittent strong radar signals and permanent narrow RFI signals originating from electronic components. The frequency bands covered are $[1285, 1325]$ MHz (top) and $[1330, 1370]$ MHz (bottom). The other polarization (not shown) experiences the same features.

3.2 Residual modulations in the final spectra

We observe residual structures in the ON-source or OFF-source spectra, independent of the processing method used (a) or (b). As shown in Fig. 4 we have observed two regimes of modulation of the spectra. The first one, with an unexpected large amplitude of $\gtrsim 100$ mJy, has a modulation period in frequency of about $3 - 4$ MHz. It is attributed to standing waves in the $\simeq 25$ m-long cables connecting NRT front-end electronics and the BAORadio analog chain, combined with a slight impedance mismatch in the BAORadio analog electronic input stage. The second one, smaller in amplitude, with $\simeq 500$ kHz period structures in frequency (see zoom in Fig. 4), is attributed to the standing waves between the large spherical mirror and the horn, located $\simeq 280$ m north of the spherical mirror. Notice that this modulation had suffered from a $\sim \pi$ phase shift between the periods, possibly due to a technical intervention at the level of the focal horn that affected its position. Unfortunately both kind of modulations not only are non uniform on the total 250 MHz bandwidth but also are time varying. Different kinds of filtering have been tried to analyze the ON or OFF source spectra alone without any success and it is the reason why we used (ON-OFF) spectra to cancel these modulations.

3.3 Radiometric calibration

We initially followed the standard NRT procedure for relative calibration, using the DAB (noise diode) signals injected at the horn level, but we found that this method induces additional instabilities, leading to a significant increase of the final signal fluctuations or noise level. Figure 5 shows the increase of fluctuations where DAB signal is used for relative cycle/cycle signal level calibration. The same effect is observed for the NRT ACRT signal. Since we determined that the NRT and
BAORadio chains are quite stable, even over durations of a few months, we decided to use only the radiometric sources and the Milky Way HI line to determine the absolute calibration.

3.3.1 Radiometric calibration using 3C161

Several transits of the radio-continuum source 3C161 have been observed in drift scan mode.

We have derived the absolute radiometric calibration coefficient \( C_a \) for the average spectra \( \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle \) by comparing the peak value of 3C161 transit, after baseline subtraction, averaged over the 2 polarizations, to the published emission intensity measurement for 3C161 \([5, 22]\) of \( 18.58 \pm 0.09 \) Jy for the continuum flux collected by a circularly-polarized total power receiver centered at 1408 MHz, with a 20 MHz bandwidth ([1398, 1418] MHz). The quoted error is a systematic error reflecting the 3 % difference between the two referenced measurements. The radiometrically calibrated spectra in Jansky, corresponding to the difference of ON-source and OFF-source for each cluster, are obtained by multiplying the average of the two polarizations by \( C_a \):

\[
S(\nu) = \frac{C_a}{2} \left( \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle_{p0} + \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle_{p1} \right),
\]
where \( C_a = 22.6 \pm 0.6 \text{ Jy/r.a.u.} \). Using the spectral fit of reference [22], we have determined the \( C_a \) coefficients for the frequency bands covered by the three Abell clusters. The coefficient is found to be constant at a few percent level, and we are thus confident that our 3C161 calibration method is valid for the whole frequency band needed to search for \( \text{H}_1 \) emission line (Section 4.2).

We have checked our calibration by measuring the \( \text{H}_1 \) line of NGC4383. We find a line strength of \( 41.1 \pm 1.4 \text{(stat)} \pm 1.1 \text{(syst)} \text{ Jy.km/s} \), in agreement with the published value \( 48.4 \pm 5.1 \text{ Jy.km/s} \) in [11, 12].

### 3.3.2 Radiometric calibration using Milky Way 1420 MHz line

The observed frequency band contains the Milky Way \( \text{H}_1 \) emission line at 1420 MHz. We have identified this line, corrected from Doppler shift (LSR correction), in both the ON-source and OFF-source observations, and compared its strength to the Leiden/Argentine/Bonn (LAB) Survey of Galactic \( \text{H}_1 \) database [18]. This procedure is complicated since the residual structures in the spectra mentioned in Section 3.2 cannot be cancelled. To minimize their impact, we modeled the base line with a spline function before extracting the Milky Way emission line strength. We have checked that the temperature measured by the LAB survey doesn’t vary significantly in a
region within few degrees around our target directions. Since the LAB survey measurements are expressed as brightness temperature, we used the standard NRT antenna temperature $T_a$ to point source intensity $I_s$ conversion factor, as given by the NRT point source efficiency of $\eta = 0.56$ and the collection area $A = 200 \times 35 = 7000 \text{ m}^2$ from expression (Gérard E., private communication):

$$2k_B T_a = \eta A I_s \quad \rightarrow \quad \frac{T_a}{I_s} = \frac{\eta A}{2k_B} = 1.42 \text{ K/Jy}$$

We computed an absolute radiometric calibration coefficient $C_b$, for each polarization signal, each observation run (day) and ON-source, OFF-source spectra, and for each observed cluster. We observed that this calibration is rather stable: Figure 6 shows the variation of the Abell85 calibration coefficient for the 32 runs over a 4 months period from April to October 2011. The derived value of $C_b \simeq 20 \pm 2 \text{ Jy/r.a.u.}$, affected by a systematic error of 5–10 %, and a statistical error of a few percent is compatible with the $C_a$ coefficient obtained from the 3C161 continuous source.

3.4 NRT standard auto-correlator data analysis

We have also analysed the data acquired with the NRT standard auto-correlator (ACRT) in parallel with the BAORadio system. After performing the analysis using the standard NRT software tools (NAPS), we developed a specific pipeline to

![Fig. 6 variation of the Abell85 calibration coefficients for the 32 used observation runs. Blue squares and circles correspond to the two polarizations (0,1) and the ON-source pointings, while red plus and cross markers correspond to the OFF-source pointings](image)
overcome some of the shortcomings of the NAPS software. Both pipelines feature steps similar to the ones described above for the BAORadio pipeline:

- We have implemented two RFI filters in our ACRT pipeline. The first one, similar to the Integration Limit RMS algorithm, nicknamed “ILR” and implemented in NAPS, compares 1-sec spectra with a mean spectra, rejecting spectra with power exceeding a threshold [26]. A second RFI filter searches for intermittent radar signals appearing as peaks in the time evolution of the total power received.

- Similar selection criteria as those listed in Section 3.1 were applied, with an additional rejection of the first 10-sec of each cycle. This rejection is necessary since the signal of the first 10-sec in the OFF-phase is often affected by the stretching of the 150 m long cable carrying the analog signal out of the chariot. Figure 7 illustrates this cable stretching effect, that has been found as a plausible suspect, after estimating the impact of stretching on the cable impedance. This data cleaning procedure retains about 50 % of the data in the ACRT analysis, to be compared with more than 90 % for the BAORadio acquisition.

- NAPS uses the standard NRT calibration procedure through diode (DAB) pulses. Since we found that this procedure increases the measured power fluctuations, we used the 3C161 calibration source instead.

![Normalized difference of power received during ON and OFF phases (in %) vs. time, for polarization p0. The acquisition cycle shown here comprises 18 back and forth moves of the focal chariot. The (ON-OFF) is the subtraction of the power during the ON phase and the OFF phase, taking into account the time shift. Since this function is only defined during the ON phase, zero values are attributed during the OFF phase to maintain the real time information. The negative peaks come from an excess of power at the beginning of some OFF phases. This is attributed to the mechanical constraints on the cables, that are different at the beginning of the ON/OFF phases (the chariot has to go back only before the OFF phases). We also expect this effect to monotonically vary with the cable progress, as observed.](image-url)
The specific pipeline we developed for the data acquired with the ACRT has better performance than the standard NAPS analysis. However, it does not reach the performance of the data taken and processed with the BAORadio system, as we show in the next section.

4 Results

4.1 Sensitivity as a function of integration time

For each cluster observation, we have applied the RFI filtering and data cleaning procedures exposed in previous sections. Then we have used the time series of \( \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle \) spectra (method \((a)\)) integrated over 1 MHz around the ACRT observation frequency (Table 1) to plot for both ACRT and BAORadio systems the evolution of the fluctuation R.M.S as a function of the integration time, the so-called radiometer curve. To compare the two systems, we have considered an “effective integration time” taking into account the useful fraction of time for ON-sky observation: 100 % for ACRT and 25 % for BAORadio. The result is shown in Fig. 9. To produce this figure, the ACRT data has been processed down to its minimum integration time of 1-sec. For BAORadio, we have processed part of the data down to 16.7 ms integration time and the whole data set beyond 8.4 sec.

In the range of integration time longer than 1-sec, the ACRT standard deviation (sigma) is larger than the BAORadio sigma by a factor two. Moreover the ACRT sigma evolution differs from a white noise trend which is a sign of additional noise in the integrated \( \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle \) in the frequency band of interest. This is due to both differences between ON and OFF power levels within the same cycle and to the cycle to cycle variations. Notice that our ACRT pipeline gives notably better results than the standard NAPS pipeline when considering the total power fluctuations between cycles, as shown in Fig. 8 (top).

For BAORadio the radiometer curve is similar to a pure white noise curve below 1-sec and remains below the ACRT curve for longer integration times. One possible origin of the “1-sec” trend change is the noise generated by the 1-sec duty cycle of the cryogenic cooling system for the low noise amplifier in the chariot. In the rest of this section, we test our radiometer curves by comparing with the global noise measurement and with a theoretical estimate.

--- noise measurement

Figure 10 shows the fluctuation or noise level for the \( \langle (\text{On})/\sigma_{\text{run}} - (\text{Off})/\sigma_{\text{run}} \rangle \) spectra calibrated with the Milky Way 21 cm emission (method \((b)\)). The noise level has been computed as the standard deviation (\( \sigma \)) along the frequencies, in a 16 bins or \( \Delta \nu = 488 \text{kHz} \) wide sliding window. We obtain very similar values for the fluctuation level of the 3C161 calibrated \( \langle (\text{On} - \text{Off})/g_{\text{cycle}} \rangle \), over the full frequency band. This is an additional indication that the calibration procedures
Fig. 8 ACRT mean \( (On - Off) / g_{cycle} \) signal integrated in the band [1320.3, 1321.3] MHz versus the cycle number for polarization p0, obtained from the standard NAPS analysis (top) and from the analysis presented in this paper (Section 3.3) (bottom).

described in Sections 3.3 and 3.3.1 are compatible. The measured noise level is nearly flat for most of the frequency band [1300, 1430] MHz, with a few narrow frequency bands where the fluctuations are significantly higher around \( \nu \approx 1313, 1329, 1356, 1376, 1382, 1386, 1402 \) MHz. We find that \( \sigma_{A85} \approx 2.7 \) mJy and \( \sigma_{A1205} \approx 1.8 \) mJy for the signal corresponding to the average of the two polarizations \( s(\nu) = (p0 + p1)/2 \), for a single frequency bin (\( \approx 30.5 \) kHz), for Abell85 and Abell1205 respectively. Using the scaling of the noise with the frequency width (see expression (1) below), we find that when averaging in 1 MHz bandwidth \( \sigma_{A85}(1 MHz) \approx 0.45 \) mJy and \( \sigma_{A1205}(1 MHz) \approx 0.3 \) mJy, which are compatible with the extrapolations from the BAOelec radiometer curve over \( t_{int} = 4882 \) s and \( t_{int} = 6277 \) s respectively (big squared dots in Fig. 9).
Theoretical expression for the noise

The expected noise level in mJy for the sum of the two polarization signal, for an instrument characterized by a collecting area $A$ and efficiency $\eta$, a system temperature $T_{sys}$, total integration time $t_{int}$ and bandwidth $\delta \nu$ can be written as:

$$\sigma^2_{pol} = 10^{29} \times \frac{\sqrt{2} k_B T_{sys}}{\eta A \sqrt{t_{int} \times \delta \nu}} \text{ mJy}$$

$$\simeq \frac{100}{\sqrt{t_{int}}} \text{ mJy for } \delta \nu = 30.5 \text{ kHz}$$

$$\simeq \frac{17.5}{\sqrt{t_{int}}} \text{ mJy for } \delta \nu = 1.0 \text{ MHz}.$$ 

The numerical expressions are obtained assuming a value of the system temperature $T_{sys} \simeq 35$ K for NRT, a collecting area $A = 7000 \text{ m}^2$, a point source efficiency of $\eta \simeq 0.56$ and for two frequency bandwidths $\delta \nu = 30.5 \text{ kHz}$ corresponding to the BAORadio spectral resolution, and $\delta \nu = 1 \text{ MHz}$ used in Fig. 9. The expected noise level would then be $\sigma^2_{pol} \simeq 1.4 \text{ mJy for } t_{int} = 4882 \text{ s and for 30.5kHz bandwidth, almost a factor 2 below the measured noise for Abell85, that we know to be degraded with respect to the white noise beyond } t_{int} = 1 \text{ s.}$. If the bandwidth is increased to 1 MHz, the expected noise level should be $18 \text{ mJy for } t_{int} = 1 \text{ s and 0.4 mJy for } t_{int} = 2000 \text{ s (blue solid line in Fig. 9).}$ The radiometer curves in Fig. 9 follow precisely the slope of these expectations up to $t_{int} = 1 \text{ s;}$ given the uncertainties on the $T_{sys}$, $A$, and $\eta$ parameters, these numerical results are in a reasonable agreement with the expectations up to $\sim 1 \text{ second.}$ Beyond $t_{int} = 1 \text{ s}$, the noise level increases and the radiometric curves departs from the basic expectation. As explained earlier, we identify a $\sim 1 \text{ second duty cycle in the cryogenic system as a possible source of this departure.}$ Nevertheless, we note that the deviation from the linearity observed up to $t_{int} = 1 \text{ s}$ remains relatively modest beyond $t_{int} = 1 \text{ s}$ with the BAORadio system and significantly smaller than with the ACRT system. Moreover, the results presented here toward the three targets have been obtained in three different frequency bands, suggesting that BAORadio system and analysis pipeline are robust over a large frequency domain.

4.2 H I signal search

We have searched for extra power above the noise level around each cluster redshift frequency (Table 1) using data from the BAORadio system which is more sensitive than ACRT system.

We have performed the cluster signal search using the methods (a) and (b) described above and obtained compatible results for the redshifted H I emission from Abell85 and Abell1205 using the sets of spectra of both methods. For the sake of clarity, we present here only the analysis of the $s(\nu) = \langle \text{On/\sigma}_{\text{On run}}\rangle - \langle \text{Off/\sigma}_{\text{Off run}}\rangle$
Fig. 9 Radiometer curve showing the standard deviation (\(\sigma\)) of the mean of the two polarization signals averaged over 1 MHz around the central frequency observed in ACRT versus integration time, obtained for BAORadio (ACRT) data for the three clusters: Abell1205 in blue (red) around 1321 MHz, Abell85 in green (brown) around 1346 MHz and Abell2440 in purple (orange) around 1302 MHz. The blue solid line represents the numerical evaluation of the theoretical expression, assuming \(T_{\text{sys}} \approx 35\) K, \(A = 7000\) m\(^2\) and \(\eta \approx 0.56\), for \(\delta \nu = 1.0\) MHz (see text). The red line (upper right) represents the curve obtained for all clusters from ACRT data analyzed with the standard NRT pipeline (NAPS). The 1\(\sigma\) dispersions for the largest \(t_{\text{int}}\) are estimated with 5 samples of the quoted integration time. The big squared dots show noise estimates from the frequency spectra (see text and Fig. 10).

spectra, as this second method insures that the average signal is zero, making the search for emission or absorption lines easier.

The spectra of the mean of two polarization channels (\(i.e. (p_0 + p_1)/2\)) from Abell85 and Abell1205 data, cleaned from the large fluctuations visible in Fig. 10, and averaged over a sliding window of \(\Delta \nu = 488\) kHz are shown in Fig. 11.

The signal we are searching for is unpolarized while RFI will appear often stronger in one linear polarization. The difference of the two polarizations signal is also shown in Fig. 11 (red triangles) and is expected to be compatible with zero for an H\(_I\) signal. We have also represented the +3 sigma detection threshold for Abell85 and Abell1205 based on the noise levels determined in Section 4.1, taking into account the sliding window size. As expected, Abell1205 data have a lower noise level, due to a larger total integration time.

- **Abell85**: Emissions with statistical significance exceeding 3 sigma are observed around 1350 MHz and 1353 MHz in the Abell85 spectrum. Terrestrial origins for extra power emission have been systematically searched for, and we found that the emission around 1350 MHz cannot be unambiguously attributed to emission.
Fig. 10  Noise level (fluctuations) in mJy as a function of frequency for both polarizations, estimated from the standard deviation (sigma) along the frequency, using a 488 kHz sliding window over the normalized $(On/g_{On} - Off/g_{Off})$ spectra calibrated using the Milky Way 21 cm emission from the full Abell85 ($t_{int} = 4882s$) and Abell1205 ($t_{int} = 6277s$) data sets. Similar results are obtained with the 3C161 calibrated $(On - Off)/g_{cycle}$ spectra over the full frequency band.

from galaxies in the beam, since we have identified intermittent radar emission at 1350 MHz. On the other hand, we have not found any suspect sporadic emission in Abell85 data as well as known RFI emission around 1353 MHz. Moreover, looking at the same frequency band but in the Abell1205 data (Fig. 11 bottom-right) we have not found any suspicious activity at 1353 MHz. So, we conclude that the signal at 1353 MHz towards Abell85 is not due to RFI and that we have detected H$_I$ emission from galaxies belonging to this cluster with high confidence level ($\sim 99 \%$).
Fig. 11 Sum (blue circles) and Difference (red triangles) (in mJy) of the two polarization signals integrated over a 488 kHz wide sliding window for the Abell85 (top) and Abell1205 (bottom). The sampling is 124 kHz. Left: the 40 MHz wide frequency band centered around Abell1205 redshift ($z \simeq 0.08$, 1320 MHz). The frequency band [1312-1315] MHz was subject to RFI and has been blanked. Right: The 40 MHz wide frequency band, centered around Abell85 redshift ($z \simeq 0.05$, 1350 MHz). Notice that the vertical scale is different for the left and right hand set of plots.

- Abell1205: H I emission in the Abell1205 spectrum is expected around 1320 MHz. We observe an excess power in the frequency band [1315, 1320] MHz, and a narrow feature exceeding marginally the 3-sigma threshold around 1318 MHz. Although the statistical significance is weaker than the Abell85, we can conclude that we have also detected H I emission from Abell1205 at 1318 MHz.
- Abell2440 spectrum is not shown since observations suffer from strong RFI and shorter exposure time.

Compared to previous H I surveys with the NRT [21, 25, 32], our detection threshold and line strength sensitivities are lower by a factor $\simeq 5$, from $\simeq 2$ Jy km/s to $\simeq 0.4$ Jy km/s, for comparable total integration times (1 ÷ 3 hours per target). One can notice also that the achieved sensitivity limits, in term of line strength $P_{21}^*$ (Table 2), are comparable to those obtained by the AGES survey toward Abell1367 [13].

### 4.3 H I line strength and mass estimates

Table 2 gives the estimated central frequencies and strengths $P_{21}$ from H I emission of $10^{10}$ $M_\odot$ hydrogen mass at the distance of the observed clusters, deduced from the expression of the total emitted power $P_{\text{emitted}} = 2.4 \times 10^{18} \frac{M_{\text{H} I}}{M_\odot}$ W.
Table 2 Redshift $z$, luminosity distance, central frequency and expected total signal strength $P^*_21$ received on Earth, from 21 cm emission of a total H I mass of $10^{10} M_\odot$ at the three cluster distances studied here

|                | $z$    | $d_L$ (Mpc) | $\nu$ (MHz) | $P^*_21$ |
|----------------|--------|-------------|-------------|----------|
| Abell85        | 0.0498 | 228         | 1353        | 0.830 (3.86) |
| Abell1205      | 0.0777 | 363         | 1318        | 0.326 (1.52) |
| Abell2440      | 0.0926 | 438         | 1300        | 0.215 (1.0) |

$P^*_21$ is given in Jy km/s and mJy MHz in parenthesis

Table 3 gives the list of galaxies within the NRT beam, around the ON source and OFF source pointings of the telescope for the two targets, in the redshift range ($z \lesssim 0.1$) covered by our observations. Assuming a gaussian beam shape for the NRT, we have kept galaxies up to a maximum distance of 2-sigma from the beam center, with H I emission frequency within the frequency band $1342 < \nu < 1362 \text{ MHz}$ for Abell85, and $1311 < \nu < 1333 \text{ MHz}$ for Abell1205. We have also listed the NRT relative beam efficiencies toward the source $\eta_r$, assuming a gaussian beam profile $4' \times 22'$, and the SDSS u,g,r band magnitudes.

We tried to fit line shapes for multiple sources to our measured spectra, to help the association of lines with optical sources having known redshifts. Given our low S/N spectra, we modeled the emission line profiles as simple gaussians. The fit procedure determined the continuum, the gaussian positions (central frequencies) and amplitudes. Approximate best values for the line widths, although weakly constrained, have been estimated within the 380 to 550 kHz range (80–120 km/s) through an iterative fitting.

We have modeled the Abell85 spectrum in the frequency range as a sum of $n = 5$ gaussian profiles, plus a continuum in the frequency range $1344 - 1358 \text{ MHz}$, while the Abell1205 spectrum in the frequency range $1310 - 1324 \text{ MHz}$ has been modeled as a sum of $n = 9$ gaussian profiles, plus a continuum. It yields

$$s(\nu) = C + \sum_{i=1}^{n} A_i \exp\left( -\frac{(\nu - v_i)^2}{2\sigma_i^2} \right)$$

The fit results for the Abell85 and Abell1205 are presented in Table 4 and shown in Fig. 12. The fit has been performed on the unbinned spectrum, the fitted model is represented as the solid black line, and the measured spectra, averaged over 244 kHz wide window is represented as blue circles with error bars.

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9 The frequencies listed in Table 3 and the H I velocities listed in Table 4 have been computed according to the optical astronomer convention and the radio astronomer convention, respectively.
Table 3  List of galaxies with redshift measurement in the NRT ON/OFF beam observed toward Abell85 (first table) and Abell1205 (second table), extracted from the NED and SDSS databases

| Galaxy label | Obj. Name                  | Type       | RA (deg) | DEC (deg) | redshift | $\nu$  | magu | magg | magr | $\eta_r$ |
|--------------|----------------------------|------------|----------|-----------|----------|-------|------|------|------|----------|
| Abell85      |                            |            |          |           |          |       |      |      |      |          |
| G1(+)        | 2MASX J00431039−0903243     |            | 10.7934  | −9.0569   | 0.0578   | 1342.81| 18.2 | 16.3 | 15.5 | 0.60     |
| G2(+)        | SDSS J004310.94−092239.7    |            | 10.7956  | −9.37772  | 0.0559   | 1345.18| 20.7 | 18.9 | 18.1 | 0.17     |
| G3(+)        | SDSS J004322.80−091635.0    |            | 10.8450  | −9.27641  | 0.0539   | 1347.72| 20.7 | 19.3 | 18.6 | 0.42     |
| G4(+)        | SDSS J004310.95−091800.3    |            | 10.7957  | −9.30009  | 0.0532   | 1348.67| 20.1 | 18.7 | 18.2 | 0.34     |
| G5(+)        | SDSS J004319.53−090912.9    |            | 10.8314  | −9.1536   | 0.0502   | 1352.46| 20.5 | 19.5 | 19.1 | 0.91     |
| G6(+)        | SDSS J004314.35−091021.3    |            | 10.8098  | −9.17261  | 0.0501   | 1352.65| 20.0 | 18.9 | 18.6 | 0.87     |
| G7(+)        | GALEXASC J004315.79−085355.1|            | 10.8160  | −8.89925  | 0.0497   | 1353.17| 21.8 | 21.2 | 21.7 | 0.40     |
| G8(+)        | SDSS (Photo-z)              | Spiral     | 10.8127  | −9.06866  | 0.051    | 1351.40| 20.7 | 19.5 | 19.4 | 0.92     |
| G9(−)        | 2MASX J00441835-0902545     | Spiral     | 11.0764  | −9.04854  | 0.0574   | 1343.34| 19.0 | 17.2 | 16.3 | 0.90     |
| Abell1205    |                            |            |          |           |          |       |      |      |      |          |
| G11(+)       | SDSS J111500.29+024756.7    |            | 168.751  | 2.79908   | 0.0799   | 1315.33| 20.3 | 18.5 | 17.8 | 0.15     |
| G12(+)       | SDSS J111505.42+024835.7    |            | 168.773  | 2.80994   | 0.0795   | 1315.79| 20.0 | 18.3 | 17.5 | 0.24     |
| G13(+)       | 2MASX J11150889+0235435     | Spiral     | 168.787  | 2.59539   | 0.0794   | 1315.88| 19.7 | 18.1 | 17.1 | 0.96     |
| G14(+)       | SDSS J111505.17+025118.8    | Spiral     | 168.772  | 2.85524   | 0.0793   | 1316.07| 18.9 | 17.8 | 17.3 | 0.14     |
| G15(+)       | 2MASX J11150843+0243335     | Spiral     | 168.785  | 2.72596   | 0.0785   | 1317.06| 18.2 | 16.8 | 16.2 | 0.54     |
| G16(+)       | 2MASX J11151499+0239533     | Spiral     | 168.812  | 2.66472   | 0.0783   | 1317.21| 19.2 | 17.6 | 16.8 | 0.49     |
| G17(+)       | 2MASX J11151546+0232363     | Spiral     | 168.814  | 2.54348   | 0.0779   | 1317.76| 18.8 | 17.1 | 16.1 | 0.59     |
| Galaxy label | Obj. Name | Type     | RA (deg) | DEC (deg) | redshift | \( \nu \) | magu | magg | magr | \( \eta_r \) |
|-------------|-----------|----------|----------|-----------|----------|--------|------|------|------|------------|
| G18\(^{(+)}\) | WISEPC J111459.91+024551.0 |          | 168.750  | 2.76446   | 0.0765   | 1319.45| 18.2 | 17.5 | 17.4 | 0.19       |
| G19\(^{(+)}\) | SDSS J1111516.72+022308.7 |          | 168.820  | 2.38577   | 0.0764   | 1319.63| 19.6 | 18.3 | 17.5 | 0.28       |
| G20\(^{(+)}\) | SDSS J111508.37+023301.4 |          | 168.785  | 2.55039   | 0.0761   | 1319.95| 19.2 | 18.2 | 17.8 | 1.00       |
| G21\(^{(+)}\) | 2MASX J11151316+0224125 |          | 168.805  | 2.40360   | 0.0731   | 1323.67| 19.4 | 17.5 | 16.6 | 0.52       |
| G22\(^{(-)}\) | SDSS J111611.93+022237.1 |          | 169.050  | 2.37700   | 0.0768   | 1319.08| 19.3 | 18.0 | 17.4 | 0.48       |
| G23\(^{(-)}\) | SDSS J111604.50+022946.6 |          | 169.019  | 2.49630   | 0.0763   | 1319.68| 20.0 | 18.1 | 17.1 | 0.81       |
| G24\(^{(-)}\) | 2MASX J11161766+0221129 | Spiral   | 169.074  | 2.35358   | 0.0763   | 1319.68| 18.8 | 17.5 | 16.8 | 0.19       |
| G25\(^{(-)}\) | 2MASX J11162139+0235209 |          | 169.089  | 2.58901   | 0.0742   | 1322.25| 19.1 | 17.2 | 16.2 | 0.17       |

In each table, the first list, galaxies numbered with \( (+) \) superscript correspond to the galaxies in the ON beam, while the second list with \( (-) \) superscript, corresponds to galaxies in the OFF Beam. \( \text{magu}, \text{magg}, \text{magr} \) are the SDSS DR10 magnitudes in the u,g,r bands. \( \eta_r \) is the NRT relative beam efficiency towards the source, assuming a gaussian beam with FWHM equal to 4' in RA, 22' in DEC. Unfortunately, very few galaxies have a known type.
Table 4 Results of the multiple gaussian line profiles fits to the ON-OFF spectrum measured toward Abell85 (top) and Abell1205 (bottom)

| Fitted line label | ν₀(MHz)         | V_{HI} (km/s) | A(mJy) | P_{21}^* (Jy km/s) |
|-------------------|----------------|--------------|--------|---------------------|
| Abell85           |                |              |        |                     |
| L1⁺               | 1349.48 ± 0.05 | 14970 ± 10   | 5.6 ± 0.8 | 0.70 ± 0.09         |
| L2⁺               | 1350.30 ± 0.10 | 14795 ± 20   | 3.0 ± 0.9 | 0.32 ± 0.09         |
| L3⁺               | 1351.10 ± 0.10 | 14625 ± 20   | 1.9 ± 0.9 | 0.17 ± 0.08         |
| L4⁺               | 1352.30 ± 0.10 | 14375 ± 20   | 5.0 ± 0.9 | 0.42 ± 0.08         |
| L5⁺               | 1352.90 ± 0.05 | 14245 ± 10   | 4.4 ± 0.9 | 0.38 ± 0.08         |
| Abell1205         |                |              |        |                     |
| L11⁺              | 1315.4 ± 0.15  | 22160 ± 30   | 1.0 ± 0.6 | 0.10 ± 0.06         |
| L12⁺              | 1315.9 ± 0.13  | 22055 ± 30   | 1.4 ± 0.6 | 0.13 ± 0.06         |
| L13⁺              | 1316.5 ± 0.10  | 21930 ± 20   | 1.7 ± 0.6 | 0.16 ± 0.06         |
| L14⁺              | 1317.0 ± 0.08  | 21825 ± 20   | 2.0 ± 0.5 | 0.19 ± 0.06         |
| L15⁺              | 1317.9 ± 0.06  | 21635 ± 15   | 2.4 ± 0.5 | 0.25 ± 0.06         |
| L16⁺              | 1319.8 ± 0.10  | 21230 ± 20   | 1.2 ± 0.6 | 0.11 ± 0.06         |
| L17⁺              | 1322.1 ± 0.15  | 20750 ± 30   | 0.9 ± 0.6 | 0.08 ± 0.05         |
| L18⁻               | 1320.6 ± 0.10  | 21065 ± 20   | 1.2 ± 0.6 | 0.11 ± 0.05         |
| L19⁻               | 1322.7 ± 0.15  | 20620 ± 30   | 0.9 ± 0.6 | 0.08 ± 0.04         |

The reduced χ² of the fit for Abell85 is 0.96 (N_{dof} = 470), to be compared with 1.08 for a constant fit. For Abell1205, the reduced χ² of 1.07 (N_{dof} = 505), to be compared with 1.15 for a constant fit.

Abell85

1. No galaxy from Table 3 could be associated with the two emission lines L1 (1349.48 MHz) and L2 (1350.3 MHz). As mentioned in the previous section, these two emission like features might be due to imperfectly cleaned RFI.

2. The 1.9 mJy line L3 (1351.1 MHz) might be associated with the galaxy labeled G8 in the Abell85 list, but the uncertainty on the photometric redshift prevents us from any definitive conclusion. Assuming η_r ≃ 0.9, the estimated H_I mass would be:

   \[ L3 : M_{H_I} \approx 2.3 \pm 1 \times 10^9 M_\odot \ (V_{HI} = 14625 \pm 20 \text{ km/s}) \]

3. The two lines L4 (1352.3 MHz) and L5 (1352.9 MHz) are probably associated with the galaxies labeled G5, G6, G7. We note that these 3 galaxies are the bluest (according to u-g) in the list, making them good (gas-rich) candidates for such an association. Assuming η_r ≃ 0.9 for L4 and η_r ≃ 0.4 for L5, we obtain the following H_I mass estimates:

   \[ L4 : M_{H_I} \approx 5.6 \pm 1.4 \times 10^9 M_\odot \ (V_{HI} = 14375 \pm 20 \text{ km/s}) \]
   \[ L5 : M_{H_I} \approx 1.1 \pm 0.3 \times 10^{10} M_\odot \ (V_{HI} = 14245 \pm 10 \text{ km/s}) \]
Fig. 12 Results of the fits of the H\textsubscript{i} signal modeled as a sum of 5 gaussian profiles for Abell85 (top), in the range [1344, 1358]MHz and as a sum of 9 gaussian profiles for Abell1205 (bottom), in the range [1310, 1324]MHz. The black curves represent the fit results, and blue circles the sum of the two polarization measurements, averaged over 244 kHz. We have represented one point every 122 kHz. Error bars are derived from the fluctuations computed along the frequency axis (see Fig. 10).

Abell1205

1. The first three lines L11-L13 (1315.4, 1315.9, 1316.5 MHz) might be associated with galaxies labeled G11 to G14 in Abell1205 galaxy list. Note that G13 is a spiral galaxy and G14 is a blue galaxy, making them the most probable optical counterparts. The total associated neutral hydrogen mass would be $M_{\text{HI}} \simeq 12 \times 10^9 M_\odot$, for $\eta_r \simeq 1$.

2. The line L14 (1317 MHz) can be associated to the Abell1205 galaxies labeled G15, G16, while the line L15 (1317.9 MHz) is likely to be due to the G17...
galaxy. Here, $G_{15}$ (spiral galaxy) and $G_{17}$ (the brightest galaxy within our redshift window) are the best candidates for the associations. Assuming $\eta_r \simeq 0.6$, we obtain the associated neutral hydrogen masses:

$L_{14}$: $M_{\text{HI}} \simeq 10 \pm 3 \times 10^9 M_\odot$ ($V_{HI} = 21825 \pm 20 \text{ km/s}$)

$L_{15}$: $M_{\text{HI}} \simeq 13 \pm 3 \times 10^9 M_\odot$ ($V_{HI} = 21635 \pm 20 \text{ km/s}$)

3. The fitted line $L_{16}$ (1319.8 MHz) can be associated with the Abell1205 galaxies labeled $G_{18}, G_{19}, G_{20}$, with a total hydrogen mass of $M_{\text{HI}} \simeq 3 \pm 1.5 \times 10^9 M_\odot$ with $\eta_r \simeq 1$. $G_{18}$ and $G_{20}$, which are bluer, are here the best candidates for the association.

4. The other fitted lines ($L_{17}, L_{18}, L_{19}$) cannot be associated to our knowledge to galaxies in the ON or OFF beam although the Table 3 might be incomplete.

A simple integration of the Abell85 spectrum above continuum in the frequency band $\nu \in [1351, 1353]$ will yield a total H I brightness of $P_{21}^* \simeq 0.75 \text{ Jy km/s}$, corresponding to a total mass of $M_{\text{HI}} \simeq 1.5 \times 10^{10} M_\odot$ for $\eta_r \simeq 0.6$, while performing a similar integration on the Abell1205 spectrum in the frequency band $\nu \in [1315, 1318.5]$ will yield a total H I brightness of $P_{21}^* \simeq 0.65 \text{ Jy km/s}$ corresponding to a total hydrogen mass $M_{\text{HI}} \simeq 3.3 \times 10^{10} M_\odot$. These values are in agreement with the estimates from the fit. It should also be noted that the quoted uncertainties are underestimated, as they do not include line width uncertainty, systematic errors due to residuals in the spectrum shape, calibration and beam efficiencies.

5 Conclusions

We have investigated the capabilities of the new BAORadio analog and digital back-end, associated with our data acquisition and processing pipeline, through a pilot observation program of search for HI emission from galaxies in clusters at redshift $z \sim 0.05 - 0.1$. More than 50 hours of observations have been carried out toward the three clusters (Abell85, Abell1205, Abell2440) and calibration sources with the BAORadio system, in parallel with the standard NRT correlator, over a period of one year. We have shown the superior RFI cleaning performance achieved thanks to the BAORadio electronic chain, offering full digitization at 500 MHz with fine time sampling ($\sim 0.1\text{ ms}$).

We have also demonstrated the high level of stability of the new system, far better than the standard NRT correlator, which suffers from the analog signal transmission over several hundred meters. Surprisingly, we have found that the standard calibration procedure used at NRT, based on noise diode pulses injected at the beginning of each observation cycle, is the source of additional signal fluctuations. We have thus relied on the system stability, associated with calibration with respect to astrophysical sources, 3C161 radio source and the Milky Way H I emission for the results which have been presented.

We have obtained the radiometer curves for both systems (BAORadio, ACRT) and the three frequency bands centered on the Abell cluster redshifted H I emission lines. After about 2000 s of integration time the BAORadio system has reached a sensitivity
of about 1.4 mJy, while the standard NRT ACRT system sensitivity is at least 5 times worse, even after extensive data cleaning. We have also identified an additional noise contribution for integration time larger than 1 s, using the BAORadio data, which might be due to the cryogenic cooling system.

Unfortunately, the spectra that we have obtained present some structuring as a function of frequency. The source of these modulations have been clearly identified: impedance mismatch between the NRT cryogenic amplifier and BAORadio analog board is responsible for the few MHz modulations, while the $\sim$ 500 kHz modulations comes from the standing waves between the NRT spherical mirror and the receiver horns. It should be noted that $\sim$ 500 kHz modulations can be partially canceled thanks to the horizontal motion of the NRT focal plane assembly along the direction of the waves propagation, but this feature was disabled during our observations due to mechanical maintenance. We have used this horizontal motion in subsequent observations which indeed decreases the $\sim$ 500 kHz modulation amplitude drastically.

Although quite challenging given the NRT sensitivity and RFI environment, our search for H I emission from galaxies within clusters in the redshift range $z \lesssim 0.1$ has been successful, thanks to the BAORadio electronic system performance and our dedicated data reduction pipeline. We are fairly confident on a detection of emission in Abell85, with $> 3\sigma$ significance level, leading to a total H I brightness of about 0.8 Jy km/s in the [1351, 1353] MHz band. Concerning the Abell1205 cluster, we report the detection of a 21 cm emission signal in the frequency band [1315, 1318] MHz, but at a lower statistical significance. The corresponding H I brightness in the integrated spectrum is about 0.6 Jy km/s. We have performed a cross identification of the detected emission lines with optically detected galaxies and have derived mass estimates for galaxies in Abell85 and Abell1205.

Obviously, larger instruments such as the Arecibo radio telescope or the upcoming SKA instruments will be more effective for such non local H I searches. It would however be possible to carry more ambitious search with NRT and BAORadio using several hundred hours of observation. The analog input stage needs however to be modified to decrease the impedance mismatch, and the acquisition system has to be upgraded. The ON-sky observation fraction of useful time could then easily be pushed to more than 50 %, as we have already demonstrated in test observations. Moreover, most of the CPU and I/O intensive steps of the RFI cleaning and data reduction could then be performed on the acquisition computers, easing the subsequent data analysis task.

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