Angular clustering of point sources at 150 MHz in the TGSS survey

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ABSTRACT

We study the angular clustering of point sources in The GMRT Sky Survey (TGSS). The survey at 150 MHz with δ > –53.5° has a sky coverage of 3.6 π steradian, i.e., 90% of the whole sky. We define our sample and study angular clustering of point sources at large scales for different subsamples. We find that there is a break in angular clustering at a scale of about one degree, this break is pronounced for subsamples that have a lower flux threshold. We compare our results with other studies of clustering of point sources. We use the available data to present the variation of clustering with the flux limit at 150 MHz. We also present results of cross-matching sources with the SDSS redshift surveys and estimation of the two point correlation function.

Key words: Cosmology: large-scale structure of Universe, observation, miscellaneous radio continuum: general

1 INTRODUCTION

Low frequency observations of radio sources give unique information about the population of ultra-relativistic electrons in the inter-stellar medium (ISM) of galaxies: synchrotron emission is the primary radiative mechanism at these frequencies (Condon 1992). Emission from ISM in galaxies and AGNs dominates over the expected flux from neutral Hydrogen via the redshifted 21 cm radiation from the early universe. This then constitutes a significant foreground that needs to be studied and removed in order to study the evolution of neutral Hydrogen in the universe. In particular this affects studies of the so called epoch of reionization (EoR) where the inter-galactic medium transitions from being neutral to almost completely ionised (Di Matteo et al. 2004; Liu et al. 2009; Jelic et al. 2008; Trott et al. 2012; Murray et al. 2017; Spinelli, Bernardi, & Santos 2018; Bowman et al. 2018). Redshifted 21 cm radiation from this epoch is likely to have observed wavelength of 1.5 – 4 m, or frequency of 75 – 200 MHz. Therefore a study of point sources and their clustering in this range of frequencies is relevant, not just from the perspective of studying radio populations but also for its impact on EoR studies. Studies of radio source clustering beyond angular correlation function require information about redshift, which is not available for an overwhelming majority of sources at present.

A number of studies have been carried out to quantify the faint source population and its clustering at low frequencies. A list of existing and ongoing radio surveys is given in Table 1.

The Giant Metrewave Radio Telescope (GMRT) was used to survey the Radio Sky at 150 MHz between 2010 and 2012 Alternative Data Release (ADR1) (Intema et al. 2017) of the TGSS survey contains a catalogue of point sources. Here, TGSS data has been analysed using the SPAM pipeline, which includes corrections for direction-dependent ionospheric phase effects. Also included are continuum stokes I images of 99.5% of the radio sky north of δ = –53° (3.6 π sr, or 90% of the full sky) at a resolution of 25′′ × 25′′ north of δ = 19° and 25′′ × 25′′ / cos(δ – 19°) south of δ = 19°, and a median noise of 3.5 mJy beam⁻¹. The extracted radio source catalogue contains positions, flux densities, sizes and more for 0.62 Million sources down to a 7 σ peak-to-noise threshold. The data analysis pipeline and data products are described in detail in Intema et al. (2017).

The median survey sensitivity is 3.5 mJy beam⁻¹ and most part of sky (about 80%) covered by TGSS has sensitivity 5 mJy beam⁻¹ (see figure 8 of Intema et al. 2017). The estimation of the TGSS confusion noise at 150 MHz and with a 25′′ beam range between 0.44 mJy beam⁻¹ and 2.5 mJy beam⁻¹ in most of the sky. The TGSS point source survey has 50 percent completeness at 25 mJy (or 7σ for point sources, with sigma being the median survey noise of

1 Proposal for the survey was made by Sandeep Sirothia, Nimisha Kantharia, Ishwara Chandra and Gopal Krishna (GTAC Cycle 18).
2 http://tgssadr.strw.leidenuniv.nl/doku.php

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2 ANALYSIS AND RESULTS

2.1 Survey Selection

Our main aim here is to do study clustering of point sources. We need to define a sample that is homogeneous and complete. The ADR1 data provides us with peak flux, source flux and noise on the individual source. We created a pixelised all-sky map for all sources in TGSS ADR1 catalogue. We removed the region with Nside = 128 and 1024 using HEALPy: python version 3.2. We used an Nside = 1024 map as selection function alongside best fit for amplitude and power law index. We estimate the posterior probability distribution of the amplitude, $A$, and power law index, $\gamma$, is defined in terms of pair counts in the data and the random catalog:

$$\omega(\theta) = \frac{N_r(N_r + 1)DD - N_d(N_r + 1)DR + 1}{RR} + 1$$

Here DD denotes the count of pairs in the data at angular separation $\theta$, and $N_d$ denotes the total number of objects considered in the analysis. Similarly, RR is the averaged pair count over a catalogue of uniformly distributed points covering the same survey area, DR is the data-random cross pair count, and $N_r$ denotes the number of points in the random catalogue. We created 10$^5$ random catalogs for clustering analysis using survey selection function as described in previous section.

To compute DD, RR and DR efficiently we use publicly available routines such as KD-tree and BD-tree (Scikit-learn Pedregosa et al. 2011) which are an implementation of spatial algorithm such as k-d tree and Ball tree data structures for fast nearest neighbour search (Bentley 1975; Omohundro 1989). We used bootstrap re-sampling method for error estimation in angular correlation (Feigelson & Babu 2012; Andrae 2010).

We find that the amplitude of the angular correlation function varies monotonically with the flux cut-off at all scales, as shown in figure 1. We find that as the flux threshold is increased, the amplitude of angular correlation function at a fixed angle increases. This is consistent with findings in earlier studies, e.g., see (Peacock & Nicholson 1991; Rengelink 1999; Magliocchetti et al. 2017). This may arise from the known correlation between the star formation rate and the stellar mass in galaxies, e.g., see (Lara-López et al. 2013), or from a higher prevalence of AGNs in more massive galaxies.

To quantify the shape of the angular correlation function, we assume a power law form: $A \theta^{-\gamma}$ (Cress et al. 1996; Rengelink 1999; Magliocchetti et al. 1998; Blake & Wall 2002; Overzier et al. 2003; Blake et al. 2004). Here $A$ is the amplitude, $\theta$ is the angle in degrees and $\gamma$ is the power law index. We estimate the posterior probability distribution alongside best fit for amplitude $A$ and power law index $\gamma$. We use the emcee (Foreman-Mackey et al. 2013) package, which is a Python implementation of MCMC sampling for

3.5 mJy beam$^{-1}$) for more detail see Intema et al. (2017). We choose to work with subsets with higher flux cutoff to ensure better completeness.

2 ANALYSIS AND RESULTS

2.1 Survey Selection

Our main aim here is to work with subsets with higher flux cutoff to ensure better completeness.

Table 1. Low frequency sky surveys. This table enumerates various sky surveys at low frequencies. Their sky coverage and sensitivity, frequency and resolution are listed here.

| Survey          | Frequency(MHz) | Resolution | Noise (mJy beam$^{-1}$) |
|-----------------|----------------|------------|-------------------------|
| VLSS (Cohen et al. (2007)) | 74             | 80″         | 100                     |
| VLSSr (Lane et al. (2014))  | 73.8            | 75″         | 100                     |
| 8C (Reed (1990))          | 38             | 4.5′ × 4.5′ csc(δ) | 200 – 300              |
| 7C (Pooley et al. (1996)) | 151            | 70″ × 70″ csc(δ) | 20                     |
| MSSS-LBA (Heald et al. (2015)) | 30 – 78 | ≤ 150′ | ≤ 50                    |
| MSSS-HB (Heald et al. (2015)) | 120 – 170 | ≤ 120′ | ≤ 10 – 15              |
| TGSS (Intema et al. (2017)) | 150            | 25″         | 5                      |
| GLEAM (Hurley-Walker et al. (2017)) | 72 – 231 | 100″      | 10                     |
| LoTTS (Shimwell et al. (2017)) | 120 – 168 | 25″        | 0.5                    |
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2.3 Spatial clustering of radio sources

Angular correlation function of a set of sources can be combined with the knowledge of the redshift distribution of sources to estimate the two point correlation function of these sources in three dimensional space (Limber 1954; Efstathiou et al. 1991; Baugh & Efstathiou 1993; Loan et al. 1997; Magliocchetti et al. 1998; Simon 2007). In order to get an estimate of the redshift distribution, we cross match TGSS sources with the SDSS data. Spectroscopic redshifts have been used here. Cross matches within a search radius of 5″ for the TGSS and SDSS catalogues were used. We chose this search radius as we expect locations of sources to be much better known than the resolution.

The number of such cross matches is very small, i.e., 829 sources with spectroscopic redshift for search radius of 5″ corresponds to flux cut-off of $\geq 50\,\text{mJy}$. Hence the redshift distribution of a vast majority of sources remains uncertain. For reference, we note that these cross matched sources are less than 3% of the 50 mJy catalogue. Hence results presented here should be thought of as first estimates. The redshift distribution of cross matches is shown in figure 4. We have also studied the variation of the distribution of sources with flux and we find that the slope of the log $N$ – log $S$ relation is close to the expected value $-1.5$. This is illustrated in Figure 5 where we show the distribution of sources in the cross-matched list as a function of the observed radio flux.

We analyse the photometric properties of galaxies with cross-matches and find that most of these are bright red galaxies (see figure 7 and discussion below.).

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**Figure 1.** Angular correlation function for the four subsets. We see that there is a break in the shape at an angle of $1^\circ$ with a power law decline at larger scales and a gentler variation at smaller scales. The amplitude of angular correlation is larger for subsamples with a high flux threshold, i.e., brighter sources cluster more strongly.

**Figure 2.** Posterior probability distribution for $A$ and $\gamma$ using angular correlation data for different flux cut-off values. This is shown for the four subsets. $1 - \sigma$ and $2 - \sigma$ contours are shown here. The outline of contours for the $50\,\text{mJy}$ subset is shown in all the panels for reference. Note that the power law is fit only at scales $\theta \geq 1^\circ$.
Where $\epsilon = \gamma_e - 3$ corresponds to stable clustering in comoving coordinates, $\epsilon = 0$ is for stable clustering in proper coordinates and $\epsilon = \gamma_e - 1$ is for clustering growth in linear regime (Efstathiou et al. 1991; Loan et al. 1997). For small angles ($\theta \ll 1$ rad) the angular correlation $\omega(\theta)$ can be related to the two point correlation function $\xi(r,z)$ if we assume the form given above (Efstathiou et al. 1991):

$$w(\theta) = \sqrt{\pi} \frac{\Gamma[(\gamma_e - 1)/2]}{\Gamma(\gamma_e/2)} A r_0^{\gamma_e} \theta^{1-\gamma_e}$$

(4)

where

$$A = \int_0^\infty \left( \frac{dl}{dz} \right) x^{1-\gamma_e} F(x)(1+z)^{-(3+\epsilon-\gamma_e)} \left( \frac{dN}{dz} \right)^2 dz$$

(5)

Here $x$ is the comoving distance at redshift $z$ and $dN/dz$ is the number of the object per unit redshift of TGSS galaxies.

We use this relation to constrain the values of $r_0$ and $\gamma_e$ for different values of $\epsilon$. We do not take the different variation of $w(\theta)$ at smaller angles into account as it pertains to very small length scales in the context of the cross-matched sample: $\theta = 1^\circ$ corresponds to a length scale smaller than 1 Mpc at $z \sim 0.1$ and most of the cross-matches are at lower redshift. The results obtained from the analysis are shown in Figure 5 showing best fit value and 1-$\sigma$ and 2-$\sigma$ confidence interval for 50 mJy flux cut-off. We find that there is some degeneracy between the two parameters from the elongated ellipsoid. We do not see any strong variation with the choice of $\epsilon$. This is to be expected as the redshift distribution of sources with cross matches is limited to low redshifts. Table 3 provides a summary of these results for the two cross-matched catalogues. In each case we find that the slope and the amplitude of the correlation function is consistent with correlation of bright red galaxies (Zehavi et al. 2011).

To explore this further we plot $u-r$ colour vs $r$-band absolute magnitude for our sample see figure 7 we used $u-r$ cut given by Strateva et al. (2001). One can clearly see that bulk of our sample is dominated by red early type galaxies. Thus the slope and amplitude of the correlation function is consistent with the type of galaxies with cross-matches. However, the number of cross-matches are so few that it is difficult to deduce the two point correlation function for the full sample.

### 3 SUMMARY

In this paper we have studied angular clustering of radio sources in the TGSS survey using the catalogues derived in the alternative data release. We have defined our main

| Survey | Ref | $\nu$ (MHz) | $S_{10\%}(\text{mJy})$ | $A \times 10^{-3}$ | $\gamma$ | Number of Sources |
|--------|-----|-------------|------------------|-----------------|--------|------------------|
| TGSS   | This Work | 150 | $\geq 50$ | 7.9 $\pm$ 0.2 | 0.833 $\pm$ 0.023 | 307634 |
| TGSS   | This Work | 150 | $\geq 60$ | 8.6 $\pm$ 0.2 | 0.809 $\pm$ 0.023 | 275780 |
| TGSS   | This Work | 150 | $\geq 100$ | 9.9 $\pm$ 0.2 | 0.787 $\pm$ 0.024 | 188269 |
| TGSS   | This Work | 150 | $\geq 200$ | 11.9 $\pm$ 0.4 | 0.810 $\pm$ 0.026 | 100985 |
| VLSS   | de Oliveira-Costa & Capodilupo (2010) | 74 | 770 | 103 $\pm$ 26 | 1.21 $\pm$ 0.35 | 68311 |
| MIYUN  | de Oliveira-Costa & Lazio (2002) | 232 | 250 | 96 $\pm$ 71 | 1.12 $\pm$ 0.11 | 34426 |
| PMN    | Loan et al. (1997) | 4.85 $\times 10^3$ | 50 | 10.0 $\pm$ 5.0 | 1.8 | 77856 |
| FIRST  | Cross et al. (1996) | 1400 | 3 | 3.7 $\pm$ 0.3 | 1.06 $\pm$ 0.03 | 190873 |
| FIRST  | Magliocchetti et al. (1998) | 1400 | 3 | 1.52 $\pm$ 0.06 | 1.68 $\pm$ 0.07 | 86074 |
| NVSS   | Blake & Wall (2002) | 1400 | 10 | 1.08 $\pm$ 0.09 | 0.83 $\pm$ 0.05 | 522341 |
| NVSS   | Overzier et al. (2003) | 1400 | 3 | 0.8 $\pm$ 0.1 | 0.8 | 86074 |
| NVSS   | Overzier et al. (2005) | 1400 | 10 | 1.0 $\pm$ 0.2 | 0.8 | 86074 |
| WENSS  | Rengelink (1999) | 325 | 35 | 2.0 $\pm$ 0.5 | 0.8 | 86461 |
| WENNS  | Blake et al. (2004) | 325 | 35 | 1.01 $\pm$ 0.35 | 1.22 $\pm$ 0.33 | 86461 |
| SUMMS  | Blake et al. (2004) | 843 | 10 | 2.04 $\pm$ 0.38 | 1.24 $\pm$ 0.16 | 68373 |

### Table 2. Best fit value of $\omega(\theta)$ at low frequencies from current study and earlier published work.

### Table 3. Best fit parameters describing the two point correlation function for the Spectroscopic cross-matched redshift distributions. All results presented here are for a flux cut-off of 50 mJy.
sample and sub samples using the rms noise and peak flux. We have studied angular clustering of these sources and our main findings are:

(i) The angular correlation function has a power law behaviour at scales larger than a degree: correlation drops rapidly at larger angular separations.

(ii) For subsets with fainter sources, the angular correlation at scales smaller than a degree has a weaker dependence on scale as compared to larger scales.

(iii) The slope of the angular correlation function shows little variation with the flux of sources.

(iv) The amplitude of the power law increases monotonically with the peak flux of sources. This is consistent with
earlier studies, e.g., see (Peacock & Nicholson 1991; Rengelink 1999; Magliocchetti et al. 2017).

(v) We have compared our findings with other studies of angular clustering of radio sources. We show that assuming a typical spectral index of $\alpha = 0.76$, the amplitude of angular clustering is insensitive to the frequency at which the sources are observed and selected. This is in agreement with Rengelink (1999).

(vi) We provide a fit to the variation of the amplitude of clustering with the flux cutoff at 150 MHz. This is potentially useful for modelling of point source foregrounds for EoR studies.

We use cross matches with the SDSS spectroscopic samples and find some common sources. Using the redshift distribution of these sources we estimate the full two point correlation function of the TGSS sources. We find that the two point correlation function has an amplitude that is comparable with optically selected bright red galaxies. This is consistent with the galaxy population identified using cross-matches. However it does not enable us to make any statements about the two point correlation function for the full population as we have identified only a very small number of TGSS sources. We do not find cross-matches for star forming galaxies, this is not unexpected given the flux limits used here (Schober, Schleicher, & Klessen 2017).

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