ABSTRACT
We investigate the clustering of HI-selected galaxies in the ALFALFA survey and compare results with those obtained for HIPASS. Measurements of the angular correlation function and the inferred 3D-clustering are compared with results from direct spatial-correlation measurements. We are able to measure clustering on smaller angular scales and for galaxies with lower HI masses than was previously possible. We calculate the expected clustering of dark matter using the redshift distributions of HIPASS and ALFALFA and show that the ALFALFA sample is somewhat more anti-biased with respect to dark matter than the HIPASS sample.

Key words: large-scale structure of the universe - radio lines: galaxies

1 INTRODUCTION
Measurements of the clustering of galaxies allows one to investigate the relationship between dark and luminous matter. By comparing galaxies selected in different ways one gains understanding of how different galaxies trace the underlying dark matter and also of processes at work in galaxy evolution. This information is important when using galaxies as probes of cosmological parameters.

A number of new radio telescopes, such as the MeerKAT, ASKAP and the SKA, are in the pipeline and they will detect huge numbers of galaxies using HI. A reliable measure of the bias of HI-selected galaxies and insight into the evolution of the bias is important for forecasting the capabilities of telescopes which will probe HI at intermediate or high-redshifts. The clustering of HI-selected galaxies has been studied by Meyer et al. (2007), Basilakos et al. (2007) and Ryan-Weber (2006). They used data from the HI Parkes All Sky Survey (HIPASS, Meyer et al. 2004), a blind survey for HI of the southern sky which generated a catalogue of 4315 sources, the bulk of which have redshifts below $z \sim 0.02$. They showed that HI-selected galaxies are less clustered than galaxies selected in other ways. Meyer et al. (2007) investigated clustering of various subsamples of HIPASS galaxies, showing that galaxies with high rotation velocities are more clustered than those with lower rotation velocities. There were indications that galaxies containing more HI are also more clustered but the differences were not as pronounced as in Basilakos et al. (2007). The latter work also measures the bias of HIPASS galaxies relative to the expected dark matter distribution.

In this paper we measure the clustering of HI-selected galaxies detected with the Arecibo L-band Feed Array (ALFA) and compiled in the partially completed ALFALFA survey (the Arecibo Legacy Fast ALFALFA survey, Giovanelli et al. 2005). The results are compared with those obtained for HIPASS. Clustering measurements in HIPASS are limited to large angular scales where the beam-size of $\sim 15$ arcmins does not cause confusion. The ALFALFA resolution is more than four times better allowing us to probe clustering on smaller scales. The rms noise per ALFALFA beam is about six times smaller, providing a catalogue of sources which spans a wider range of redshifts and includes galaxies with lower HI masses. We are thus able to measure clustering of HI-selected galaxies in regimes that have not yet been explored and to investigate trends seen in HIPASS, using an independent survey.

The outline of the paper is as follows: In §2 we give a short introduction to the HIPASS and ALFALFA surveys. The computation of the angular and spatial two-point correlation functions is described in §3. The results are presented, discussed and compared with earlier work in §4. Finally, §5 concludes with a short summary.

2 DATA
HIPASS covers all the southern sky with $\delta < \pm 2^\circ$ and can detect HI with velocities in the range $300 \text{ km s}^{-1} - 12700 \text{ km s}^{-1}$. The rms noise per beam is $\sim 13$ mJy (Meyer et al. 2004). To exclude structure associated with the Milky-Way, like high-velocity clouds and low mass satellites, we only use sources with recessional velocities larger...
than 600 km s\(^{-1}\). The average mass of HI in HIPASS galaxies is \(3.24 \times 10^9 M_\odot\).

When completed, the ALFALFA Survey (Giovanelli et al. 2005) will cover 7000 deg\(^2\) of sky with high galactic latitude and to a depth of \(cz \sim 18000\) km s\(^{-1}\). The rms noise of the survey is \(\sim 2.2\) mJy and the beam-size is \(\sim 3.6\) arcminutes. Currently the ALFALFA survey contains three strips covering a total area of \(\sim 400\) deg\(^2\). These are the two strips centred on the Virgo region and the anti-Virgo strip. They contain 1796 sources with \(cz > 600\) km s\(^{-1}\). The first completed Virgo strip is defined by \(11^h 44^m < \alpha < 14^h 00^m\) and \(12^\circ < \delta < 16^\circ\) and contains 708 sources. The second Virgo strip contains 556 galaxies within \(11^h 36^m < \alpha < 13^h 52^m\) and \(8^\circ < \delta < 12^\circ\) (Kent et al. 2008). The anti-Virgo strip contains 488 sources within \(22^h 00^m < \alpha < 03^h 04^m\) and \(26^\circ < \delta < 28^\circ\) (Saintonge et al. 2008). A circular region, with radius of \(1^\circ\) centred on M 87, has been removed from the survey area due to the interference of M 87 (Giovanelli et al. 2007). The average ALFALFA HI mass is \(2.48 \times 10^8 M_\odot\). The source density of the ALFALFA catalogue is approximately 20 times higher than that of the HIPASS survey.

Figure 1 displays the normalised redshift distributions of the HIPASS and ALFALFA surveys as well as the distribution of the ALFALFA sources in the three, spatially separated strips.

![Figure 1](image-url)  
**Figure 1.** Plot of the normalised redshift distribution of the HIPASS and ALFALFA surveys as well as the distribution of the ALFALFA sources in the three, spatially separated strips.



### 3 TWO-POINT CORRELATION FUNCTIONS

Here we review some basic properties of the angular and projected two-point correlation functions (\(\omega\) and \(\Xi\) respectively) and indicate their relations to the three dimensional (3-D) real-space two-point correlation function, \(\xi\). Subsequently, we introduce the estimator used here and discuss the construction of the random samples. We do not employ the weighted correlation functions used in Meyer et al. (2007) as we are interested in comparing the results of the two surveys and in comparing our results with those predicted for dark matter within a \(\Lambda\)CDM model. The unweighted measurements suffice for this work and we are able to check our unweighted results against those of Meyer et al. (2007).

#### 3.1 The Angular Two-Point Correlation Function

The angular correlation function, \(\omega\), is a simple measure of the clustering of galaxies as a function of angular separation on the sky, \(\theta\), which does not require redshift information. It is calculated by counting galaxy pairs within a given angular separation bin and comparing this number to a corresponding figure derived from a random catalogue with the same area and shape. The angular correlation, \(\omega(\theta)\), gives the excess probability, over random, of finding two galaxies separated by angle \(\theta\).

If we assume a redshift-dependent power law describes the 3-D real-space correlation function, \(\xi(r,z) = (r/r_0)^{-\gamma}(1 + z)^{-\gamma(3+\omega)}\) (as in Peebles 1980 and Loan et al. 1997), then the angular correlation function is related to the spatial correlation function by the Limber equation (Rubin 1954; Limber 1954):

\[
\left(\frac{\theta}{\theta_0}\right)^{1-\gamma} = \frac{\int_0^{\infty} N(z) (1+z)^{-\gamma(3+\omega)} \pi d(z) d(\theta) \left(\frac{\theta}{\theta_0}\right)^{1-\gamma} \Gamma(\frac{1}{\gamma})}{\left(\int_0^{\infty} N(z) dz\right)^2} \tag{1}
\]

where \(d(z)\) is the comoving distance and \(N(z)\) is the redshift number density distribution of the sources (cf. Figure 1). We use \(\epsilon = 0.8\), consistent with the expected clustering behaviour in linear theory, although the surveys are so shallow that the evolution of \(\xi\) could be ignored. The measured values for the logarithmic slope \(\alpha = 1 - \gamma\) and the correlation length \(\theta_0 (\omega(\theta_0) = 1)\) can then be used to determine the 3-D parameters \(r_0\) and \(\gamma\).

The errors for \(\omega\) are calculated using jack-knife resampling (Lupton 1993). For this purpose the data are split up into \(N\) RA-bins and the correlation function is recalculated repeatedly each time leaving out a different bin. Thus a set of \(N\) values \(\{\omega_i, i = 1, ..., N\}\) for the correlation function are obtained and the jack-knife error of the mean, \(\sigma_{\omega,\text{mean}}\), is given by

\[
\sigma_{\omega,\text{mean}} = \sqrt{\frac{(N-1) \sum_{i=1}^{N} (\omega_i - \bar{\omega})^2}{N}} \tag{2}
\]

The HIPASS sample has been divided into 24 RA bins while for the ALFALFA catalogue we use 12 bins such that each bin contains approximately the same area of the sky.

#### 3.2 The Projected Two-Point Correlation Function

The projected correlation function, \(\Xi(\sigma)\), is determined by the number of pairs at given radial and projected separations, \(\pi\) and \(\sigma\), and a subsequent integration along the radial direction. For that purpose the absolute radial distance between a pair of galaxies, \(\pi = |v_1 - v_2|/H_0\), and their angular separation, \(\theta\), are converted into a projected distance,
\[ \sigma = [(v_i + v_j)/H_0] \tan(\theta/2). \]

Thus,

\[ \Xi(\sigma) = \frac{2}{\sigma} \int_0^{D_{\text{limit}}} \xi(\sigma, \pi) d\pi \]  

where \( D_{\text{limit}} \) is the limit where the integral converges. Here we set \( D_{\text{limit}} = 25 \, h^{-1}\text{Mpc} \approx 2500 \, \text{km s}^{-1} \). The projected correlation function is related to the real-space correlation function by (e.g., Davis & Peebles 1983):

\[ \Xi(\sigma) = \frac{2}{\sigma} \int_0^\infty \xi(r) \frac{r dr}{(r^2 - \sigma^2)^{1/2}}. \]  

Assuming that the projected and real-space correlation functions follow power laws within the region of interest \( (r < 10 \, h^{-1}\text{Mpc}) \), the parameter for the real-space correlation can be derived from the projected one by the following expression:

\[ \frac{\Xi(\sigma)}{\sigma} = \left( \frac{r_0}{\sigma} \right)^\gamma \frac{\Gamma(1/2) \Gamma((\gamma - 1)/2)}{\Gamma(\gamma/2)} \frac{\Gamma(1/2) \Gamma((a_\sigma - 1)/2)}{\Gamma(a_\sigma/2)^{1/2}}. \]  

More specifically, we calculate \( r_0 \) and \( \gamma \) by fitting a power law, \( \Xi(\sigma)/\sigma = (\sigma/r_0)^{-a_\sigma} \), using the Levenberg-Marquardt nonlinear least-squares method. The parameters of the real-space correlation function are then given by

\[ r_0 = \sigma_0 \left( \frac{\Gamma(1/2) \Gamma((a_\sigma - 1)/2)}{\Gamma(a_\sigma/2)^{1/2}} \right)^{-1/2}. \]

\[ \gamma = a_\sigma. \]

Therefore, similar to the angular correlation function the projected correlation function can be used to determine the real-space clustering. We apply both methods to determine the real-space clustering strength based on the HIPASS and the ALFALFA surveys and compare the results.

### 3.3 Estimator and random sampling

Three different estimators are commonly used to determine the two-point correlation function (Davis & Huchra 1982; Hamilton 1993; Landy & Szalay 1993). In this work we use the Landy & Szalay (1993) estimator as it reduces errors caused by edges and holes within a given catalogue. In particular, this is important for the ALFALFA survey with the hole caused by M 87 (Giovanelli et al. 2007) and the large edge effects due to the three strips. The estimator is of the form:

\[ \xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}, \]  

where \( r \) is the separation distance which has different meanings for the different correlation functions. For the angular correlation it denotes the separation angle, \( \theta \), for the projected correlation function it is the projected distance, \( \sigma \), and for the real-space correlation it indicates the real-space distance \( r \). \( DD(r) \) is the number of data-data pairs, \( DR(r) \) is the number of data-random pairs, and \( RR(r) \) is the number of random-random pairs all with separations \( r \).

The random catalogues were generated with uniform distributions on the sky and redshift distributions which resemble the distribution of recessional velocities in the survey smoothed using kernel density estimation (Wand & Jones 1994). Throughout this work we use random samples that are equal in size compared to the corresponding data set.

We repeat the random catalogue generation 20 times and the calculation of random pairs in order to reduce the variance from the random sampling.

### 3.4 The angular correlation function of dark matter

Based on Limber’s equation, the redshift distributions of HIPASS and ALFALFA and the expression for the nonlinear power spectrum discussed in Peacock & Dodds (1994), we predict the angular correlation function of dark matter using the cosmological parameters given in Komatsu et al. (2009). The bias parameter, \( b \), at various angles is then determined by

\[ b = \sqrt{\omega_{\text{HI}}/\omega_{\text{dark matter}}}. \]  

### 4 RESULTS

#### 4.1 The full HIPASS and ALFALFA samples

##### 4.1.1 Angular correlation functions

Figure 2 shows the angular correlation functions for HIPASS and ALFALFA data as well as the predicted correlation functions of cold dark matter weighted with the redshift distributions of the surveys. The straight lines are power law fits for pair separations in the range between 0.1 and 8\( ^\circ \) for ALFALFA and between 1 and 10\( ^\circ \) for HIPASS data. The projected clustering of dark matter (in a ΛCDM model) with redshift distributions of HIPASS and ALFALFA are shown by the green dashed line and the magenta dotted line respectively.

The measured slopes in the two surveys agree reasonably well. As expected, the value of \( \theta_0 \) is lower for ALFALFA since it is deeper than HIPASS and the clustering in 3-D is washed out in the 2-D projection. ALFALFA also detects galaxies with lower HI masses which are potentially less clustered.
4.1.3 Inferred spatial correlations

The uncertainties are fairly large.

Table 1. The angular clustering fitted parameters, $\theta_0$ and $a_\theta$.

|            | HIPASS          | ALFALFA         |
|------------|-----------------|-----------------|
| $\theta_0$ | 0.603 $\pm$ 0.04$^\circ$ | 0.044 $\pm$ 0.013$^\circ$ |
| $a_\theta$ | 0.56 $\pm$ 0.02  | 0.59 $\pm$ 0.06  |

Table 2. The projected clustering fitted parameters, $\sigma_0$ and $a_\sigma$.

|            | HIPASS     | ALFALFA    |
|------------|------------|------------|
| $\sigma_0$ | 6.29 $\pm$ 0.36 $h^{-1}$Mpc | 5.34 $\pm$ 1.08 $h^{-1}$Mpc |
| $a_\sigma$ | 1.62 $\pm$ 0.04  | 1.68 $\pm$ 0.13  |

4.1.2 Projected correlation functions

Figure 3 shows the projected correlation functions for the HIPASS and ALFALFA surveys. The lines represent power law fits and the corresponding parameters are presented in Table 2. Once again the slopes, $a_\sigma$, agree well while the amplitude of clustering, $\sigma_0$, in ALFALFA is lower (although the uncertainties are fairly large).

4.1.3 Inferred spatial correlations

Table 3 shows the spatial correlation function parameters inferred from the angular and projected correlation functions obtained using Eq. 1 and Eq. 6. The subscripts, $\theta$ and $\sigma$, indicate which correlation function has been used to derive these parameters. The two values obtained for $r_0$ in HIPASS are within 2$\sigma$ of each other and agree well with the unweighted value of 2.7 obtained by Meyer et al. (2004). The two ALFALFA values are consistent with each other and indicate somewhat lower clustering than HIPASS.

4.1.4 Bias estimation

The predicted angular correlation function of dark matter is compared with our results in Figure 3. We have calculated the bias for the two surveys at each data point in the plot. For HIPASS, in the $1-10^6$ range, we find bias values ranging from 0.54 to 0.70, with an average of 0.63. This is fairly consistent with the value of 0.68 obtained by Basilakos et al. (2007). For ALFALFA, on the same angular scales, the values range between 0.41 and 0.62, with an average of 0.52. Our results thus indicate that the ALFALFA sample is somewhat more anti-biased than the HIPASS sample. This is consistent with the idea that ALFALFA includes galaxies with lower HI mass which are less clustered than the higher mass galaxies detected in HIPASS. We note, however, that the lower values are found at large scales where the narrowness of the strips may affect measurements more severely.

4.2 Correlation functions of different ALFALFA subsamples

4.2.1 Flux and HI mass subsets

The ALFALFA data has been subdivided into two equivalent parts based on the flux of the sources. For these subsamples the angular and projected correlation functions were recalculated as described in section 3. In agreement with Meyer et al. (2007) we find that the two correlation functions compare well with each other and with the correlation function of the whole data set indicating a negligible dependence of clustering on HI flux.

We also split the samples evenly into high and low HI-mass subsamples. The clustering parameters obtained are shown in Table 4. Our results for HIPASS are consistent with those of Meyer et al. (2007), indicating that the galaxies with higher HI-masses are more clustered. Interestingly, the same trend is not apparent in the ALFALFA survey but the uncertainties are fairly large.

We did not attempt to separate the galaxies according to their rotation velocities as this requires additional data to estimate inclinations.

4.2.2 Small Field effects

The Virgo regions contain over-densities of galaxies that are associated with the Virgo and Coma clusters. There is the concern that the results will be biased by the presence
of such dominant large-scale structure within the relatively small survey fields. To investigate this, the correlation functions of the three regions were calculated separately and are shown in Figure 4. Measurements in the three regions agree to within their uncertainties, indicating that the presence of the big clusters within the Virgo regions do not effect the results significantly. We note however, that the Anti-Virgo region is near the Perseus-Pisces supercluster which causes a slight over-density in that field at a similar redshift (z ≈ 0.025). To be sure that over-densities in all three fields at this redshift were not biasing our results, we cut the galaxies with redshifts between ~ 0.02 and 0.03 out of the samples and recalculated the correlation functions. The results are also shown in Figure 4 and it is clear that the correlation functions with and without the redshift cuts are completely consistent within the uncertainties.

As an additional check on the effect of the small fields on the measured clustering strength, we calculated the integral constraint (Peebles 1984; Ratcliffe et al. 1998) for a single field, and obtained a value of 0.145 which indicates an effect within the uncertainty of the correlation function derived from the ALFALFA data.

5 SUMMARY AND CONCLUSIONS

We have measured the clustering of HI-selected galaxies using the ALFALFA survey data and compared this with results for HIPASS. Our two methods for determining the real-space correlation function agree well and our results for HIPASS agree with those found by Meyer et al. (2004). The real-space clustering in ALFALFA appears to be even lower than in HIPASS, consistent with the idea that ALFALFA probes galaxies with lower HI-masses that are less clustered than their high-mass counterparts. Our measurements of high- and low-mass subsamples in ALFALFA do not provide evidence to support this idea but the uncertainties on the measurements are large.

We have calculated the clustering of dark matter expected within a ΛCDM model with redshift distributions of HIPASS and ALFALFA. We then calculated the bias of ALFALFA sources over the range 1 – 10°, finding a value of 0.62 at 1° and an average value of 0.52 over the whole range. The significant anti-bias of galaxies with low HI-mass is important to consider when estimating the signal-to-noise of experiments planned for the SKA and its pathfinders.

ACKNOWLEDGEMENTS

We thank the South African Square Kilometre Array Project, National Research Foundation and Centre for High Performance Computing for support. We also thank the referee for helpful comments.

REFERENCES

Basilakos S., Plionis M., Kovač K., Voglis N., 2007, MNRAS, 378, 301
Davis M., Huchra J., 1982, ApJ, 254, 437
Davis M., Peebles P. J. E., 1983, ApJ, 267, 465
Giovanelli R., Haynes M. P., Kent B. R., Per illat P., Saintonge A., Brosch N., Catinella B., Hoffman G. L., et al., 2005, AJ, 130, 2598
Giovanelli R., Haynes M. P., Kent B. R., Saintonge A., Stierwalt S., Alf a T., Balonek T., Brosch N., et al., 2007, AJ, 133, 2569
Hamilton A. J. S., 1993, ApJ, 417, 19
Kent B. R., Giovanelli R., Haynes M. P., Martin A. M., Saintonge A., Stierwalt S., Balonek T. J., Brosch N., et al., 2008, AJ, 136, 713
Komatsu E., Dunkley J., Nolta M. R., Bennett C. L., Gold B., Hinshaw G., Jarosik N., Larson D., et al., 2009, ApJS, 180, 330
Landy S. D., Szalay A. S., 1993, ApJ, 412, 64
Limber D. N., 1954, ApJ, 119, 655
Loan A. J., Wall J. V., Lahav O., 1997, MNRAS, 286, 994
Lupton R., 1993, Statistics in theory and practice. Princeton Univ Pr
Meyer M. J., Zwaan M. A., Webster R. L., Brown M. J. I., Staveley-Smith L., 2007, ApJ, 654, 702
Meyer M. J., Zwaan M. A., Webster R. L., Staveley-Smith L., Ryan-Weber E., Drinkwater M. J., Barnes D. G., Howlett M., et al., 2004, MNRAS, 350, 1195
Peacock J. A., Dodds S. J., 1996, MNRAS, 280, L19
Peebles P., 1980, The large-scale structure of the universe. Princeton Univ Pr
Ratcliffe A., Shanks T., Parker Q. A., Fong R., 1998, MNRAS, 296, 173
Rubin V. C., 1954, Proceedings of the National Academy of Science, 40, 541
Ryan-Weber E. V., 2006, MNRAS, 367, 1251
Saintonge A., Giovanelli R., Haynes M. P., Hoffman G. L., Kent B. R., Martin A. M., Stierwalt S., Brosch N., 2008, AJ, 135, 588
Wand M., Jones M., 1995, Kernel smoothing. Chapman and Hall/CRC

Table 3. The real-space clustering parameters, r0 and γ derived from the angular correlation function (indicated by subscript θ) and from the projected correlation function (indicated by subscript σ).