Probing the bispectrum at high redshifts using 21 cm HI observations

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ABSTRACT
Observations of fluctuations in the redshifted 21 cm radiation from neutral hydrogen (HI) are perceived to be an important future probe of the universe at high redshifts. Under the assumption that at redshifts \( z \leq 6 \) (Post-Reionization Era) the HI traces the underlying dark matter with a possible bias, we investigate the possibility of using observations of redshifted 21 cm radiation to detect the bispectrum arising from non-linear gravitational clustering and from non-linear bias. We find that the expected signal is \( \sim 0.1 \) mJy at 325 MHz \((z = 3.4)\) for the small baselines at the GMRT, the strength being a few times larger at higher frequencies \((610 \) MHz, \(z = 1.3)\). Further, the magnitude of the signal from the bispectrum is predicted to be comparable to that from the power spectrum, allowing a detection of both in roughly the same integration time. The HI signal is found to be uncorrelated beyond frequency separations of \( \sim 1.3\) MHz whereas the continuum sources of continuum are expected to be correlated across much larger frequencies. This signature can in principle be used to distinguish the HI signal from the contamination. We also consider the possibility of using observations of the bispectrum to determine the linear and quadratic bias parameters of the HI at high redshifts, this having possible implications for theories of galaxy formation.

Key words: cosmology: large scale structure of universe - intergalactic medium - diffuse radiation

1 INTRODUCTION
Quantifying non-Gaussian features in the large-scale matter distribution is an important issue in cosmology. It is widely accepted that the large-scale structures originated from initially small density fluctuations which were a Gaussian random field. Non-Gaussian features arise as the fluctuations grow through the process of gravitational instability (eg. Peebles 1980), and quantifying these at various stages of the growth is expected to yield a significant amount of information. The three-point correlation function and its Fourier transform, the bispectrum, are the lowest order statistics sensitive to non-Gaussian features.

The determination of the three-point correlation function was pioneered by Peebles and Groth (1975) using the galaxies in the Lick and Zwicky angular catalogues. Later studies of the three point correlation function using galaxy surveys include Peebles (1980), Bean et al. (1983), Efstathiou & Jedrzejewski (1984), Hale-Sutton et. al (1980), Jing, Mo & Borneet (1991), Gaztanaga & Frieman (1994), Frieman & Gaztanaga (1994), Jing & Borneet (1998). The recently completed Two -degree Field Galaxies Redshift Survey (2dFGRS) and the currently ongoing SDSS have been used to measure the galaxy three-point correlation function at an unprecedented level of accuracy (2dFGRS, Jing & Borneet 2004, Kayo et.al 2004, Gaztanaga et al. 2003, SDSS ) allowing various issues like the luminosity and colour dependence to be addressed. There have recently been a few measurements of the bispectrum for the IRAS galaxies (Feldman et al. 2001, Scoccimarro et al. 2001) and for the 2dFGRS ( 2002Verde et al. 2002) which have (as discussed later) been used to estimate the galaxy bias.

All the measurements of the three-point correlation function or the bispectrum mentioned here are restricted to low redshifts \((z < 1)\). This limitation arises because they are based on galaxy surveys which do not extend to very high redshifts. For example the 2dFGRS which is the largest completed redshift survey extends to a maximum redshift of around \(z = 0.3\). Further, a galaxy or quasar survey extending out to large redshifts \((z > 1)\) would select only the brightest objects which would be sparse in number. These...
objects would be distributed in the densest regions which are known to have a highly biased distribution and their distribution would not be representative of the underlying matter distribution. In this paper we discuss how observations of the redshifted 21 cm emission from neutral hydrogen (HI) can be used to measure the bi-spectrum at high redshifts (∼ 1 and higher).

The HI density in the redshift range 1.7 – 5.5 is known from observations of Ly-α absorption lines along lines of sight to quasars (Storrie-Lombardi, McMahon & Irwin 1996; Storrie-Lombardi, & Wolfe 2000; Péroux et al. 2001; Prochaska, Herbert-Fort & Wolfe 2003). These observations indicate that Ω_b(z), the comoving density of neutral gas expressed as a fraction of the current critical density, has a value ∼ 10^{-2}. Recent observations (Prochaska, Herbert-Fort & Wolfe 2003) show that Ω_b(z) drops by about 25% at z = 2.2 – 2.5. Current observations of Ω_b(z) are consistent with no evolution at higher redshifts (3 ≤ z ≤ 5.5). The bulk (∼ 70%) of the HI resides in high column-density regions (2 × 10^{20} cm^{-2}) which are possibly the progenitors of present day galaxies. The redshifted 21 cm (1420 MHz) emission from this HI is present as a background radiation in radio observations at all frequencies below 1420 MHz. The fluctuations in this background radiation arise from fluctuations in the HI density and from peculiar velocities at the redshift where the radiation originated (Bharadwaj, Nath and Sethi 2001, hereafter BNS). The possibility of detecting this holds the potential of being an important tool to probe the large-scale structures in the redshift range z = 1 – 6. This is particularly significant in the context of the GMRT (Swarup et al. 1991) which operates in several bands in the frequency range of interest. It is also interesting to note that the fluctuations in the background HI radiation is expected to exceed the fluctuations in the CMBR by a factor of 10 – 100 over the frequency range of interest (BNS).

Complex visibilities at different baselines and frequencies are the primary quantity measured in radio interferometric observations. Correlations between pairs of visibilities directly probe the three dimensional power spectrum of HI fluctuation at the redshift where the radiation originated. This has been studied in a series of papers (Bharadwaj and Sethi 2001; Bharadwaj and Pandey 2003; Bharadwaj & Srikant 2004) which develop the relation between visibility correlations and the HI power spectrum, and test the currently accepted scenario for structure formation. The bispectrum has been perceived to be a more effective statistics for quantifying non-Gaussianity in the weakly non-linear regime and its theory has been developed in Fry (1994), Hivon et al. (1995), Matarrese et al. (1997), 1996-Verde et al. 1998, Scoccimarro et al. (1998), Scoccimarro, Couchman & Frieman (1999) and Scoccimarro et al. (2001). These investigations show that it possible to use observations of the bispectrum (or equivalently the three point correlation function) to determine the linear and quadratic bias parameters. This has been actually carried out using various galaxy surveys like the APM galaxies and the IRAS galaxies (Feldman et al. 2001; Scoccimarro et al. 2001). In a recent analysis 2002-Verde et al. 2002 have analysed the bispectrum of the 2dFGRS to conclude b_1 = 1.04 ± 0.11 for the linear bias parameter and b_2 = −0.054 ± 0.08 for the quadratic bias parameter, indicating that the 2dFGRS galaxies are an unbiased tracer of the underlying dark matter. Further, the linear bias parameter was used in combination with the redshift distortion parameter β ∼ Ω_m (HI) / B_1 measured from the same survey (Peacock et al. 2001) to determine the density of the universe Ω_m = 0.27 ± 0.06. A new analysis of the three point correlation function of the 2dFGRS galaxies (Gaztanaga et al. 2003) confirms that the large-scale structures formed through gravitational instability starting from Gaussian initial conditions. The study concludes that the galaxies do not trace the underlying dark-matter distribution with b_1 = 0.93^{+0.10}_{-0.10} and c_2 = B_2 / B_1 = −0.34^{+0.11}_{-0.08}. Observations of the HI bispectrum would allow us to carry out such studies at redshifts z > 1, providing further tests of the gravitational instability picture. Further, it would be possible to determine the bias of the HI at high redshifts, this being a potential probe of galaxy formation.

The cosmological evolution of the neutral hydrogen during the Epoch of Reionization (z = 6 – 20) and the pre-Reionization era (z > 20), and the expected redshifted 21 cm signal are topics of very intense research (e.g. Scott and Rees 1990; Madau, Meiksin and Rees 1997; Gnedin & Ostriker 1997; Shaver et al. 1998; Tozzi et al. 2001; Iliev et al. 2003; Furlanetto, Sokasian, & Hernquist 2004; Miralda-Escude 2003; Zaldarriaga, Furlanetto and Hernquist 2004; Loeb & Zaldarriaga 2003; Bharadwaj & Ali 2004; Zoroub & Silk 2004; Bharadwaj and Ali 2005; Bharadwaj and Pandey 2005; Barkana & Loeb 2005).
on the central value \( \nu \) which is not shown as an explicit argument. The value of \( \nu \) will be clear from the context of the discussion. Further, throughout our analysis we assume that all frequency differences are much smaller than the central frequency i.e. \( \Delta \nu / \nu \ll 1 \). The definition of the three visibility correlation \( S_3 \) closely follows that of \( S_2 \).

It has been shown that the two-visibility correlation probes the power spectrum of HI fluctuations (Bharadwaj and Sethi 2001, Bharadwaj and Ali 2005) and the three visibility correlation the bispectrum (Bharadwaj and Pandey 2005). Considering \( S_2(\mathbf{U}_1, \mathbf{U}_2, \Delta \nu) \) first, we note that it has a significant value only when \( |\mathbf{U}_2 + \mathbf{U}_1| < (\pi \theta_0)^{-1} \). Therefore we restrict the analysis to \( \mathbf{U}_1 = -\mathbf{U}_2 = \mathbf{U} \) which we denote as \( S_2(\mathbf{U}, \Delta \nu) \). This is related to the redshift space HI power spectrum \( P_{\text{HI}}(k) \) as

\[
S_2(\mathbf{U}, \Delta \nu) = \frac{P_{\text{HI}}(k)}{2\pi^2} \int_0^\infty dk_3 \text{Re} \left[ k_3 \Delta \nu \right] \cos(k_3 \Delta \nu) \cdot (3)
\]

where \( r_0 \) is the comoving distance to the HI whose 1420 MHz radiation is observed at a frequency \( \nu \), \( \nu' = dr/d\nu \), \( \mathbf{k} = k_1 \mathbf{m} + (2\pi/r_0) \mathbf{U} \) and \( L_0 = 2.5 \times 10^2 \frac{\Omega_m h^2}{0.02} \left( \frac{\Omega_m}{0.3} \right)^{-1} M_\odot \). A point to note is that \( P_{\text{HI}}(k) \) includes the effects of redshift space distortions, and is therefore anisotropic along the line of sight \( \mathbf{m} \). We further note that \( S_3 \) is real and isotropic i.e it does not depend on the direction of the baseline \( \mathbf{U} \) whereby we can write \( S_3(\mathbf{U}, \Delta \nu) \).

Considering the three visibility correlation \( S_3(\mathbf{U}_1, \mathbf{U}_2, \mathbf{U}_3, \Delta \nu_1, \Delta \nu_2) \) next, this has a significant value only if \( |\mathbf{U}_1 + \mathbf{U}_2 + \mathbf{U}_3| \leq (\pi \theta_0)^{-1} \). We therefore restrict our analysis to only those combinations of baselines for which \( \mathbf{U}_1 + \mathbf{U}_2 + \mathbf{U}_3 = 0 \). Further \( S_3 \) is real and it depends only on the shape and size of the triangle which is completely specified by the magnitude of the three baselines \((\mathbf{U}_1, \mathbf{U}_2, \mathbf{U}_3)\). We have

\[
S_3(\mathbf{U}_1, \mathbf{U}_2, \mathbf{U}_3, \Delta \nu_1, \Delta \nu_2) = \frac{P_{\text{HI}}(k)}{12 \pi^2 r_0^2} \int dk_1 dk_2 \cos(k_1 \Delta \nu_1 + k_2 \Delta \nu_2) \times B_{\text{HI}}(k_1, k_2, k_3) \cdot (4)
\]

where \( k_1 = k_{1l} \mathbf{m} + (2\pi/r_0) \mathbf{U}_1, k_2 = k_{2l} \mathbf{m} + (2\pi/r_0) \mathbf{U}_2, k_3 = -(k_{1l} + k_{2l}) \mathbf{m} + (2\pi/r_0) \mathbf{U}_3 \) and \( B_{\text{HI}}(k_1, k_2, k_3) \) is the redshift space HI bispectrum.

It is next necessary to specify the form of the redshift space HI power spectrum \( P_{\text{HI}} \) and bispectrum \( B_{\text{HI}} \). Fluctuations in the redshifted HI radiation arise from fluctuations in the HI density and from HI peculiar velocities, and it is necessary to include both these effects in \( P_{\text{HI}} \) and \( B_{\text{HI}} \). We assume that the HI traces the dark matter with a possible bias, and retain terms up to the quadratic order in the relation between the fluctuations in the HI density \( \delta_{\text{HI}} \) and the fluctuations in the dark matter density \( \delta \)

\[
\delta_{\text{HI}} = b_1 \delta + b_2 \delta^2 \cdot (5)
\]

where \( b_1 \) and \( b_2 \) are the linear and quadratic bias parameters respectively. A non-zero \( b_2 \) would indicate nonlinear biasing of HI distribution with respect to underlying mass distribution. It is also assumed that the peculiar velocities are determined by the dark matter which dominates the dynamics.
The HI power spectrum \( P_{\text{HI}}(k) \) is related to the real space dark matter power spectrum \( P(k) \) as
\[
P_{\text{HI}}(k) = b_{\text{HI}}^2 \bar{x}_{\text{HI}}^2 (1 + \beta \mu^2)^2 P(k)
\]
where \( \mu \) is the cosine of the angle between \( k \) and the line of sight \( m \), and \( \beta = (\Omega_m h^2) / b_1 \approx (\Omega_m h^2) / 1 \) is the linear distortion parameter. The term \( (1 + \beta \mu^2)^2 \) incorporates the effect of peculiar velocities, and \( \bar{x}_{\text{HI}} \) is the mean hydrogen neutral fraction. Converting \( \Omega_{\text{gas}} \) to the mean hydrogen neutral fraction, \( x_{\text{HI}} = \bar{x}_{\text{HI}} \), gives us \( P_{\text{HI}} = 50 \Omega_{\text{gas}} h^2 \) or \( \bar{x}_{\text{HI}} = 2.45 \times 10^{-2} \). It should be noted that \( \delta \ll 1 \) and terms higher than \( \delta^2 \) have been dropped in the power spectrum.

For the HI bispectrum we assume
\[
B_{\text{HI}}(k_1, k_2, k_3, z) = \bar{x}_{\text{HI}}^3 B_{\text{b}}(k_1, k_2, k_3, z)
\]
where \( B_{\text{b}} \) is the redshift space bispectrum calculated by Verde et al (1998). We have used the form of \( B_{\text{b}} \) given in equation (11) of Verde et al. (1998), the expression being quite lengthy we do not reproduce it here.

We note that \( B_{\text{b}}(k_1, k_2, k_3) \) has a quadratic dependence on the dark matter power spectrum \( P(k) \), it depends on the bias parameters \( b_1 \) and \( b_2 \), and on the parameters of the background cosmological model. The value of \( B_{\text{b}} \) also depends on the shape of the triangle formed by \( (k_1, k_2, k_3) \).

The fact that the neutral hydrogen is in discrete clouds makes a contribution which we do not include here. This effect originates from the fact that the HI emission line from individual clouds has a finite width, and the visibility correlation is enhanced when \( \Delta \nu \) is smaller than the linewidth of the emission from the individual clouds. Another important effect not included here is that the fluctuations become significantly non-linear at low \( z \). Both these effects have been studied for the power spectrum using simulations (Bharadwaj & Srikant 2004).

The simple analytic treatment adopted here suffices for the purposes of this paper where the main focus is to estimate the magnitude and the nature of the HI signal, and to investigate the feasibility of using such observations to probe structure formation at high redshifts.

### 3 RESULTS AND DISCUSSION

We present results for the two and three visibility correlation signal expected from HI at high \( z \). In calculating the expected signal we have used the GMRT parameters, but it is straightforward to scale the results presented here to make the visibility correlation predictions for other radio telescopes. The only telescope parameter which enters equations (3) and (4) is \( \theta_0 \), which is the beam size of the individual antenna in the array. Further, it should be noted that \( \theta_0 \approx 0.6 \times \theta_{\text{FWHM}} \). The value of \( \theta_0 \) will depend on the physical dimensions of the antennas and the wavelength of observation. For the GMRT \( \theta_0 = 1^\circ \) at 325 MHz. We scale this using \( \theta_0 \propto \lambda \) to obtain \( \theta_0 \) corresponding to different observation frequencies. We note that the smallest baseline at the GMRT is a little smaller than \( U = 100 \) while the largest is around \( U \sim 10,000 \), and we present results for \( U \) in the range \( 10 \sim 10,000 \). It may be noted that unless mentioned otherwise, we use the values \( (b_1, b_2) = (1.0, 0.5) \) for the bias parameters.

![Figure 1](image_url)

Figure 1 shows the expected two visibility correlation signal \( S_2(U,0) \) as a function of \( U \) for the different values of the central frequency shown in the figure.

To estimate the magnitude of the expected three visibility correlation signal \( S_3(U_1, U_2, U_3, \Delta \nu_1, \Delta \nu_2) \), we restrict our analysis to equilateral triangles for which the size of the baseline \( U \) completely specifies the triangle. We further restrict our analysis to \( \Delta \nu_1 = \Delta \nu_2 = \Delta \nu \) in which case we can use the notation \( S_3(U, \Delta \nu) \). The ratio \( \left| S_2(U,0) \right| / \left| S_3(U,0) \right| \) quantifies the relative strength of \( S_3 \) as a fraction of \( S_2 \). The first point to note is that the three visibility correlation signal is comparable in magnitude to the two visibility correlation signal. The ratio of the signal strengths is of order unity for the small baselines (\( U \leq 1000 \)) at 325 MHz and it is somewhat higher at higher frequencies. Further, \( S_3 \) falls faster than \( S_2 \) with increasing \( U \). It is possible to understand both these features of \( S_3 \) in terms of the fact that the bispectrum is quadratic in the power spectrum whereby it grows faster with time and it has a steeper \( k \) dependence at large \( k \).

The bispectrum \( B_{\text{b}}(k_1, k_2, k_3) \) depends on the shape and size of the triangle formed by \( k_1, k_2, \text{ and } k_3 \). This dependence varies with the bias parameters \( (b_1, b_2) \), and this can be used to observationally determine the values of the bias parameters. To study how the shape and bias dependence manifests itself in \( S_3 \), we have considered bilateral triangles for which two sides are of length \( U \) with opening angle \( 120^\circ \) and the third side of length \( \sqrt{3} U \). We study the ratio \( \left| S_3(U, \Delta \nu) \right|_{120^\circ} / \left| S_3(U, \Delta \nu) \right|_0 \) for \( \Delta \nu = 0 \) where the
subscripts E and B refer to equilateral and bilateral triangles respectively. Figure 3 shows the results at 610MHz (\(z = 1.3\)), the behaviour at other frequencies is similar. We find that \(S_3\) does not show any significant dependence on the triangle shape at baselines smaller than \(U \sim 1000\). There is a shape dependence at larger baselines where \(S_3\) decreases faster for the equilateral triangles than for the bilateral triangles. Further, the ratio has a distinct dependence on the values of the bias parameters. The first point to note is that the ratio is independent of \(b_1\) for \(b_2 = 0\). For other values of \(b_2\) we find that the \(U\) dependence of the ratio \(\left| \frac{S_3(U,0)}{S_3(U,\Delta \nu)} \right|^\frac{1}{3} / |S_3(U,0)|^\frac{1}{3}\) at the large baselines is sensitive to both \(b_1\) and \(b_2\). It should, in principle, be possible to use observations of the shape dependence of \(S_3\) to determine the bias parameters.

We next consider the correlation between visibilities at different frequencies. The results are presented at fixed values of the baselines, and Figures 3 and 4 show \(\left| S_2(U, \Delta \nu) \right|^\frac{1}{2} / |S_2(U,0)|^\frac{1}{2}\) and \(\left| S_3(U, \Delta \nu) \right|^\frac{1}{3} / |S_3(U,0)|^\frac{1}{3}\) respectively, both at the central frequency of 610MHz. We find that the correlations decay rapidly as the frequency separation \(\Delta \nu\) is increased. We have \(S(U, \Delta \nu) = 0\) at \(\Delta \nu \sim 1.3\) MHz for \(U = 100\), and there is a weak anticorrelation \(S_2 < 0\) for larger \(\Delta \nu\). The visibilities at larger baselines get decorrelated faster with increasing \(U\), and the zero crossing is at \(\sim 0.7\) MHz at \(U = 100\). The three visibility correlation shows a similar behavior, the main difference being that \(\left| S_3(U, \Delta \nu) \right|^\frac{1}{3}\) decays much faster than \(\left| S_2(U, \Delta \nu) \right|^\frac{1}{2}\) with increasing \(\Delta \nu\). It may be noted that the overall behavior is similar at other values of the central frequency, with the difference that \(S_2\) and \(S_3\) decay faster with increasing \(\Delta \nu\) at lower values of the central frequency.

An important issue which we have not addressed here in any detail is the extraction of the HI signal from various contaminants which are expected to dominate at low frequencies. The issue of extracting the redshifted 21 cm signal has received considerable attention (eg. Shaver et al. 1990; DiMatteo, et al. 2004; Oh et al. 2003; Morales and Hewitt 2004; Zaldarriaga, Furlanetto and Hernquist 2004; Cooray & Furlanetto 2004; Santos et al. 2003; Wang, Tegmark, Santos & Knox 2003; Morales, Bowman & Hewitt 2003). The contribution from the continuum sources of contamination at two different frequencies is expected to be correlated even at...
large $\Delta \nu$, whereas the HI signal is found to be uncorrelated beyond something like 1.3 MHz or even less depending on the value of $U$. It is then, in principle, straightforward to fit the visibility correlations $S_2$ and $S_3$ at large $\Delta \nu$ and remove any slowly varying component thereby separating the contaminants from the HI signal. We also use this opportunity to note that this is a major advantage of using visibility correlations as compared to the angular power spectrum which has been found to have substantial correlations even at two frequencies separated by $\sim 10$ MHz (Santos et al. 2003).

System noise is inherent in all radio interferometric observations. System noise and the observation time needed to detect the HI signal is another important issue. Here we briefly discuss the signal to noise ratio and approximate integration time required to detect the HI signal for $S_2$ and $S_3$. We consider an array of $N$ antennas, the observations lasting a time duration $t$, with frequency channels of width $\delta \nu$ spanning a total bandwidth $B$. It should be noted that the effect of a finite channel width $\delta \nu$ has not been included in our calculation which assumes infinite frequency resolution. This effect can be easily included by convolving our results for the visibility correlation with the frequency response function of a single channel. Preferably, $\delta \nu$ should be much smaller than the frequency separation at which the visibility correlation becomes uncorrelated. We use $N$ to denote the frequency separation within which the visibility correlations are correlated. We use $N_2$ and $N_3$ to denote the rms. noise in $S_2$ and $S_3$. We have assumed that thermal noise are Gaussian random fields. It is well known that $N_2 = \left( \frac{2kBT_{\text{SYS}}}{A_{\text{ef}}} \right)^2 \frac{1}{\delta \nu t}$ (Thompson, Moran & Swenson 1984), and we have $N_3 \sim \left( \frac{2kBT_{\text{SYS}}}{A_{\text{ef}}} \right)^3 \frac{1}{(\delta \nu)^2} \frac{1}{t}$, where $T_{\text{SYS}}$ is the system temperature and $A_{\text{ef}}$ is the effective area of a single antenna. The noise contribution will be reduced by a factor $1/\sqrt{N_3}$ if we combine $N_3$ independent samples of the visibility correlation. A possible observational strategy for a preliminary detection of the HI signal would be to combine the visibility correlations at all baselines and frequency separations where there is a reasonable amount of signal. This gives $N_0 = N(N-1)/2 \frac{B/\delta \nu}{(S/\delta \nu)}$, for the two visibility correlation and $N_0 = N(N-1)(N-2)/6 \frac{(B/\delta \nu)(S/\delta \nu)^2}{(3/2)^2}$ for the three visibility correlations. Combining all of this we have

$$[N_2]^{1/2} \sim \left( \frac{2kBT_{\text{SYS}}}{A_{\text{ef}}} \right)^2 \left( \frac{2}{N(N-1)B} \right)^{1/4} \frac{1}{\delta \nu t}^2$$

and $[N_3]^{1/3} \sim \frac{2kBT_{\text{SYS}}}{A_{\text{ef}}} \left( \frac{6}{N(N-1)(N-2)B^2} \right)^{1/6} \frac{1}{t}^{1/2}$. Using values for the GMRT at $\sim 600$ MHz, $(2kBT_{\text{SYS}}/A_{\text{ef}}) = 144$ Jy, $B = 16$ MHz, there are 14 antennas within $U \leq 1000$ where the signal is strong and $S = 0.5$ MHz beyond which the signal is uncorrelated we find that it is possible to achieve noise levels of $[N_2]^{1/2} \sim 0.03$ mJy and $[N_3]^{1/3} \sim 0.045$ mJy which are below the signal with 200 hrs of integration. Our present estimations indicate that 200 to 1000 hours of observation are needed to detect the HI signal.

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Probing the bispectrum at high redshifts.

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