Bayesian redshift-space distortions correction from galaxy redshift surveys

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ABSTRACT

We present a Bayesian reconstruction method which maps a galaxy distribution from redshift-space to real-space inferring the distances of the individual galaxies. The method is based on sampling density fields assuming a lognormal prior with a likelihood given by the negative binomial distribution function modelling stochastic bias. We assume a deterministic bias given by a power law relating the dark matter density field to the expected halo or galaxy field. Coherent redshift-space distortions are corrected in a Gibbs-sampling procedure by moving the galaxies from redshift-space to real-space according to the peculiar motions derived from the recovered density field using linear theory with the option to include tidal field corrections from second order Lagrangian perturbation theory. The virialised distortions are corrected by sampling candidate real-space positions (being in the neighbourhood of the observations along the line of sight), which are compatible with the bulk flow corrected redshift-space position adding a random dispersion term in high density collapsed regions. The latter are defined according to the eigenvalues of the Hessian. This approach presents an alternative method to estimate the distances to galaxies using the three dimensional spatial information, and assuming isotropy. Hence the number of applications is very broad. In this work we show the potential of this method to constrain the growth rate up to $k \sim 0.3 h \, \text{Mpc}^{-1}$. Furthermore it could be useful to correct for photo-metric redshift errors, and to obtain improved BAO reconstructions.

Key words: cosmology: large-scale structure of the Universe – cosmology: theory – galaxies: general – methods: observational – methods: numerical

1 INTRODUCTION

Galaxy redshift surveys produce the three-dimensional distribution of luminous sources tracing the underlying dark matter field. However, their inferred line-of-sight position is a combination the so-called Hubble flow, i.e. their real distance, and their peculiar motion. The modifications produced by this are referred to as redshift space distortions (RSD). Many astronomical studies are limited by these distortions, such as a proper environmental study [Nuza et al. 2014]. Nevertheless, RSD can also be used to constrain the nature of gravity and cosmological parameters (see e.g. Berlind, Narayanan & Weinberg 2001; Zhang et al. 2007; Jain & Zhang 2008; Guzzo et al. 2008; Neseris & Perivolaropoulos 2008; Song & Koyama 2009; Song & Percival 2009; Percival & White 2009; McDonald & Seljak 2009; White, Song & Percival 2009; Song et al. 2010; Zhao et al. 2010; Song et al. 2011 for recent studies). The measurement of RSD have in fact become a common technique [Cole, Fisher & Weinberg 1993; Peacock et al. 2001; Percival et al. 2004; da Angela et al. 2008; Okumura et al. 2008; Guzzo et al. 2008; Blake et al. 2011; Jennings, Baugh & Pascoli 2011].

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2 METHOD

Our method essentially follows the algorithm (ARGO-code) proposed in Kitaura & Enßlin (2008) and Kitaura, Gallerani & Ferrara (2012) by iteratively sampling the density and peculiar velocity fields within a Gibbs sampling process (for the pioneering iterative correction of linear RSD see Tahil et al. 1991):

\[ \delta \sim p(\delta | N(\{r\}), \{b_p\}, C, w), \quad \{r\} \sim p(\{r\} | \{s_{\text{obs}}\}, \{\mathbf{v}(\delta, f_0, r_s, H, \{v_p\})\}). \]

In the first Gibbs-sampling step: \( \delta \) is the dark matter over-density field, \( p(\delta | N(\{r\}), \{b_p\}, C, w) \) the posterior distribution function of density fields given the number counts of galaxies in real-space on a grid \( N(\{r\}) \), a covariance matrix \( C \equiv \langle \delta \delta^\dagger \rangle \) (the power-spectrum in Fourier-space), a set of parameters describing galaxy bias \( \{b_p\} \), and a three dimensional completeness \( w \). In the second Gibbs-sampling step we obtain the real-space position \( \{r\} \) from the redshift-space position of galaxies and the sampled peculiar velocity fields \( \{v\} \), which depend on the large scales, on the over-density field, the growth factor \( f_0 \), and a smoothing scale \( r_s \); and in the nonlinear regime additional information about the Hessian \( H \) and parameters describing the velocity of galaxies \( \{v_p\} \).

2.1 Density field reconstruction

We will restrict ourselves to a simple set of assumptions and demonstrate that they are sufficient for the scope set in this work, namely correct for redshift-space distortions. The first Gibbs-sampling iteration assumes that the galaxies are

\[ s_{\text{obs}} = r + v_c(\mathbf{r}) + v_r(\mathbf{r}), \]

with \( r \) denoting the projection along the line-of-sight. Let us discuss both redshift-space contributions separately below.

Figure 1. Upper panel: power spectra of the catalogue in redshift-space (red), in real-space (black); and of the reconstructed catalogues with only coherent flows (dashed green) with 1-sigma contour based on 1000 reconstructions (magenta), coherent flows including virialisation corrections (dashed blue) with 1-sigma contour (cyan). Lower panel: ratio between the power spectra in redshift-space \( P^c(k) \) and in real-space \( P^r(k) \) with the same colour code.
2.2.1 Coherent redshift-space distortions

Coherent redshift-space distortions are responsible for the squashing effect of galaxy clusters along the line of sight (see Hamilton 1987 for a review). This produces an enhancement of power on large scales, the so-called Kaiser factor (Kaiser 1987).

For simplicity we focus in this work on linear theory based on the density field ($\delta$). We are aware that improvements could be found based on the linearised density field ($\log(1+\delta)$), which we get for free in our formalism. However, it is also true that the logarithmic transformation introduces a constant offset which we do not want to consider here, as it was shown in Neyrinck et al. 2009 (for more general relations including linearisations see Kitaura et al. 2012 and references therein). We simply consider a Gaussian smoothing (with radius $r_S$) of the overdensity field to optimise the velocity divergence to overdensity relation. For this component we do not assume any stochastic component, but directly move each galaxy from its redshift-space position $s^{\text{obs}}$ to its coherent red-space position $r^{\text{coh}}$ at iteration $i$, according to the coherent bulk flow motion $v^{\text{coh},i}(r^{i-1})$ based on the red-space position from the previous iteration $i-1$:

$$r^{i}_{\text{coh}} = s^{\text{obs}} - v^{\text{coh},i}(r^{i-1}),$$

with $v_{\text{r}} \equiv (v \cdot \hat{r})/H(a)$, where $v$ is the full three dimensional velocity field, $\hat{r}$ is the unit sight line vector, $H$ the Hubble constant and $a$ the scale factor.

2.2.2 Dispersed redshift-space distortions

Further in the nonlinear regime in deep gravitational wells, galaxy clusters are quasi-virialised, and produced so-called fingers-of-god which are elongated structures along the line-of-sight (Jackson 1972). This reduces the clustering towards small scales. A method aiming at correcting these effects needs thus to enhance the clustering of galaxies in clusters. We do so by first making sure that the galaxies come from collapsed regions in real-space. To this end we demand that the real-space candidate positions along the line-of-sight come from cells in which all the eigenvalues of the Hessian are positive (Hahn et al. 2007) and above a certain overdensity threshold $\delta_{b}$. This supposes another quantitative application of the cosmic web classification, in addition to the first of such kind presented in Zhao et al. (2015). For each real-space candidate position $r_{k}$ we sample the virialised motion component from a Gaussian with dispersion $\sigma(r_{k}) = \eta \rho_{H}(r_{k}) (r)$:

$$v^{\text{r}}(r_{k}) = \mathcal{G}\left(\sigma(r_{k}), \forall \lambda(H(\delta > 0)) \hat{r}\right),$$

with additional parameters $\eta$ and $\epsilon$ (see Kitaura et al. 2014).

We can then find coherent real-space positions $r^{\text{coh}} = r^{i}_{k} + v^{\text{r}}(r_{k})$ and select the closest one in each iteration: $\text{min}(r^{\text{coh}} - r^{\text{coh}}_{k})$. Additionally, to ensure that the clustering of clusters is enhanced we demand that the local density of the candidate’s real-space position is larger or equal than in the previous iteration: $\delta(r_{k})^{i} = \delta(r_{k})^{i-1}$. We note that a similar approach was taken using the kigen-code (Kitaura 2013) to correct for fingers-of-god in a forward approach (see Heß, Kitaura & Gottlöber 2013).

3 APPLICATION TO MOCK DATA

We will focus in this work on mock galaxies constructed using the halo abundance matching technique based on the CMASS LRG sample (see Rodriguez-Torres et al in prep), and the BigMultiDark (BtMD) N-body simulation.

3.1 Reference N-body simulation and CMASS LRG galaxy catalogue

In particular, we performed a halo abundance matching using the redshift 0.5763 from one of the BtMD simula-
additional smoothing (2nd panel), with an optimal smoothing of $r_{S} = 7 h^{-1} \text{ Mpc}$ (3rd panel), including virialised RSD correction (4th panel). The lower panels show the corresponding ratio of the 2D power spectra, (left panel:) between the true catalogue in redshift-space and in real-space, and (for the 3 panels on the right) between the corresponding reconstructed real-space catalogue and the true catalogue in real-space.

Figure 3. The upper panels show the 2D power spectra $P(k_{\perp}, k_{\parallel})$ corresponding to the mock galaxy catalog in real-space (colour-coded contour regions), in redshift-space (dashed lines), including the reconstructed galaxy field in real-space (solid lines): without any additional smoothing (2nd panel), with an optimal smoothing of $r_{S} = 7 h^{-1} \text{ Mpc}$ (3rd panel), including virialised RSD correction (4th panel). The lower panels show the corresponding ratio of the 2D power spectra.

3.2 Reconstruction results

To avoid systematic effects in our study, we neglect incompleteness due to the survey geometry or the radial selection function, and neglect light-cone evolution effects. All these issues will be considered in a forthcoming work (Ata et al in prep). We compute the redshift-space position for each galaxy in the plane parallel approximation. We then compute the corresponding density field on a cubical region with $128^3$ cells. This permits us to make efficient computations of the 2D power spectrum. We note however, that our ARGO code has been implemented to deal with non-parallel RSD. We obtain converged Gibbs-sampling chains after about 1000 iterations in terms of converged power spectra and also according to our convergence study demonstrated in [Ata, Kitaura & Müller 2015]. We have tested here different levels of deviation from Poissonity. As in [Ata, Kitaura & Müller 2015] we find that the stochastic bias can enhance the power towards high $k_{S}$, however, this is not essential to our work. The smoothing scale $r_{S}$ and the threshold $\delta_{th}$ can be tuned to compensate for that. Since we do not aim at getting the perfectly unbiased dark matter density field in this work, but to correct for RSD, we will show only results with very high $\beta$, effectively sampling from the Poisson likelihood. An extension of this work investigating also the reconstructed dark matter field will be presented in Ata et al. in prep.

We run three reconstruction chains, two correcting only for coherent RSDs, and the third one correcting also (partially) for virialised RSDs.

(i) The first RSD correction is based on coherent peculiar motions directly derived from the density field on a mesh using linear theory.

(ii) The second one uses a smooth density field with Gaussian smoothing radius of $7 h^{-1} \text{ Mpc}$ obtained in a parameter study to optimally correct for RSD up to higher $k_{S}$.

1 http://www.multidark.org/MultiDark/
(iii) The third one includes virialised corrections as described in [2.2.2]

The resulting power spectra considering 1000 reconstructions only for the latter two cases for clarity are shown in Fig. [1]. The first case yields a similar result on large scales, however underestimating the power in intermediate and small scales. Here we can clearly see that the Kaiser factor is corrected and that the nonlinear RSD correction increases the clustering power towards small scales being closer to the true real-space catalogue. Fig. [2] shows the monopole and quadrupole in configuration space. We can see from these plots that the two different reconstructions: coherent with optimal smoothing or coherent and virialised motions corrections yield similar results. The left panel shows how accurately the real-space BAO can be obtained from redshift-space. However the right choice of the smoothing scale is important here, or a nonlinear virialised treatment to obtain a close BAO peak to the true one. We will quantify this improvement investigating also BAO reconstruction in a forthcoming work. Interestingly, the full nonlinear RSD correction algorithm shows better agreement with the true real-space quadrupole not only on small scales being closer to zero, but also at large scales, displaying less artificial spikes, present in the pure coherent RSD corrections. However, the different quality in the reconstructions can be better appreciated in Fig. [3] showing the 2D power spectra. The anisotropic pattern in redshift-space can be clearly seen. In particular, the enhancement of power due to the Kaiser effect is very prominent. A reconstruction of the peculiar velocity field with our method corrects the RSD in a remarkable way. We can see that an optimal choice of the smoothing scale can considerably improve the reconstruction. This is furthermore improved to scales of about $k \sim 0.3 \, h \, \text{Mpc}^{-1}$ when including virialised motions corrections.

4 SUMMARY AND DISCUSSION

We have presented in this work a Bayesian technique to correct for both coherent and virialised redshift-space distortions present in galaxy catalogues by estimating the distance to the individual galaxies. We have demonstrated that this technique is accurate at least up to $k \sim 0.3 \, h \, \text{Mpc}^{-1}$ in the isotropisation of the 2D power spectrum based on precise galaxy mock catalogues describing the CMASS LRG sample. Although the method is general enough there to be precise down to far smaller scales, as indicated by the recovered power spectra.

An application of this technique to the BOSS DR12 data including power spectrum sampling will be presented in a subsequent publication (Ata et al. in prep).

While traditional RSD measurements focus on the growth rate, an approach like the one presented in this work is complementary and more general. We refer to a recent application of a joint analysis of density fields and anisotropic power spectra including growth rate estimation, see Granett et al. [2014]. The advantage of the approach presented in the present work is that it deals with nonlinear structure formation, nonlinear and stochastic galaxy bias, yielding also, as a by-product the real-space positions of the individual galaxies.

This technique is promising for a broad number of applications, such as correcting for photo-metric redshift-space distortions including the cosmic web information, or to make precise environmental studies, as demonstrated in Nuza et al. [2014] with a similar forward method recovering the corresponding primordial fluctuations. We have demonstrated in particular that it is a potentially interesting technique for the estimation of the growth rate, or for an improved BAO reconstruction. These topics will be investigated in detail in forthcoming publications using this technique.

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