Baryon acoustic oscillations with the cross-correlation of spectroscopic and photometric samples

Atsushi J. Nishizawa, Masamune Oguri and Masahiro Takada
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, Chiba 277-8582, Japan

ABSTRACT
The baryon acoustic oscillation (BAO) measurement requires a sufficiently dense sampling of large-scale structure tracers with spectroscopic redshift, which is observationally expensive especially at high redshifts $z \gtrsim 1$. Here we present an alternative route of the BAO analysis that uses the cross-correlation of sparse spectroscopic tracers with a much denser photometric sample, where the spectroscopic tracers can be quasars or bright, rare galaxies that are easier to access spectroscopically. We show that measurements of the cross-correlation as a function of the transverse comoving separation rather than the angular separation avoid a smearing of the BAO feature without mixing the different scales at different redshifts in the projection, even for a wide redshift slice $\Delta z \simeq 1$. The bias, scatter, and catastrophic redshift errors of the photometric sample affect only the overall normalization of the cross-correlation which can be marginalized over when constraining the angular diameter distance. As a specific example, we forecast the expected accuracy of the BAO geometrical test via the cross-correlation of the Sloan Digital Sky Survey (SDSS) and Baryon Oscillation Spectroscopic Survey (BOSS) spectroscopic quasar sample with a dense photometric galaxy sample that is assumed to have a full overlap with the SDSS/BOSS survey region. We show that this cross-correlation BAO analysis allows us to measure the angular diameter distances to a fractional accuracy of about 10% at each redshift bin over $1 < z < 3$, if the photometric redshift errors of the galaxies, $\sigma_z/(1+z)$, are better than 10–20% level.

Key words: distance scale — large-scale structure of Universe.

1 INTRODUCTION
Various cosmological data sets such as the cosmic microwave background (CMB; Hinshaw et al. 2012), the Type Ia supernova observations (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999; Kessler et al. 2009; Suzuki et al. 2012) and the baryon acoustic oscillation (BAO) measurements (Eisenstein et al. 2005; Percival et al. 2007, 2010; Beutler et al. 2011; Blake et al. 2011; Anderson et al. 2012) have shown increasing evidence that the cosmic expansion today is in the accelerating expansion phase. The cosmic acceleration is the most tantalizing problem in cosmology.

Among others, the BAO measurement is recognized as one of the most promising geometrical tests, because it rests on the physics of the CMB anisotropies in the early universe, which is remarkably well described by the linearized perturbation theory. The tight coupling between baryons and photons prior to the decoupling epoch of $z \approx 1100$ leaves a characteristic imprint on the pattern of large-scale structure tracers such as galaxies and quasars – the so-called BAO scale. The BAO scale is now precisely constrained as $\sim 150$ Mpc from the CMB observations (Hinshaw et al. 2012), which can be used as a ‘standard ruler’ to infer the cosmological distances from the observed correlation function of the tracers (Hu & Haiman 2003; Seo & Eisenstein 2003).

The BAO measurements mostly utilize a large data from wide-area redshift surveys of galaxies, such as the 6dF Galaxy Survey (6dFGS), the Sloan Digital Sky Survey (SDSS), the Baryon Oscillation Spectroscopic Survey (BOSS) and the WiggleZ survey. With the success of these surveys, there are several future BAO surveys targeting higher redshift ranges of $z \gtrsim 1$, including the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) survey, the Extended Baryon Oscillation Spectroscopic Survey (eBOSS), the BigBOSS, the Subaru Prime Focus Spectrograph project (Ellis et al. 2012), and the satellite Euclid mission. How-
ever, extending the BAO measurement to higher redshifts ($z \sim 2 - 4$) is observationally expensive, because the target galaxies become increasingly fainter and spectroscopic surveys of such faint galaxies having a wide-area coverage are quite time-consuming\(^\text{10}\).

In addition to these spectroscopic BAO analysis, there have been attempts to measure the BAO feature in the correlation function of photometric galaxy samples (Blake et al. 2007; Padmanabhan et al. 2007; Carnero et al. 2012; Seo et al. 2012). A wide-area, multi-colour photometric survey is relatively easy to carry out compared to a spectroscopic survey of similar area coverage. In fact, there are many planned imaging surveys, including the Subaru Hyper Suprime-Cam (HSC) Survey\(^\text{11}\), the Dark Energy Survey (DES)\(^\text{12}\), Euclid and the Large Synoptic Survey Telescope (LSST) project\(^\text{13}\), for which the primary science driver is weak lensing based cosmology. However, the photometric BAO measurements are challenging for several reasons. First, the photometric BAO analysis is based on the angular correlation function of the galaxies, which is by nature two-dimensional and therefore loses the clustering information in the line-of-sight direction. Secondly, the projection along the line-of-sight mixes the different physical scales and smears the BAO feature in the angular correlation. The projection also reduces the overall amplitude of the angular correlation function. Thirdly, the BAO feature inferred from the photometric samples can be significantly affected by statistical and systematic (catastrophic) errors of the photometric redshifts (photo-zs). For example, including the photo-z outliers in the analysis can easily induce a bias in the BAO peaks, which in turn causes a bias in the inferred distance.

In this paper, we propose to use the cross-correlation between the spectroscopic and photometric tracers of large-scale structure as an alternative BAO method. This method is particularly useful when sampling of the spectroscopic tracers is too sparse to measure the BAO feature via its auto-correlation analysis. Since a photometric survey usually has a much denser sampling, the cross-correlation mitigates the shot noise contamination to improve clustering measurements. We argue that smearing due to the line-of-sight projection can be avoided by measuring the correlation function as a function of the transverse comoving separation rather than the angular separation. As a specific example, we consider the cross-correlation of the SDSS Data Release 7 (DR7) and BOSS Data Release 9 (DR9; hereafter SDSS/BOSS) spectroscopic sample of quasars with photometric galaxies to estimate the expected accuracy of the derivable geometrical test. The SDSS/BOSS quasars are bright and can easily be observed spectroscopically, but have a too sparse sampling for the auto-correlation analysis. When making the forecast, we also include the broad-band shape information of the cross-correlation in addition to the BAO feature (also see Cooray et al. 2001).

This paper is organized as follows. In Section 2, we describe explicit expressions for the cross-correlation analysis as a function of the transverse comoving separation as well as its counterpart in Fourier space, and also derive the covariance matrix. We show our basic results in Section 3. In Section 4, we show the expected accuracy of the geometrical test via the use of the cross-correlation of the SDSS/BOSS spectroscopic quasar sample with a dense photometric galaxy sample. We summarize our results in Section 5. Unless otherwise stated, we employ a concordance Λ cold dark matter (ΛCDM) model (Komatsu et al. 2011), with $\Omega_m h^2 = 0.137$ and $\Omega_b h^2 = 0.023$ for the matter and baryon physical density parameters, $\Omega_k = 0.721$ for the cosmological constant assuming a flat geometry and $\Delta_e = 2.43 \times 10^{-5}$, $n_s = 0.96$ and $\alpha_s = 0$ for the primordial power spectrum parameters.

\section{BAO Feature in the Projected Correlation Function}

\subsection{Transverse cross-correlation function and the power spectrum}

In this paper, we consider a method that uses the cross-correlation of a photometric sample with a spectroscopic sample for measuring the BAO scale. A key idea is to consider the cross-correlation measured as a function of the transverse comoving separation rather than the angular separation

$$w(R) \equiv \frac{1}{n_s n_p} \left[ \langle n_s(\gamma_s; z_s) n_p(\gamma_p) \rangle - 1 \right],$$

(1)

where quantities with subscripts ‘s’ and ‘p’ denote those for spectroscopic and photometric samples, respectively; $n_s(\gamma_s; z_s)$ and $n_p(\gamma_p)$ are the projected number density fields for the spectroscopic and photometric samples in the directions of $\gamma_s$ and $\gamma_p$ on the celestial sphere, respectively; $z_s$ is the redshift of each spectroscopic object. Thus the density field of the spectroscopic sample is described as a function of both $z_s$ and the angular position. The transverse radius $R$ is defined in terms of their observed angular positions of $\gamma_s$ and $\gamma_p$ and the redshift $z_s$ as

$$R = d_A(z_s) \cos^{-1}(\gamma_s \cdot \gamma_p) \simeq d_A(z_s) |\theta_s - \theta_p|.$$ (2)

The quantity $d_A(z_s)$ is the comoving angular diameter distance to each spectroscopic object. Note that this conversion requires to assume a background cosmological model. The unit vector on the celestial sphere, $\gamma_s$, is given as $\gamma_s \equiv (\sin \vartheta \cos \varphi, \sin \vartheta \sin \varphi, \cos \vartheta)$. In the last equality on the right-hand side (rhs) of equation (2), we used the flat-sky approximation\(^\text{14}\). Observationally, the cross-correlation is estimated from the average of all the pairs separated by the same separation $R$ within a given width, compared to the cross-correlation of the spectroscopic sample with random catalogues that are constructed based on the same selection function as in the photometric catalogue.

A notable advantage of the $R$-average over the angle average is that it can preserve the physical scales inherent in large-scale structure such as the scale of BAO in which we are interested. On the other hand, the $\theta$-average mixes different scales in large-scale structure, thus smearing the BAO scale in the observed cross-correlation function. We emphasize that this $R$-average is useful when a spectroscopic catalogue is available for the cross-correlation measurement. In contrast, in the case of the auto-correlation analysis of photometric samples, the conversion from $\theta$ to $R$ is severely affected by photo-z uncertainties, which can lead to a smearing and systematic offset of the BAO feature.

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\(^{10}\) We note that the BAO feature at $z \lesssim 2.3$ has been recently detected from the three-dimensional correlation function of the Lyman-$\alpha$ forests that are identified in the BOSS quasar spectra (Busca et al. 2013; Slosar et al. 2013).

\(^{11}\) http://www.naoj.org/Projects/HSC/index.html

\(^{12}\) http://www.darkenergysurvey.org

\(^{13}\) http://www.lsst.org/lsst/

\(^{14}\) In the flat-sky approximation, the unit vector is expanded around the North Pole as $\gamma \simeq (\vartheta \cos \varphi, \vartheta \sin \varphi, 1)$, and the two-dimensional flat-space vector can be defined as $\vec{\theta} \equiv (\vartheta \cos \varphi, \vartheta \sin \varphi)$. 

We can express the projected cross-correlation function in terms of the power spectrum as follows. First, considering the spectroscopic sample redshift distribution, the projected cross-correlation can be expressed as

\[ w(R) = \int_0^\infty \frac{dz_p}{P(z_p)} \frac{d\bar{w}(\theta; z_h)}{dz_p} |_{R = d_A(z_h)} \theta, \]

where \( \bar{w}(\theta; z_h) \) is the angular cross-correlation function of a spectroscopic sample at redshift \( z_h \), with a photometric sample, \( p(z_h) \) is the redshift distribution of the spectroscopic sample, normalized as \( \int_0^\infty \frac{dz_p}{P(z_p)} = 1 \), and the average with the notation \( |R = d_A(z_h) \theta \) indicates that the redshift average for a given \( R \) is done by averaging the angular correlation function \( \bar{w}(\theta; z_h) \) under the condition \( R = d_A(z_h) \theta \) according to the discussion around equations (1) and (2). \( \bar{w}(\theta; z_h) \) is defined in terms of the angular power spectrum as

\[ \bar{w}(\theta; z_h) = \frac{1}{4\pi} \sum_l (2l + 1) C(l; z_h) P_l(\cos \theta). \]

Here \( P_l(\theta) \) is the \( l \)th order Legendre polynomials. For a flat universe, the angular power spectrum is given in terms of the three-dimensional power spectrum, in a standard manner (e.g., Dodelson 2003), as

\[ C(l; z_h) = \frac{2}{\pi} \int dr W_p(r) \int k^2 dk P_{\theta}(k; z_h, z_j)(kr_j)(kr), \]

where \( P_{\theta}(k; z_h, z_j) \) is the three-dimensional cross-power spectrum between the spectroscopic objects at redshift \( z_h \) and photometric objects at \( z_j \); \( r \) is the radial distance given as a function of redshift for a given cosmology, \( r = r(z_h) \), and \( r_j = r(z_j); \) \( j(\theta) \) is the \( l \)th order spherical Bessel function; \( W_p(r) \) is the selection function of the photometric sample, normalized as \( \int dr W_p(r) = 1 \) (see below for an example). Note that \( r(z) = d_A(z) \) for a flat universe.

Using the flat-sky approximation and the Limber’s approximation (Limber 1954), the projected cross-correlation function can be simplified as

\[ w(R) = \frac{1}{2\pi} \int k^2 dk C_{\theta}(k) J_0(kR), \]

where \( J_0(x) \) is the zeroth-order Bessel function, and the transverse comoving separation separation \( R \) is defined for spectroscopic redshift \( z_h \) of each sample used in the average. The projected cross-power spectrum \( C_{\theta}(k) \) is given by a simple form:

\[ C_{\theta}(k) = \int dr p(z) \frac{dz}{dr} W_p(r) P_{\theta}(k; z). \]

Note that the power spectrum \( C_{\theta}(k) \) has a dimension of \( \text{Mpc}^2 \) so that \( k^2 C_{\theta}(k) \) becomes dimensionless. We use \( C_{\theta}(k) \) for the usual angular power spectrum and \( C_{\theta}(k) \) for the Fourier counterpart of the \( w(R) \) throughout the paper. We have checked that, for the fiducial set-up we study in this paper, the Limber’s approximation is accurate at sub percent level for the BAO scale.

We assume that we can, based on photo-z technique, select photometric objects that have similar photo-z to the spectroscopic redshift. Even in the presence of large photo-z errors, the cross-correlation method is very powerful in the sense that it can statistically select photometric objects that are physically clustering with the spectroscopic sample (Newman 2008; McQuinn & White 2013). Including photo-z bias and outliers in the sample simply dilutes the cross-correlation signals, but does not change the shape so that the BAO scale is not shifted. If the spectroscopic sample used in the cross-correlation measurement is in a narrow range of redshifts, \( z_h, z_h + \Delta z_h \), the projected power spectrum reads

\[ C_{\theta}(k) \approx \int_{r_h}^{r_h + \Delta r_h} |dr| W_p(r) \frac{1}{\Delta r_h} P_{\theta}(k; z_h), \]

where \( r_h \) and \( r_h + \Delta r_h \) are the radial distances to redshifts \( z_h \) and \( z_h + \Delta z_h \), respectively, and we have used \( \Delta r_h p(z) (dz/dr) = 1 \). The factor \( \int_{r_h}^{r_h + \Delta r_h} |dr| W_p(r) \) is the fraction of photometric objects among the whole photometric sample that reside in the spectroscopic redshift bin \( [z_h, z_h + \Delta z_h] \) and thus are physically correlated with the spectroscopic sample. Therefore the factor gives a dilution factor of the cross-correlation signal due to the photo-z errors. The factor \( 1/\Delta z_h \) in front of \( P_{\theta}(k; z_h) \) accounts for the fact that the cross-correlation amplitude is reduced with increasing the width of spectroscopic redshift bin. The above equation explicitly shows that the inclusion of the photo-z outliers does not change the shape of the cross-correlation, but simply affects the overall normalization. Also importantly, the projected cross-correlation, measured against \( R \) instead of the angular separation, can measure the three-dimensional power spectrum \( P_{\theta}(k; z_h) \) at given spectroscopic redshift and at a particular \( k \). Put another way, the projected cross-correlation does not mix the power spectrum of different Fourier modes, which is not the case for the angular power spectrum. It should also be noted that the projected cross-correlation is not affected by redshift-space distortion (RSD) due to the peculiar motions of the tracers. In particular, the non-linear RSD, the so-called Finger-of-God effect, is very difficult to accurately model (Hikage et al. 2012), and therefore the cross-correlation may have a practical advantage.

Next, let us consider the case where the spectroscopic sample is in a given redshift bin with \( z_h = [z_{h, \text{low}}, z_{h, \text{up}}] \), where \( z_{h, \text{low}} \) and \( z_{h, \text{up}} \) are the lower and upper bound of the redshift bin, respectively. Here for simplicity we consider a uniform distribution of the spectroscopic sample within the given redshift bin

\[ p(z) = \begin{cases} \frac{1}{\Delta z_h}, & \text{if } z \in [z_{h, \text{low}}, z_{h, \text{up}}], \\ 0, & \text{otherwise}, \end{cases} \]

where \( \Delta z_h = z_{h, \text{up}} - z_{h, \text{low}} \). The uniform redshift distribution is not a critical assumption, and can be easily generalized to a case that the spectroscopic sample has a non-uniform redshift distribution. For photometric objects used for the cross-correlation measurement, we would select the objects if the best-fitting photo-zs are in the range of the spectroscopic redshift bin. Here we employ the simplified assumption that the probability for photo-zs obeys a Gaussian distribution

\[ p_p(z|z_p) = \frac{1}{\sqrt{2\pi}\sigma_z} \exp \left( -\frac{(z_p - z)^2}{2\sigma_z^2} \right), \]

where we assumed the photometric objects with the best-fitting photo-z, \( z_p \), obey a single population, \( \sigma_z \) is the 1σ photo-z error, and \( z \) is its true redshift. The probability satisfies the normalization \( \int_{-\infty}^{\infty} dz \ p_p(z|z_p) = \int_{-\infty}^{\infty} dz \ p(z|z_p) = 1 \). Given the distribution, if the photometric objects whose photo-zs are in the range of the spectroscopic redshift range, \( z_p \in [z_{p, \text{low}}, z_{p, \text{up}}] \), the probability distribution for the true redshift is computed as

\[ p(z|z_p) \in [z_{p, \text{low}}, z_{p, \text{up}}] = \int_{z_{p, \text{low}}}^{z_{p, \text{up}}} dz_p \ p_p(z|z_p) = \frac{1}{2} \left( \erf(x_{p, \text{low}}) - \erf(x_{p, \text{up}}) \right), \]

where \( \erf(x) \) is the error function and \( x_{p, \text{low}} = (z_{p, \text{low}} - z)/\sqrt{2}\sigma_z \). Taking into account the overall redshift distribution of
the photometric sample, we can derive the redshift distribution of the photometric sample based on the photo-$z$ selection:

$$n_{p \in z_a}(z) = \frac{1}{2} n_p(z) \left[ \text{erf}(x_{up}) - \text{erf}(x_{low}) \right],$$  \hspace{1cm} (12)

where $n_p(z)$ is the redshift distribution of the photometric sample for which we assume $n_p(z) = (z^2/2z_0^3) \exp[-z/z_0]$ parametrized by $z_0$ (see Oguri & Takada 2011). Throughout the paper we assume $z_0 = 0.4$, yielding the mean redshift $\langle z \rangle = 1.2$, and assume the bias parameter of the photometric sample to $b_p = 1.5$. Hence, the selection function of the photometric sample in each $z_a$ bin used for the cross-correlation is given as

$$W_p(r) = \frac{n_{p \in z_a}(z) \, dz}{n_p(z) \, dr},$$  \hspace{1cm} (13)

where $n_{p \in z_a}$ is the normalization factor, defined as $n_{p \in z_a} \equiv \int_0^\infty dz \, n_{p \in z_a}(z)$, so as to satisfy the condition $\int_0^\infty dr \, W_p(r) = 1$.

We will study how the accuracy of the BAO measurement changes with quantities such as $\sigma_z$ and $\Delta z_a$, as well as the number densities of spectroscopic and photometric samples.

In Fig. 1, we show an example of a photometric galaxy distribution, with different photo-$z$ uncertainties, when the photometric galaxies are divided in redshift bins, which are chosen to match with the spectroscopic sample. In this example, we divide the whole sample into three subsamples as $z_p \in [0.6, 1.0], [1.0, 1.8]$ and $[1.8, 3.2]$. The photo-$z$ errors cause a leakage of the photometric galaxies from the spectroscopic redshift bin.

### 2.2 Covariance matrix

The error covariance matrix quantifies the accuracy of measuring the projected cross-correlation for a given survey, and is used for the Fisher matrix analysis presented in Sec. 4. Since angular scales at different redshifts are scaled to match the transverse comoving scale for an assumed cosmological model, the measured projected cross-correlation is two-dimensional, given as a function of the comoving scales in units of Mpc. Assuming a Gaussian error for the projected power spectrum, which is a good approximation at BAO scales (Takahashi et al. 2009), we can extend the standard formula for the covariance matrix of angular power spectra (Knox 1995) to obtain the covariance matrix of the projected cross-correlation function as

$$\text{Cov}[C_{sp}(k), C_{sp}(k')] = \frac{\delta_{kk'}}{N_{\text{mode}(k)}} \times \left[ C_{sp}(k)^2 + \left( 1 - \frac{1}{n_s} \right) C_{pp}(k) + \frac{1}{n_{p \in z_a}} \right],$$  \hspace{1cm} (14)

where $N_{\text{mode}(k)}$ is the number of independent Fourier mode discriminated by the given survey area defined as

$$N_{\text{mode}(k)} = \frac{2\pi k \Delta k}{\left( \frac{2\pi}{d_A(z_{\text{low}})} \right)^2},$$

$$= 2k \Delta k \, d_A(z_{\text{low}})^2 f_{\text{sky}},$$  \hspace{1cm} (15)

with $f_{\text{sky}}$ being the sky coverage defined as $f_{\text{sky}} \equiv \Omega_s/4\pi$. The quantities $\bar{n}_s$ and $n_{p \in z_a}$ are the projected number densities of the spectroscopic sample and the photometric sample having photometric galaxy distribution, with different photo-$z$'s values within the spectroscopic redshift bin, respectively. The number densities are in units of $\text{Mpc}^{-3}$. In the above equations, we assumed that the fundamental model of the two-dimensional Fourier decomposition is defined as the projected scale at the lowest redshift for a given survey area, $k_l \equiv 2\pi/[d_A(z_{\text{low}}) \theta_s]$.

The expression for the covariance matrix (equation 14) can be used to understand why the cross-correlation can be useful for the BAO analysis when the spectroscopic catalogue has too sparse sampling of the targets, i.e., $C_{sp} \ll 1/n_s$. We assume that the photometric sample has a high number density in the spectroscopic redshift bin, i.e., $C_{pp} \gg 1/n_{p \in z_a}$, at the BAO scale, and the cross-correlation coefficient between the spectro-
Figure 3. Comparison of the projected and angular power spectrum at the mean redshift $\bar{z} = 1.4$. Left: the angular autopower spectrum of photometric samples in the photo-$z$ bins $z_p = [1.4 - \Delta z/2, 1.4 + \Delta z/2]$. The thick and thin curves show the power spectrum for the bin width of $\Delta z_p \approx 0.365$ and 0.05, which corresponds to the width of the comoving radial distance, $\Delta r = 0.5$ and 1.5 Gpc$/h$, respectively. The solid and dashed curves are the spectra assuming the photo-$z$ accuracies of $\sigma_z/(1 + z) = 0.05$ or 0.3, respectively. Each thin dotted line shows the shot noise level for the photometric samples, which typically have the projected number density more than $10^5$ deg$^{-2}$ for an imaging survey we are interested in. Middle: similar to the left-hand panel, but for the cross-power spectrum between the spectroscopic and photometric samples, as a function of the transverse comoving separation (equation 7), where the transverse mode $k$ is rescaled to the multipole via the distance to the spectroscopic sample by $l = kr(z = 1.4)$ for an illustrative purpose. The solid and dashed curves are for the photo-$z$ accuracies of the photometric galaxies, as in the left-hand panel. The cross-correlation preserves the BAO wiggles compared to the left-hand panel. Right: the projected auto-power spectrum for the spectroscopic samples. The figure shows that, for a spectroscopic survey with a small number density $\bar{n}_s < 10^2$ deg$^{-2}$, the BAO wiggles in the auto-spectrum are difficult to measure due to the significant shot noise.

Figure 4. Similar to Fig. 3, but for the cross-correlation function in configuration space, $w(R)$. As in Fig. 3, the top and dashed curves are the cross-correlation function assuming the photo-$z$ errors of $\sigma_z/(1 + z) = 0.05$ and 0.3, respectively. The two curves differ for the redshift widths; the wider bin width changes only the amplitude of $w(R)$, but preserve the overall shape and BAO feature. For comparison, the dotted lines show the angular cross-correlation $w(\theta = R/d_s)$ for the same width of the (photometric) redshift bin; the BAO peak is significantly smeared.

with the case of the autopower spectra of the spectroscopic sample, $(S/N)_s \propto (C_{ss}\bar{n}_s)^2$, yielding the S/N ratio $(S/N)_sp/(S/N)_ss \simeq r^2/(C_{ss}\bar{n}_s) \gg 1$. Thus the cross-correlation can give a higher S/N ratio for a measurement of the projected power spectrum at the BAO scales. In practice, however, the spectroscopic sample allows a measurement of the three-dimensional power spectrum, which contains more Fourier modes than in the projected power spectrum. In the next section, we present a more quantitative comparison between the methods using the cross-correlation and the three-dimensional auto-correlation.

Fig. 2 shows the photometric and spectroscopic samples for which we think the cross-correlation method discussed in this paper is useful, if the two survey regions are overlapped. The spectroscopic quasar catalogues of the SDSS/BOSS surveys have a wide coverage of redshifts up to $z_s \simeq 4$, but have a much lower number density than in the photometric galaxies available from the upcoming imaging surveys such as the Subaru HSC Survey or Euclid. The redshift distribution of the photometric sample shown in Fig. 2 is deeper than what is usually assumed for the HSC survey or Euclid, but we note that for the cross-correlation analysis we can use fainter galaxies than galaxies used for the weak lensing analysis. We also note that our results are not very sensitive to the choice of the number density distribution of the photometric sample.

3 RESULTS

3.1 Projected power spectrum

In Fig. 3 we compare the auto- and cross-power spectra for spectroscopic and photometric samples at mean redshift $\bar{z} = 1.4$. Here the cross-power spectra are computed as a function of the transverse
comoving separation as described in the previous section. Here, we consider the redshift bin around \( z = 1.4, z = [z - \Delta z/2, z + \Delta z/2] \) with widths \( \Delta z = 0.365 \) and 1.05, which correspond to the radial distance widths of \( \Delta r = 0.5 \) and 1.5 Mpc/h, respectively.

To model the photo-z errors, we use the parametrization given in Ma et al. (2006) as

\[
\sigma_z = \lambda_s (1 + \bar{z}),
\]

and consider the two cases of \( \lambda_s = 0.05 \) and 0.3. The BAO feature is smeared in the angular auto-power spectra of photometric samples, while the BAO feature persists in the projected auto- or cross-power spectra using the spectroscopic sample (see also below). Comparing the solid and dashed curves shows that the larger photo-z errors cause a more significant dilution of the power spectrum amplitudes, thereby smearing the BAO oscillatory feature. The figure also shows the shot noise levels. For ongoing or upcoming imaging surveys, we typically have more than \( 10^4 \) deg\(^{-2} \) galaxies (see Fig. 2), and thus the power spectrum measurement has a sufficient S/N ratio. However, the photo-z errors dilute the spectrum amplitude and smear the BAO feature, suggesting that it would be difficult to use the angular auto-power spectrum of the photometric galaxies for an unbiased BAO geometrical test, as we will discuss below. While the projected cross-power spectra shown in the figure also have a more diluted amplitude as photo-z uncertainties increase (see equation 8), we can still use the unsmeared BAO feature for estimating the angular diameter distance.

To be comprehensive, we also show the expected cross-correlation function in configuration space, \( w(R) \), instead of the power spectrum in Fig. 4. As in the power spectrum, the overall shape and the BAO feature are preserved in the \( R \)-average case, whereas the BAO peak is significant smeared in the angle-average.

### 3.2 Forecast for the cross-correlation BAO measurement

In this section, we study forecasts for the use of the projected power spectrum for measuring the BAO feature. In Fig. 5, we show the projected power spectrum as a function of the transverse wavenumber, divided by the no-wiggle power spectrum (with the BAO feature being smoothed out), in order to highlight the BAO feature. Note that we used the transfer function in Eisenstein & Hu (1998) to compute the no-wiggle spectrum for the same cosmological model. Although we assume a linear galaxy bias multiplicative-factor for both the spectroscopic (with bias parameter values based on those measured for SDSS quasars; Ross et al. 2009) and photometric samples (\( b_p = 1.5 \)), we include the effect of nonlinear clustering on the matter power spectrum, using the publicly available code, RegPT (Taruya et al., 2012), that includes up to the two-loop order contributions based on the refined perturbation theory. We show the cross-power spectra up to a certain maximum wavenumber, \( k_{\text{max}} \), which is determined so that the non-linear matter power spectrum at the mean redshift is expected to be accurate to within 1 per cent level accuracy in the amplitude compared to the simulation (Taruya et al. 2009, 2012). The figure clearly shows that the projected cross-power spectrum preserves the BAO feature, even for a wide redshift bin. On the other hand, the BAO feature is smeared in the angular correlation. We also notice that, for the higher redshift slice, the BAO feature remains up to the greater wavenumber due to the less evolving nonlinearities.

We estimate forecasts for detecting the BAO feature in the projected cross-spectrum by using the \( \chi^2 \) difference between the power spectra with and without the BAO feature:

\[
\Delta \chi^2 \equiv \sum_{i} \frac{[C_{\text{sp}}(k_i) - C_{\text{nw}}(k_i)]^2}{\text{Cov}[C_{\text{sp}}(k_i), C_{\text{sp}}(k_i)]},
\]

(17)

where \( C_{\text{sp}} \) and \( C_{\text{nw}} \) are the cross-power spectra with and without the BAO feature, and the summation is up to the maximum wavenumber determined as in Fig. 5. Note that \( \Delta \chi^2 \) does not include the broad-band shape information of the cross-power spectrum, and only quantifies the significance of detecting the BAO feature in the cross-power spectrum, assuming that the spectrum with the BAO wiggles is the underlying true spectrum (see the next section for a more quantitative forecast of the BAO analysis). The denominator is the covariance matrix (equation 14) for which we assumed the Gaussian error. To compute \( \Delta \chi^2 \), we assume that the spectroscopic sample has a projected number density of \( n_p = (20\Delta z) \) deg\(^{-2} \) in the redshift bin, where \( \Delta z \) denotes the redshift bin width. For the photometric sample, we employ \( n_p = 1.8 \times 10^4 \) deg\(^{-2} \) (50 arcmmin\(^{-2} \)) for the total number density. These numbers roughly resemble the SDSS/BOSS quasar spectroscopic sample and the Subaru HSC Survey or Euclid imaging surveys, respectively. We here assume a full-sky coverage (\( f_{\text{sky}} = 1 \)) for both the spectroscopic and photometric catalogues. We note that the chi-square difference scales as \( \Delta \chi^2 \propto f_{\text{sky}} \) (see equations (14), (15) and (17)). We then assume that we can select the photometric objects, which have photo-z’s in the spectroscopic redshift bin, and take into account the redshift distribution of photometric objects as well as the effect of photo-z errors using the method in Sec. 2.1.

Fig. 6 shows the \( \Delta \chi^2 \) values for the cross-power spectrum assuming various combinations of the survey parameters. If the two surveys have a sufficiently wide area coverage for their overlapping region, the projected cross-power spectrum allows a detection of the BAO feature. We compare the results with a BAO analysis for the spectroscopic sample alone. Similarly to equation (17), we can define the differential \( \chi^2 \) to quantify the sensitivity of the three-dimensional power spectrum to the BAO feature:

\[
\Delta \chi^2_{3D} = \frac{1}{V_{\text{survey}}} \int \frac{2\pi k^2 dk}{(2\pi)^3} \left[ \frac{P_s(k) - P_{\text{nw}}(k)}{P_s(k) + \bar{n}_p^{-1}} \right]^2,
\]

(18)

where \( P_s(k) \) is the three-dimensional power spectrum of the spectroscopic sample and \( V_{\text{survey}} \) is the survey volume. We ignore the RSD for simplicity (Kaiser 1987). The figure shows that, if the photo-z accuracies of \( \sigma(z_p)/(1 + z) \) are better than 10-20 per cent, the cross-correlation can achieve a more significant detection of the BAO feature than in the three-dimensional power spectrum.

### 4 Geometrical Test with the Cross-Correlation Method

In this section, we present more quantitative estimates on the power of the cross-correlation method for determining the angular diameter distance. For this forecast, in contrast to the preceding section, we include the broad-band shape information of the cross-power spectrum, extending the method in Seo & Eisenstein (2003) to a two-dimensional cross-correlation analysis. As a specific example, here we consider the cross-correlation BAO analysis assuming the SDSS/BOSS spectroscopic quasar catalogues (Schneider et al. 2010; Paris et al. 2012) as the spectroscopic sample (as shown in Fig. 2) and a mock photometric sample which has full overlap with the spectroscopic sample, as the photometric sample. We assume the total area of 10000 deg\(^2 \) for the overlapping area. We consider six redshift bins with the mean redshifts ranging from 0.7 to 2.9.
The expected significance of the BAO detection, $\Delta \chi^2$ (equation 17), for the cross-correlation analysis with different combinations of spectroscopic and photometric samples. We estimate the significance by comparing the cross-power spectra with and without the BAO wiggles, as in Fig. 5, but do not include the broad-band shape of the power spectrum. In each panel, the thick solid curves show the $\Delta \chi^2$ values for the projected cross-power spectrum ($C_{sp}(k)$), the thick dashed curves are for the angular cross-power spectrum ($C_{sp}(l)$), and the thin horizontal line is for the projected auto-correlation of the spectroscopic sample ($C_{ss}(k)$). For comparison, we also show the result when the BAO feature is extracted from the three-dimensional power spectrum analysis ($P_{3D}(k)$), which is estimated using equation (18). The number density of the spectroscopic sample is fixed to $\bar{n}^{\text{tot}}_p = 50 \text{arcmin}^{-2}$, and the total number density of the photometric sample is assumed to be $\bar{n}^{\text{tot}}_p = 50 \text{arcmin}^{-2}$. Results are shown for three mean redshifts, $\bar{z}_s = 2.5$ (top panels), 1.4 (middle) and 0.8 (bottom). Left: $\Delta \chi^2$ is calculated under the conditions that the photo-z accuracy is fixed to $\lambda_z = 0.1$ and the redshift bin width is varied from $\Delta r = 0.1$ to 1.5 Gpc$/h$. Right: $\Delta \chi^2$ is calculated with a fixed redshift bin width $\Delta r = 1.5$ Gpc$/h$, but with varying photo-z accuracies.

The projected number density in each bin is estimated using the redshift distribution in Fig. 2. We use the bias parameters of the quasars in each redshift bin based on the measurement by Ross et al. (2009). For the photometric sample, we again assume the total number density of $\bar{n}^{\text{tot}}_p = 50 \text{arcmin}^{-2}$, and compute the number density in each redshift bin taking into account the photo-z error (see Sec. 2.1). Table 1 summarizes the set of the survey parameters.

The cross-correlation is measured as a function of the transverse separation between the pairs of the spectroscopic and photometric objects. The transverse separation, the separation distance between each pair perpendicular to the line-of-sight direction, can be inferred from the observed angular separation on the sky, $R \propto \Delta \theta$ (see equation 2). For this conversion, we need to assume a reference cosmological model to relate the observable $\Delta \theta$ to the quantity $R$. Thus the transverse wavenumber is given as

$$k_{\perp, \text{ref}} = \frac{D_A(z)}{D_A(\text{ref})}k_{\perp}.$$  

The quantities with “ref” are the quantities from the observable assuming a “reference” cosmological model, and the quantities without the subscript denote the underlying true quantities. Since the reference cosmological model assumed generally differs from the underlying true cosmology, it causes an apparent shift in the cross-power spectrum. Thus the observed cross-power spectrum is given as

$$C_{sp}^{\text{obs}}(k_{\perp, \text{ref}}; z) = \frac{D_A(\text{ref})(z)^2}{D_A(z)^2}C_{sp}(k; z) + P_A(z),$$  

where $P_A(z)$ is the residual shot noise\(^{15}\). Since we consider a wide

\(^{15}\) Suppose that the spectroscopic and photometric samples reside in their host haloes, which have the number densities of $n_{h1}$ and $n_{h2}$, and assume that some fractions of the two samples have the common host haloes which
Table 1. A summary of survey parameters we consider for the forecast, and the expected fractional errors of determining the angular diameter distance, \( \sigma(D_A)/D_A \), including marginalization over the other parameters. Here we consider the SDSS/BOSS spectroscopic quasar catalogue for the spectroscopic sample, and the Subaru HSC- or Euclid-type galaxy sample for the photometric sample. \( z_s \) and \( \Delta z_s \) are the mean redshift and the redshift width for each redshift bin of the spectroscopic sample taken in the hypothetical cross-correlation analysis. \( b_s, \beta \) and \( n_s \) are the linear bias, the linear RSD and the number density in each redshift bin (see text for the details). \( k_{\text{max}} \) is the maximum wavenumber used for the Fisher matrix analysis. For each redshift bin, we cross-correlate the spectroscopic sample with the photometric galaxies based on their photo-zs assuming the photo-z errors of \( \lambda_s = 0.01, 0.1 \) and 0.3, respectively (see equation 16). \( n_p \) is the number density of the photometric galaxies in each redshift bin (see equation 12). We follow Seo & Eisenstein (2003) and Ellis et al. 2012, for details. We also include the normalization parameter \( A(z_i) \) which models an uncertainty in the normalization of the cross-power spectrum in each redshift bin due to unknown bias uncertainties for both the photometric \( (b_p) \) and spectroscopic \( (b_s) \) samples. As discussed above, the marginalization over \( A(z_i) \) also takes account of photo-z uncertainties. \( \beta_i(z_i) \) is a nuisance parameter to model the residual shot noise parameter. In addition to these parameters, we include the optical depth and angular diameter distance to the last scattering surface, \( \tau \) and \( D_{\Lambda,CMB} \), respectively, to the Fisher matrix to describe the CMB prior.

To make a parameter forecast, we include the following set of parameters:

\[
\theta = \{ \Omega_m, \Omega_m h^2, \Omega_b h^2, A_s, \alpha_s, D_A(z_i), A(z_i), \beta_i(z_i) \}, \quad (21)
\]

where \( \Omega_m h^2 \) and \( \Omega_b h^2 \) are the matter and baryon density parameters today, \( A_s \), is the amplitude of the primordial curvature perturbation at \( k_{\text{P}} = 0.005 \) Mpc and \( \alpha_s \) and \( \beta_i \) are the tilt and running of the primordial power spectrum (Komatsu et al. 2011). The parameter \( D_A(z_i) \) is the angular diameter distance to the ith redshift bin which is treated as an independent parameter from other cosmological parameters (see e.g., Seo & Eisenstein 2003; Ellis et al. 2012, for details). We also include the normalization parameter \( A(z_i) \) which models an uncertainty in the normalization of the cross-power spectrum in each redshift bin due to unknown bias uncertainties for both the photometric \( (b_p) \) and spectroscopic \( (b_s) \) samples. As discussed above, the marginalization over \( A(z_i) \) also takes account of photo-z uncertainties. \( \beta_i(z_i) \) is a nuisance parameter to model the residual shot noise parameter. In addition to these parameters, we include the optical depth and angular diameter distance to the last scattering surface, \( \tau \) and \( D_{\Lambda,CMB} \), respectively, to the Fisher matrix to describe the CMB prior.

The full Fisher matrix can be expressed by a simple sum of two Fisher matrices, \( F = F_{\text{CMB}} + F_{\text{CC}} \), where \( F_{\text{CC}} \) denotes the Fisher matrix from the cross-correlation measurement:

\[
F_{\alpha\beta}^{\text{CC}} = \sum_{i} \sum_{k_{n}=k_{f}} \partial C_{nn}(k_{n}, z_i) \partial C_{\theta\theta}(k_{n}, z_i), \quad (22)
\]

where \( \partial C_{\theta\theta}(k_{n}, z_i) \) is set to the maximum scale up to which the non-linear matter power spectrum at the mean redshift is expected to be accurate to within 1% level as in Fig. 5. As the large-scale structure has less non-linearity at higher redshifts, we can theoretically model the cross-power spectrum more accurately up to the larger wavenumber, enabling tighter constraints on the angular diameter distances.

For comparison, we also show a forecast for using the three-dimensional power spectrum of the spectroscopic sample to estimate the cosmological distances, \( H(z_i) \) and \( D_{A}(z_i) \). We follow the methods in Seo & Eisenstein (2007) (also see Ellis et al. 2012). We model the RSD (Kaiser 1987) and its non-linear effects (Eisenstein et al. 2007) for the three-dimensional power spectrum with

| \( z_s \) | \( \Delta z_s \) | \( b_s \) | \( \beta(z_s) \) | \( n_s \) (deg\(^{-2}\)) | \( k_{\text{max}} \) (h/Mpc) | Area (deg\(^2\)) | \( \lambda_s \) (10\(^4\)deg\(^{-2}\)) | \( n_p \) (10\(^4\)deg\(^{-2}\)) | \( \sigma(D_A)/D_A \) |
|---|---|---|---|---|---|---|---|---|---|
| 0.7 | 0.2 | 1.52 | 0.352 | 3 | 0.21 | 10,000 | 0.01 | 2.4 | 0.076 |
| 0.1 | 2.2 | 0.095 |
| 0.3 | 1.7 | 0.132 |
| Spec auto correlation | 0.191 |
| 0.9 | 0.2 | 1.70 | 0.333 | 3 | 0.23 | 10,000 | 0.01 | 2.4 | 0.095 |
| 0.1 | 2.3 | 0.095 |
| 0.3 | 1.7 | 0.137 |
| Spec auto correlation | 0.237 |
| 1.2 | 0.4 | 2.01 | 0.299 | 3.5 | 0.25 | 10,000 | 0.01 | 4.0 | 0.084 |
| 0.1 | 3.9 | 0.098 |
| 0.3 | 3.0 | 0.141 |
| Spec auto correlation | 0.369 |
| 1.6 | 0.4 | 2.49 | 0.252 | 3.5 | 0.29 | 10,000 | 0.01 | 2.7 | 0.080 |
| 0.1 | 2.7 | 0.103 |
| 0.3 | 2.4 | 0.188 |
| Spec auto correlation | 0.475 |
| 2.2 | 0.8 | 3.36 | 0.193 | 10 | 0.35 | 10,000 | 0.01 | 2.3 | 0.068 |
| 0.1 | 2.6 | 0.084 |
| 0.3 | 3.2 | 0.188 |
| Spec auto correlation | 0.032 |
| 2.9 | 0.6 | 4.60 | 0.144 | 10 | 0.42 | 10,000 | 0.01 | 0.5 | 0.075 |
| 0.1 | 0.6 | 0.133 |
| 0.3 | 1.4 | 0.536 |
| Spec auto correlation | 0.036 |
We consider the power spectrum in order to highlight the BAO feature, where we used Eisenstein & Hu (1998) to compute the no-wiggle spectrum. The projected power spectrum divided by the no-wiggle linear power spectrum for the input spectrum. The spectra are plotted up to $k_{\text{linear}}$ when the non-linearity of the matter power spectrum is considered (see text for details), while thin curves show the cross-power spectra in linear theory. The spectra are plotted against the wavenumber using the conversion $kr(\bar{z}) = 1$.

The dotted curves are the non-linear power spectrum using the no-wiggle linear power spectrum for the input spectrum.

additional parameters: $\beta_0 = \frac{d}{d \ln D(z_i)} / d \ln a / h$, and $H(z_i)$. The fiducial value of $\beta$ is listed in Table 1. However the results are not sensitive to the details, because the power spectrum information at relevant wavenumber bins is limited by the shot noise contamination for the sparse spectroscopic sample we are interested in.

Table 1 and Fig. 7 show an expected accuracy of the angular diameter distance measurement in each redshift bin via the cross-correlation method. The cross-correlation method allows for an improvement in the geometrical test compared to the threedimensional auto-power spectrum analysis, by reducing the shot noise contamination. For the SDSS/BOSS spectroscopic quasar catalogues, the cross-correlation method improves the fractional accuracy to better than 10% in each redshift bin, if the photometric galaxy survey has a full overlap with the SDSS/BOSS footprints and if we can select adequate galaxy samples whose photo-$z$ errors are better than $\lambda_\beta = 0.1 - 0.2$ (see equation 16). Also, an advantage of this method is to determine the angular diameter distance up to a high redshift of $z \simeq 3$, where the cosmic expansion is well in the decelerating expansion phase.

5 SUMMARY

In this paper, we have studied how the cross-correlation between a spectroscopic and a photometric sample can be used for the two-dimensional BAO measurement. We have shown that, with the aid of the spectroscopic sample, the cross-correlation preserves the BAO feature in the probed transverse scales, even for the projection over different redshifts such as $\Delta z \simeq 1$, while the angular (cross)-correlation suffers from a smearing of the BAO feature due to unavoidable photo-$z$ errors that cause a mixing of the different physical scales in a particular angular scale (see Fig. 3). There are several notable advantages of this method. First, the cross-correlation significantly reduces the shot noise contamination in the measurement. Secondly, any statistical or systematic (catastrophic) photo-$z$ errors affect only the overall normalization of the cross-correlation function, and do not change the shape of the power spectrum.

The cross-correlation method can be useful, if the spectroscopic sample has a wide coverage of redshift, but does not have a sufficiently high number density for the BAO measurement via the autocorrelation analysis. As a specific example, we have considered the SDSS/BOSS spectroscopic quasar sample to estimate the feasibility of the cross-correlation method, motivated by the fact that wide-area imaging surveys, such as the Subaru HSC Survey and Euclid, overlap with the SDSS/BOSS survey footprints. Here the SDSS/BOSS quasar sample has a wide redshift coverage of $0 < z \lesssim 4$ and wide area coverage of about $10000 \text{deg}^2$, but has too small number density of $\sim 10^2 \text{deg}^{-2}$ per unit redshift interval to implement the BAO measurement via the autocorrelation analysis. On the other hand, the planned imaging surveys likely provide a much denser sampling of galaxies such as $10^5 \text{deg}^{-2}$ per redshift range. We have shown that the cross-correlation allows a more accurate BAO measurement over $0.7 < z \lesssim 3$ than in the autocorrelation of the spectroscopic sample or the angular power spectrum of the photometric galaxies (see Figs. 6 and 7 and Table 1), if the photometric redshift is reasonably good, $10 - 20\%$ level in the fractional accuracy, in order not to have a severe dilution in the measured cross-correlation. As shown in Fig. 7, the better photo-$z$ accuracy of $\sigma_z/(1 + z_e) = 1\%$ does not improve constraints on $D_A$ significantly compared to the $10\%$ photo-$z$ ac-
accuracy. Hence the 10–20% of the photo-z accuracy is sufficient for the cross-correlation BAO study, which can easily be achieved for the current and upcoming multi-band photometric galaxy surveys.

The expected accuracy of the angular distance measurement in Fig. 7 is from both the BAO feature and the broad shape of the power spectrum. The projected cross-correlation allows us to measure the shape of the three-dimensional power spectrum (see Eq. (8)), although the overall normalization is affected by photo-z errors. Hence, the method can also be used to constrain the tilt and running index of the primordial power spectrum. Also, as an ultimate possibility, the cross-correlation method may enable to use the observed radius of dark matter haloes in the projected distance. If we have a good knowledge on the virial radius of dark matter haloes as well as have a good estimator of halo masses, to observe the virial radius can be used to infer the angular diameter distance. This is relevant for cluster-shear weak lensing, which probes the halo and dark matter cross-correlation (Oguri & Takada 2011). Given that the clusters have follow-up spectroscopic redshfits, we can expect a high-precision measurement of the halo-matter cross-correlation at small scales down to a few Mpc, which correspond to the virial radii of massive haloes. Thus the virial radius may serve as another standard ruler that can lead to even higher-precision measurements of the angular diameter distances. This is an interesting possibility and may worth exploring further.

We note that the cross-correlation technique developed in this paper can also be used to constrain the primordial non-Gaussianity via measurements of the largest-scale cross-power spectra (Dalal et al. 2008; McDonald 2008; Slosar et al. 2008; Taruya et al. 2008). Again, by measuring the cross-correlation as a function of the transverse comoving separation, we can avoid the smearing effect due to the projection which reduces the enhanced power at the largest scales of $k \lesssim 0.01 h / \text{Mpc}$.

Spectroscopic observations of quasars, or more generally bright, rare galaxies, are relatively inexpensive in terms of the observation time needed for a given telescope. Such objects are also very interesting subjects for astronomical studies. The method developed in this paper can add a cosmological science case when combined with wide-area imaging surveys that have an overlap with the spectroscopic survey. The method is useful when designing joint spectroscopic and photometric surveys including a science case of the two-dimensional BAO analysis.

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