ON THE PERFORMANCE OF QUASAR REVERBERATION MAPPING IN THE ERA OF TIME-DOMAIN PHOTOMETRIC SURVEYS

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ABSTRACT

We quantitatively assess, by means of comprehensive numerical simulations, the ability of broadband photometric surveys to recover the broad emission line region (BLR) size in quasars under various observing conditions and for a wide range of object properties. Focusing on the general characteristics of the Large Synoptic Survey Telescope (LSST), we find that the slope of the size–luminosity relation for the BLR in quasars can be determined with unprecedented accuracy, on the order of a few percent, over a broad luminosity range and out to $z \sim 3$. In particular, major emission lines for which the BLR size can be reliably measured with LSST include Hα, Mg II $\lambda 2799$, C III] $\lambda 1909$, C IV $\lambda 1549$, and Ly$\alpha$, amounting to a total of $\gtrsim 10^5$ time-delay measurements for all transitions. Combined with an estimate for the emission line velocity dispersion, upcoming photometric surveys will facilitate the estimation of black hole masses in active galactic nuclei over a broad range of luminosities and redshifts, allow for refined calibrations of BLR size–luminosity–redshift relations in different transitions, as well as lead to more reliable cross-calibration with other black hole mass estimation techniques.

Key words: galaxies: active – methods: data analysis – quasars: emission lines – quasars: supermassive black holes – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Mass estimation of supermassive black holes (SMBHs) in active galactic nuclei (AGN) relies on locally established relations between the SMBH mass and various source observables, such as the luminosity and the velocity dispersion of the broad emission line region (BLR; Kaspi et al. 2000; Peterson et al. 2004; Vestergaard & Peterson 2006; Bentz et al. 2009; Denney et al. 2009). Whereas the adequacy of such relations has been demonstrated for local samples of objects where several independent means for estimating black hole (BH) masses exist (e.g., via the reverberation mapping technique and the stellar velocity dispersion in the inner regions of the host; Onken et al. 2004), it is not clear that this approach is also warranted at higher $z$, where one probes earlier cosmic times and is sensitive only to the most luminous sources at those epochs (Netzer 2003). Further, as quasar observables in a given spectral band are redshift-dependent, it is not clear that intercalibration of various phenomenological relations (e.g., between luminosity, the particular emission line probed, and SMBH mass), even if justified, is free of biases (Denney et al. 2009). In this respect, the challenge in SMBH mass estimates at high-$z$ is akin to the cosmological distance scale problem, with more data and better control of systematics required to place them on firmer ground.

With upcoming (photometric) surveys that will monitor a fair fraction of the sky to unprecedented depth and photometric accuracy and with good cadence, the time-domain field of quasar study, and specifically reverberation mapping of the BLR, is expected to undergo a major revision (Chelouche & Daniel 2012). As has been demonstrated in several previous works (Haas et al. 2011; Chelouche & Daniel 2012; Chelouche et al. 2012; Chelouche 2013; Chelouche & Zucker 2013; Edri et al. 2012; Pozo Nuñez et al. 2012, 2013; Zu et al. 2013), whereas individual emission lines cannot be resolved using photometric means, their signal can be recovered at the light curve level (see also Rafter et al. 2013), and reverberation mapping is, in principle, possible.

In this work, we build upon the formalism of Chelouche & Zucker (2013) and provide more realistic benchmarks for reverberation mapping using broadband photometric surveys, having in mind the characteristics of the Large Synoptic Survey Telescope (LSST) experiment. Specifically, we are interested in the ability of photometric campaigns to determine BLR-associated time delays in individual sources as well as statistically in subsamples of sources. This paper is organized as follows. Section 2 describes the model used here for constructing mock AGN light curves in different bands as well as the analysis technique employed to recover the input line-to-continuum time delays. Section 3 provides benchmarks for the measurement of the line-to-continuum time delay under various assumptions concerning the sampling, redshift determination accuracy, filter choice, object properties, and the priors used in the analysis. The discussion, with particular emphasis on LSST-enabled science, follows in Section 4 and the summary in Section 5.

2. LIGHT CURVE SIMULATIONS AND THEIR ANALYSIS

Below we specify our approach for simulating quasar light curves. For demonstrative purposes, we use the characteristics of the LSST and standard cosmology.  

The terms AGN and quasars are used here interchangeably.

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($h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7)$. 

7
2.1. Continuum Light Curves

We model the continuum light curve, \( f_c \), using the method of Timmer & Koenig (1995) so that its Fourier transform is of a power law form, \( f_c(\omega) \sim \omega^\gamma \), where we choose \( \gamma = -1.3 \) to be the frequency power law slope (note that our definition for \( \gamma \) differs from that used in, e.g., Giveon et al. 1999, who report instead slopes for the power spectrum). Our choice of \( \gamma \) results in a power spectrum that is somewhat redder than the one that characterizes continuous first-order autoregressive [CAR(1)] processes, for which \( \gamma = -1 \) (Kelly et al. 2009). This is in better agreement with the slopes found by high-cadence observations of AGN using Kepler data (Mushotzky et al. 2011) and may be more characteristic of the variability of high-\( z \) sources given the cadence and lifetime of the LSST experiment (Ivezic et al. 2008). We explore departures from our chosen value of \( \gamma \) in Section 3.

2.1.1. The Light Curve Variance

The normalized variability measure (i.e., the standard deviation of the light curve normalized by the mean flux level, and ignoring measurement uncertainties) in some filter \( j \), which is characterized by a central wavelength, \( \lambda_j \), is \( \sigma_j^f \) and depends, in principle, on the quasar luminosity, \( L \), its redshift, \( z \), and the wavelength range probed. Other quasar properties, such as radio loudness, BH mass, and its Eddington ratio may also be important but are not taken into account in the present treatment of the problem. In particular, we do not consider blazars or sources where the jet contributes significantly to the variability.

Our model for \( \sigma_j^f \) is of the form

\[
\sigma_j^f(L, \lambda, z) = \sigma_j^f(z = 0) L_{\text{opt}, 45}^\beta (\frac{\lambda_j}{\lambda_{\text{opt}}})^\xi (1 + z)^\gamma, \tag{1}
\]

where \( \sigma_j^f(z = 0) \) is the rest-frame normalized variability, \( L_{\text{opt}, 45} = L_{\text{opt}}/10^{45} \text{erg s}^{-1} \), where \( L_{\text{opt}} \) is the rest-frame optical luminosity of the AGN, and \( \beta, \xi, \gamma \) are power law indices whose values are discussed below and are assumed to be independent of redshift and AGN characteristics.

Motivated by the fact that the variance of the light curve is

\[
\sigma_j^2 = \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} |\hat{f}(\omega)|^2d\omega \sim \omega_{\text{min}}^{2\gamma+1} \quad \text{(here we assumed red-noise spectra and } \omega_{\text{min}} \to \infty),
\]

we note that, unless the physical bound on \( \omega_{\text{min}} \) is observable (e.g., when a spectral break lies in the frequency range probed by the time series), the reduced variability measure of the light curve depends on the duration of the experiment, \( \Delta \), so that \( \sigma_j^f \sim \Delta^{-1/2} \). For an experiment of a fixed duration over the entire sky (e.g., LSST) we get that \( \sigma_j^f \sim (1 + z)^{\gamma+1/2} \) because of this time dilation effect alone. Nevertheless, a further effect determines the final value of \( \epsilon \); observationally, it is well established that longer (rest) wavelength data have smaller variations such that their reduced variability measure \( \sim \lambda^{-0.8} \) hence \( \xi = -0.8 \) (Garcia et al. 1999; Giveon et al. 1999; Meusinger et al. 2011). Therefore, observing quasars over a broad range of redshifts, using a particular band, would lead to an independent redshift dependence of the form \( \sigma_j^f \sim (1 + z)^{0.8} \). Combining the two sources for redshift dependence, we obtain, for \(-1.3 < \gamma < -1, 0 < \epsilon < 0.3 \).

In this work, we do not consider the possibility of quasar evolution, i.e., an intrinsic dependence of quasar variability on the cosmological epoch, an assumption that appears to be consistent with the data (Meusinger et al. 2011). If present, this could imply more enhanced (suppressed) high-\( z \) variability of quasars than assumed here, thereby facilitating (restricting) reverberation mapping.

The luminosity dependence of the normalized variability measure is determined by searching for a reasonable agreement between the model predictions (Equation (1)) and the combined variability data set for Seyfert galaxies (Sergeev et al. 2005) and Palomar-Green (PG) quasars (Giveon et al. 1999; Kaspi et al. 2000) at low \( z \). The model is then scaled up to higher \( z \) using Equation (1), and its predictions are checked against data for luminous high-\( z \) objects (Kaspi et al. 2007), which cover the relevant timescales. The normalization constant, \( \sigma_j^f(z = 0) \), and \( \beta \) are then simultaneously determined, yet we note that the solution may not be unique, and we make no attempt to cover the plausible solution phase space in this work. We find that \( \beta \sim -0.2 \) and \( \sigma_j^f(z = 0) \sim 0.2 \) provide an adequate description for the median reduced variability measure of all data sets. Nevertheless, we caution that (1) the normalized variability measure for some Seyfert galaxies is somewhat underestimated due to host contamination in the Sergeev et al. (2005) data set (Cackett et al. 2007), and that (2) some of the high-\( z \) objects in the Kaspi et al. (2007) sample are extremely radio-loud objects, blazars, whose variability may not be characteristic of the bulk of the high-\( z \) radio-quiet population.

Lastly, individual objects show considerable scatter around the typical (median) normalized variability measure at a given luminosity range. We find that a model where Equation (1) is multiplied by a factor \( e^\delta \), where \( \delta \) is a Gaussian random variable with a standard deviation of 0.4 and a zero mean, qualitatively agrees with the observations (see Figure 1). Overall, our model provides a fair statistical description of quasar variability, which is in line with the qualitative statistical framework considered in this work. However, it is not designed to account for the full
richness of quasar variability (e.g., with a possible dependence also on the BH mass or the Eddington ratio), nor for the particular properties of extreme AGN types (e.g., the narrow line objects) and the possibility of truly nonstationary light curve behavior.

2.1.2. Time Delays

It is known that the continua light curves of quasars in different bands are highly correlated (Ulrich et al. 1997). Nevertheless, there are a few examples of low-luminosity Seyfert 1 galaxies showing discernible lags between the continuum light curves in different bands (Collier et al. 1998, 2001; Chelouche & Zucker 2013; Chelouche 2013). These are consistent with a physical picture in which the inner accretion disk irradiates its outer parts, resulting in longer wavelength reprocessed emission lagging the short wavelength one (see, however, Korista & Goad 2001 for a different interpretation of the data). We note, however, that such time delays have not been established for high-luminosity sources or in high-\(z\) quasars.

In cases where continuum transfer effects across the accretion flow are relevant, the light curve in some band \(k\) may be obtained from the light curve in band \(j\) by means of a convolution with an appropriate transfer function, \(\psi_j(t)\). For simplicity, we shall assume a rectangular function such that \(\psi_j(t) = 1/2\tau_{jk}\) and is defined in the range \(t \in [0, 2\tau_{jk}]\), where \(\tau_{jk}\) is the time delay between the bands (for more theoretically motivated transfer functions see Cackett et al. 2007; Chelouche 2013 and references therein). We use theoretically expected time delays from standard thin accretion-disk theory, which seem to be supported by the current data, such that

\[
\tau_{jk} = 7\tau_{opt,45}^{0.5}(1 + z)^{-1/3} \left[ \frac{\lambda_k - \lambda_j}{5500\, \text{Å}} \right]^{4/3} \text{days}, \tag{2}
\]

where we implicitly assumed that \(\lambda_k > \lambda_j\) and normalized according to Chelouche (2013). The redshift dependence results from the combined effect of cosmological time dilation and the smaller sizes of the accretion disk probed by shorter wavelength emission that enters the optical bands at higher \(z\). The continuum light curve in band \(k\) is then set once \(f^j_c\) is determined by

\[
f_k^c = f^j_c \ast \psi(\tau_{jk}), \tag{3}
\]

where “\(\ast\)” denotes convolution. If Shakura & Sunyaev (1973) disks provide a fair description of the accretion physics in AGN, then this relation is expected to hold except for objects with the lowest/highest accretion rates. In those physical regimes, advection becomes relevant (Abramowicz et al. 1988; Narayan & Yi 1994).

2.2. Line and Nonionizing Continuum Emission

Once the wavelength-dependent (ionizing) continuum emission from the accretion disk has been defined for all bands, the contribution of emission lines and line blends as well as variable nonionizing continuum emission from the outer regions (e.g., Balmer and Paschen continuum emission from the BLR, Korista & Goad 2001, and heated dust emission from its far outskirts Netzer & Laor 1993) must be included. To this end, we compiled a list of major emission components and estimated their relative contribution and time delays with respect to the adjacent continuum level from a mean quasar composite spectrum (Vanden Berk et al. 2001) and from various reverberation mapping campaigns (Kaspi et al. 2000, 2007; Peterson et al. 2004; Metzroth et al. 2006; Suganuma et al. 2006; Bentz et al. 2010; Barth et al. 2013; Chelouche et al. 2013). We note that we consider luminosity-independent rest equivalent width values in this work, which is a clear simplification given the scatter observed (Shen et al. 2011) and the presence of the Baldwin effect, i.e., the anticorrelation between line equivalent width and AGN luminosity (Baldwin 1977; Taniguchi & Chelouche 2013). These are consistent with a high-luminosity composite (Vanden Berk et al. 2001), we expect the median equivalent width for LSST objects to be comparable to, or somewhat larger than, that assumed here. Throughout this work, we assume that the time delays for a given emission line (or blend) scale as \(\tau_{opt}^{0.5}\) (Bentz et al. 2009; Chelouche et al. 2013, but see Kaspi et al. 2005) and that the variance in the line light curves is comparable to that in the continuum (Kaspi et al. 2000; Woo 2008). Table 1 lists the various emission components used in this work, to which we refer henceforth as emission lines.

The total AGN light curve in band \(j\) is then given by

\[
f^j(t) = f^j_c(t) + \sum_{i=1}^{N} \left[ f_i^j \ast \psi_i(\tau_i(L, z)) \right] \frac{\bar{\eta}_i(\lambda_i(z)) W_0^i(z)}{\int d\lambda \eta_i(\lambda)}, \tag{4}
\]

where the summation is over all entries in Table 1. Here, \(\psi_i\) is the line transfer function for the \(i\)th emission feature and is assumed to be of a rectangular form (see above), which starts at zero lag and extends out to \(2\tau_i\) (\(\tau\) is the time delay). The telescope throughput curve for band \(j\), \(\bar{\eta}_j(\lambda)\), is shown in Figure 2 for the proposed set of LSST filters (including telescope efficiency and atmospheric effects). The rest equivalent width values for the relevant transitions, \(W_0\), are given in Table 1. We define the mean efficiency for an emission component centered on \(\lambda_i\) as

\[
\bar{\eta}_i(\lambda_i) = \frac{\int d\lambda \eta_i(\lambda) \phi(\lambda - \lambda_i)}{\int d\lambda \phi(\lambda - \lambda_i)}, \tag{5}
\]

where \(\phi(\lambda)\) is the profile of the emission component. For simplicity, we assume rectangular profiles with a width \(\delta \lambda = 30\, \text{Å}\) for the emission lines (this corresponds to velocities of \(\gtrsim 10^3\, \text{km s}^{-1}\), typical of broad line widths). For large-scale continuum emission (e.g., the Balmer bump), we assume a rectangular profile that spans the wavelength range given in Table 1 (rows 32–34).

Examples for the light curves in different LSST bands for a \(z = 0\), \(L_{opt,45} = 1\) AGN are shown in Figure 2. For clarity, we do not consider in this example the decreasing variance with wavelength (Equation (1)) and assume that measurement uncertainties are negligible (those effects are included in the full calculations presented in Sections 3 and 4). Clearly, light curves in all bands are, to zeroth order, similar due to the dominant contribution of correlated continuum processes. Nevertheless, finite differences are noticeable: at progressively redder bands, the light curves are less spiky due to transfer effects across the accretion disk, which suppress small-scale fluctuations (e.g., compare the light curve in the \(y\) band and the driving continuum signal). In addition, the finite contribution of emission lines and
in the coming decades, we consider the following observing

\[ \text{Chelouche & Zucker 2013).} \]

...associated with major emission lines (Chelouche & Daniel 2012; ...quality data, allowing for the measurement of time delays as-

\[ \text{...between light curves in different bands can be detected in good-} \]

...is made for the combined contribution of higher-order emission lines red-ward

\[ \text{of the edge ionization energy.} \]

...depends on the (normalized) continuum level at \( \sim 1000 \) days, which is due to the lagging contribu-

\[ \text{...is considerably noisier than the quasar's, with the latter being characterized by a smaller variance. The effect of seasonal gaps is also evident.} \]

\[ \text{2.3. Sampling and Measurement Noise} \]

Blends to the broadband flux leads to longer trend deviations and further suppresses small-scale fluctuations. For example, the (normalized) \( r \)-band light curve lies below the driving continuum level at \( < 500 \) days, but below the driving continuum light curve at \( \sim 1000 \) days, which is due to the lagging contribution of the \( \text{He} \) line to the flux. A more prominent effect is seen in the \( y \) band, where a considerably delayed large-amplitude contribution from dust emission is apparent. Such differences between light curves in different bands can be detected in good-quality data, allowing for the measurement of time delays associated with major emission lines (Chelouche & Daniel 2012; Chelouche & Zucker 2013).

\[ \text{2.3.1. Host Contribution} \]

Finite aperture observations result in some of the host light contributing to the signal and may lead to additional noise under varying seeing conditions. \[ \text{For high-\( z \) sources, which are the bulk of the AGN population in upcoming surveys (see Section 4), the contribution of the host decreases sharply because the surface brightness scales as \( (1 + z)^{-4} \) and galaxies are rest-UV faint relative to the nuclear emission. To mitigate host contamination problems in faint low-\( z \) objects, large-aperture photometry or image-subtraction techniques (Alard & Lupton 1998) provide viable solutions. For the LSST, image-subtraction techniques will be part of the standard reduction pipeline and are expected to reduce varying seeing effects down to photon noise levels. Simulating second-order host galaxy subtraction effects, which could affect a small fraction of the quasar population, is beyond the scope of the present work and will not alter the main conclusions of this paper.} \]

\[ \text{Notes. BLR emission features (i.e., lines, line blends, and continua) are included in} \]

| ID   | \( \lambda_i \) (Å) | \( W_0 \) (Å) | \( r \) (days) |
|------|---------------------|--------------|---------------|
| (1) Lyα | 1033               | 9.8          | 42            |
| (2) Ly∀ | 1126               | 93.7         | 42            |
| (6) N vi | 1240              | 1           | 18            |
| (7) Si iv | 1397               | 8           | 50            |
| (8) C iv | 1549               | 24          | 40            |
| (9) C iii | 1909               | 21          | 120           |
| (10) Fe ii | 2077              | 2.5         | 50            |
| (11) Fe ii | 2324              | 3.6         | 50            |
| (12) Mg ii | 2799              | 32         | 70            |
| (13) Fe ii | 2964               | 5           | 50            |
| (14) He i | 3189               | 1          | 100           |
| (15) Fe ii | 3498              | 1.4        | 50            |
| (16) Hα | 4103               | 5         | 36            |
| (17) Fe ii | 4160               | 1         | 50            |
| (18) Hγ | 4342               | 13        | 60            |
| (19) Fe ii | 4564               | 20        | 200           |
| (20) He i | 4687               | 1         | 40            |
| (21) Hβ | 4863               | 46        | 100           |
| (22) Fe ii | 5305               | 22        | 200           |
| (23) He i | 5877               | 5         | 100           |
| (24) Ha | 6565               | 195       | 130           |
| (25) He i | 7067               | 3         | 100           |
| (26) O i | 8457               | 10        | 200           |
| (27) Fe ii | 9202               | 4         | 200           |
| (28) Paα | 9545               | 7         | 150           |
| (29) Paδ | 10049              | 21        | 150           |
| (30) He i | 10830              | 36        | 100           |
| (31) Paγ | 10941              | 7         | 150           |

| (32) Balmer cont. | 3400–4000a | 100 | 30 |
| (33) Paschen cont. | 6500–8300a | 300b | 150 |
| (34) Hot dust | 10000–200000b | 10000 | 500 |

Notes. BLR emission features (i.e., lines, line blends, and continua) are included in this work, with their parameters (\( W_0 \) and \( r \)) given in the rest frame; see Table 2 in Vanden Berk et al. (2001) for wavelength definitions. Quoted lags correspond to an \( L_{\text{opt},45} = 1 \) quasar (see the text).

\[ a \text{ Approximate wavelengths are used. For the recombination continua, allowance is made for the combined contribution of higher-order emission lines red-ward of the edge ionization energy.} \]

\[ b \text{ The flux in this component is poorly constrained, and } W_0 \text{ is inspired by the theoretical calculations of Kwan & Krolik (1981) and Korista & Goad (2001).} \]

\[ \text{10 https://www.lsstcorp.org/opsim/home} \]

\[ \text{11 http://dls.physics.ucdavis.edu/etc/} \]

\[ \text{12 Note that a constant host contribution to the light curves is immaterial because reverberation mapping algorithms are insensitive to it (Welsh 1999; Chelouche & Zucker 2013).} \]
Figure 2. Light curve simulations in photometric bands. Upper panel shows a typical $z = 0$ AGN spectrum (Vanden Berk et al. 2001; Glikman et al. 2006) and the contribution of the various emission features to the broadband flux assuming LSST throughput curves. Bottom panels exhibit the broadband light curves in individual panels (red curves) with the total contribution of BLR emission features denoted in percent in each panel. For clarity, measurement uncertainties are not shown but are included in the final mock light-curve products (see Figure 3). For comparison, the driving continuum light curve is shown as a black line in each panel and the normalized light curves of prominent emission features as dashed magenta lines (and a purple solid line for the H$\alpha$ light curve contributing to the $r$ band). Note the smoother appearance of the light curve in the redder bands due to signal transfer effects in a geometrically thick region (the effect of reduced variability with increasing wavelength is separately and phenomenologically treated in Section 3).

(A color version of this figure is available in the online journal.)

Figure 3. Representative mock light curves for the $u$ band (magenta) and the $y$ band (black) for a $z = 0.5$ Seyfert galaxy (left column) and a bright quasar at $z = 3$ (arbitrary shifts between the broadband light curves were introduced for clarity) using 15 s exposures with LSST. DDF light curves are shown as dots while UNS as circles (only for the Seyfert galaxy case). Note the markedly different variability amplitude of luminous vs. less-luminous objects and the generally higher variance at shorter wavelengths (see the text).

(A color version of this figure is available in the online journal.)

2.4. Analysis

We apply the photometric reverberation mapping technique of Chelouche & Zucker (2013) to our mock photometric light curves. Briefly, one considers a pair of filters, one of which is relatively line-rich, while the other one is line-poor, and calculates the multivariate correlation function (MCF) to deduce a lag. In cases where the noncontinuum emission contribution to the line-rich band is dominated by a single emission line, while the other (line-poor) band is devoid of emission components other than the primary ionizing continuum, the lag is the line-to-continuum time delay to a good approximation (Chelouche & Zucker 2013). Denoting the line-poor (fluxed) light curve as $f_c(t)$ and the line-rich (fluxed) light curve as $f_{cl}(t)$, then, to first-order approximation, the model for $f_{cl}(t)$ is

$$f_{cl}(t) = (1 - \alpha) f_c(t) + \alpha f_c(t - \tau),$$

where $\alpha$ is the relative emission line contribution to the signal in the band, and $\tau$ is the line-to-continuum lag. One may deduce both $\alpha$ and $\tau$ by searching for the peak of the MCF defined by

$$R(\alpha, \tau) = \frac{1}{N \sigma^2(f_{cl})} \sum_{i=1}^{N} f_{cl}(t_i) f_{cl}^m(t_i, \tau, \alpha),$$

where $\sigma$ is the standard deviation of the time series, and $N$ is the number of points in the sum (see Chelouche & Zucker 2013 and references therein for further details). Unlike Chelouche & Zucker (2013), we do not carry out Monte Carlo simulations on a case-by-case basis to test for the significance of individual solutions because this would result in prohibitively long execution times on current hardware. As we shall show below (Section 3.1), it is possible to effectively screen against unphysical solutions.\(^{13}\)

Whereas the MCF method has been shown to work well in regions of the spectrum with relatively sparse emission line

\(^{13}\) The degree to which improved lag statistics for large samples of AGN may be obtained by considering the significance of individual measurements is worth exploring in future studies. This awaits better error-estimation algorithms for reverberation mapping and further improvements in computer hardware.
While no band may be strictly free from BLR emission, we identify $f_c$ with the band characterized by the smallest contribution of BLR emission features to its flux (e.g., the y band for $0.1 < z < 0.2$ sources using our emission model; see Figure 4). It should be emphasized that the suitability of any given band to serve as $f_c$ depends not only on the relative emission line contribution to the flux but also on the host galaxy contribution to it and the effect of seeing in nearby faint AGN, as well as on the number of visits and how far in wavelength the band is removed from the line-rich band in question (see further details in Section 3.4). Once $f_c$ is defined, time-delay measurements proceed via the calculation of the MCF with respect to each of the line-richer bands, resulting in up to five time-delay measurements per object.

In this work, we take the following approach to benchmark photometric reverberation mapping: the deduced time delay is compared to the (input) time delay of the emission component that contributes most to the line-rich band. This is certainly a reasonable interpretation when one dominant emission line exists, and the degree to which it is generally useful is critically examined below (Section 3.3).

3. RESULTS

3.1. Single Emission Line

We first consider the simplest case, where a single emission line, $\lambda_\alpha$, is present in the spectrum, and attempt to recover its delay from photometric light curves that are characterized by DDF sampling in continuous viewing mode. For simplicity, all quasars are placed at $z = 0.01$ (i.e., resulting in high signal-to-noise (S/N) light curves) and span a broad range of luminosity; in this case, $f_c$ is the r-band light curve, and we arbitrarily assign the z-band light curve to $f_c$. Unless otherwise stated, on the order of $10^5$ objects were simulated, and the MCF was calculated for each, resulting in the time-delay statistics provided below.

Figure 5 shows the recovered radius–luminosity relation for $\lambda_\alpha$. On average, the slope of the lag–luminosity relation is well traced over the intermediate luminosity range. In particular, the deduced slope of the size–luminosity relation for $\sim 30,000$ objects with $10^{43} \text{erg s}^{-1} < L_{\text{opt}} < 10^{45} \text{erg s}^{-1}$ is $0.502 \pm 0.003$, which is in excellent agreement with the input value. At the low-luminosity end, the effects of sampling discretization are evident as time lags approach the sampling period, and the transfer function is undersampled. At the high-luminosity end, clear deviations from the input size–luminosity relation are evident as the survey’s lifetime (10 yr for the first phase of the LSST) is comparable to the lag, and the full extent of the transfer function cannot be observed. In particular, the recovered lag distribution for $L > 10^{46} \text{erg s}^{-1}$ objects is considerably skewed to unphysically short lags. As we discuss below, reliable time-delay measurements are possible provided additional information exists.

Considering the ratio between the output (i.e., recovered) and input quantities ($O/I$) for quasars of all luminosities, we

14 http://www.lsst.org/files/docs/sciencebook/SB_10.pdf

15 We do not consider luminosity-function statistics in this section (see Section 4).

16 Realistically, the BLR sizes for a given emission line in quasars of a given set of properties, such as luminosity, follow a physical distribution of some form rather than reflect on a single value. The resulting distribution functions for the recovered lags could therefore be somewhat broader than calculated here. Currently, higher moments of the BLR size–luminosity relations are poorly understood hence not included in our model.

17 The uncertainty was determined by considering subsamples of the data and obtaining fit statistics by means of bootstrapping.
see that most points cluster, as expected, around $O/I \sim 1$ (Figure 6). In particular, lag measurements that considerably deviate from the input lag are very likely to result in an offset solution for $\alpha$: e.g., lag solutions for the most luminous sources in Figure 5 are skewed to shorter lags and to low $\alpha$ values, which do not match the input values. Therefore, provided that independent information on $\alpha$ is available—for example, through spectroscopic observations or from statistical knowledge of the quasar population as a whole—it is possible to screen against nonphysical solutions by rejecting highly discrepant $\alpha$ values. Generally, allowing for smaller uncertainty margins on $\alpha$ results in a smaller scatter in the lag measurement, and also with fewer objects contributing to the sample (not shown).

As “valid solutions” in this work, we consider $\alpha$ values that deviate from the input value by no more than $\pm 40\%$. This criterion seems to provide satisfactory results for a large range of object redshifts and luminosities (see Section 4), and is consistent with the results of Shen et al. (2011), who show that $\sim 90\%$ of all H$\alpha$ rest-equivalent width measurements for SDSS quasars lie within a similar interval. Valid solutions under our $\alpha$-interval definition are relatively well clustered around the input values as can be seen in Figure 5. In particular, even for the most luminous sources, whose line transfer function is poorly sampled by the data, it is possible to identify reliable solutions in a fraction of all objects (note how the green points follow the input relation up to high luminosities in Figure 5).

There is a statistically significant and consistent $\lesssim 20\%$ overestimation of the median lag with $\alpha$ being underestimated by a similar factor (see the bulk of points in Figure 6). This small but significant effect can only be detected with good enough statistics and reliable independent lag measurements, hence it could not have been determined by Chelouche & Zucker (2013) in their analysis of Sergeev et al. (2005) data. The underlying reason for these offsets has to do with the MCF formalism being effectively blind to the structure of the line transfer function on short timescales. In particular, any emission line contribution to the light curve at short times (e.g., due to clouds that lie closer to our sightline and whose reprocessed radiation arrives nearly simultaneously with the continuum light curve), may be regarded as pure continuum emission. This is not surprising because line and continuum emission cannot be independently traced by photometric data. Considering narrower emission-line transfer functions, whose centroids are identical yet rise at finite times—i.e., the reverberating signal is sufficiently removed from zero lags—results in a reduced bias (Figure 7; see also Zu et al. 2013 who use a narrow Gaussian transfer function). Similarly, the small offset in $\alpha$ also vanishes, indicating its common origin: by not being able to trace part of the transfer function, the relative contribution of the line to the photometric light curve is effectively diminished. This in turn means that some information about the transfer function of emission lines is lurking also in broadband photometric data.

Lastly, we wish to study the effect of the power-density spectral shape, $\gamma$, on the ability of the MCF algorithm to reliably recover time delays. In particular, a considerable range of power law indices have been found to characterize quasar light curves with slopes $-1.7 < \gamma < -0.4$ (Giveon et al. 1999; Mushotzky et al. 2011). To this end we consider a narrow range of intermediate luminosity objects (so that sampling issues are irrelevant) and plot the statistics of the recovered signal in Figure 8. As shown, the $\gamma$ range covered by most AGN lies around a sweet spot in the parameter space, where the scatter in individual time delays around the median value is minimal and the fraction of objects for which reliable time-lag solutions are obtained peaks (as before, we use the constraint that the recovered $\alpha$ deviates by less than $\pm 40\%$ from the input value). For objects whose light curves show considerable variability only at the longest timescales (i.e., $\gamma < -1.6$),
of unphysical solutions is somewhat increased for small \( \gamma \) lag measurements are less reliable. Similarly, the fraction of objects showing the greatest dispersion around the spectrum of the object does not substantially alter these results (Figure 8).

From zero lags, corresponding to less BLR material along the sightline to the observer, result in a smaller lag bias (see the text). Changing the power-density spectrum of the object does not substantially alter these results (Figure 8).

(A color version of this figure is available in the online journal.)

the recovered lags show the greatest dispersion around the median lag: whereas the latter quantity is robust, individual lag measurements are less reliable. Similarly, the fraction of unphysical solutions is somewhat increased for small \( \gamma \) values. At the other extreme, where AGN light curves gradually resemble white noise (\( \gamma > -0.5 \)), the fraction of objects with physical solutions drops significantly, and the dispersion in the lag increases so that lag measurements become unreliable. Moreover, even statistical averages become meaningless as the algorithm prefers to fit white noise with white noise, and the median time delay goes to zero. The slight increase in the fraction of “reliable” physical solutions that satisfy our \( \alpha \) criterion for \( \gamma > -0.4 \) (note the last bin in Figure 8) is purely artificial and has to do with the fact that the recovered \( \alpha \) in this limit is drawn from a uniform distribution in the range \([0, 1]\). We note that the aforementioned (transfer-function dependent) offset in the median lag depends relatively little on \( \gamma \) for the parameter range typical of quasars (Giveon et al. 1999; Mushotzky et al. 2011).

### 3.2. Sampling

Realistic experiments rarely benefit from strictly uniform sampling because seasonal gaps, telescope downtimes, bad weather, and scheduling constraints are all limiting factors. The effect of different sampling patterns on the size–luminosity relation for H\( \alpha \) (again, neglecting other lines), are shown in Figure 9. Generally, with more timescales characterizing the observing pattern, the noisier the measurement becomes. In particular, introducing 120 day seasonal gaps results in noisier lag measurements around those timescales, which act as effective solution attractors. Interestingly, there is a tendency for the algorithm to somewhat overestimate the lag around the gap timescale (Figure 9). Again, erroneous lag measurements can be discarded using additional information, if available, on \( \alpha \): screening against discrepant \( \alpha \) solutions, some \( \sim 35\% \) of all measurements are discarded, and the remaining solutions match well the input size–luminosity relation of the BLR. Specifically, the cluster of overestimated time-delay solutions around seasonal gap timescales is naturally excluded by this filtering scheme.

Experimenting instead with UNS-like sampling for the LSST, and restricting our analysis to light curves with 200 visits in each band, we find that the ability to recover short delays (e.g., in faint enough AGN or in high-ionization emission lines) is compromised. In particular, the sampling period in this case is \( \sim 20 \) days, which is on the order of the minimal lag that can be reliably recovered. As before, using prior knowledge on \( \alpha \) reduces the scatter, especially at the low-luminosity end of the quasar population, which is characterized by the shortest lags and allows for a better characterization of the size–luminosity relation.

Lastly, we consider UNS, with one of the bands having 200 visits, and the other band a mere 60 visits\(^{18} \) (e.g., the \( r \) and \( u \) filters given the current version of the Opsim). In this case, the scatter is considerably increased (note the highly broadened lag distributions in Figure 9) as is the minimal time delay that can be reliably recovered; e.g., measuring the H\( \alpha \)-lag for low-luminosity AGN is impossible. Discarding nonphysical solutions using our current screening algorithm is effective over a relatively narrow luminosity range (\( 10^{46} \text{ erg s}^{-1} < L < 10^{46} \text{ erg s}^{-1} \)), but even then individual measurements contain little information, with only large ensembles being able to characterize the typical time delay up to a \( \sim 40\% \) bias. Our calculations show that further screening the sample for objects showing the greatest variance in their light curves may be useful to further narrow down the lag distributions, yet it is not clear that such a selection would provide an unbiased view of the quasar population as a whole, hence it is not considered here.

Additional tests for the MCF solution may prove beneficial (see

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\(^{18} \) We do not find significant differences between cases in which the sampling is interchanged between the line-rich and line-poor bands.
Chelouche & Zucker 2013 for one possible version of such a test) in further weeding out erroneous solutions. These, however, are beyond the scope of the present work due to their prohibitive computational demands (see also Section 2.4).

Simulations show that more reliable solutions under sparse sampling may be obtained when the emission line contribution to the band is larger. This may occur in cases where effectively narrower photometric bands are considered or when stronger emission lines are probed (see Figure 9 and Section 4 discussing the results for the Ly$\alpha$ line). In particular, for $\alpha \rightarrow 1$ the MCF reduces to standard cross-correlation techniques with their advantages and shortcomings (Netzer & Peterson 1997; Welsh 1999 and references therein).

We note that, in the limit of truly random sampling, infinite characteristic timescales of the time series exist, and the solution phase space is uniformly covered (not shown). In such cases it is practically impossible to deduce the true lag, regardless of whether additional information on $\alpha$ exists.

### 3.3. Multiple Emission Lines

Here we include all emission lines and blends (as well as the Paschen and Balmer bumps and dust emission) listed in Table 1 and examine the ability of the MCF algorithm to recover the line-to-continuum time delay. More specifically, we first identify the line-poor band and associate its light curve with $f_c$. We then determine the (effective) $\tau$ and $\alpha$ from the MCF for each filter combination. The solutions are then compared to the input lags and the relative contributions to the flux of the emission features that contribute the most to each of the line-rich bands. That is, whether a particular emission component contributes solely to the flux in the line-rich band, or whether its contribution is only slightly larger than that of the other emission components contributing to the same band, does not alter our interpretation of the signal.

Results for individual objects having a luminosity of $10^{45.5}$ erg s$^{-1}$ over the redshift range $0 < z < 3$, assuming DDF sampling with seasonal gaps, are shown in Figure 10 for the different bands. For the chosen luminosity, the algorithm is able to determine a lag up to $z \lesssim 2$. Specifically, as the S/N decreases, the recovered time-delay distribution extends to shorter recovered lags whence becoming less reliable. Nonphysical solutions may be discarded, as before, using prior information on $\alpha$, leading to solutions that hover around the input value, with a typical scatter of 50% (see also the upper panels of Figure 11).

Interestingly, some filter combinations give rise to more biased results. For example, time-delay measurements in the $r$ band for $z \sim 0.2$ objects (here, the $u$ band is the line-poor band), show a factor $\sim 2$ overestimation of the lag (see Figures 10 and 11). The primary reason for that has to do with the fact that, at such redshifts, Fe II and H$\beta$ have comparable contributions to the flux in the $r$ band, with the former transition being characterized by longer time delays (Barth et al. 2013; Chelouche et al. 2013; see our Table 1). We also note that, at $z \sim 0.2$, the contribution of the emission lines to the $r$ band is only slightly larger than that to the $u$ band (see Figure 4), and caution is advised when interpreting the signal.

It is also interesting to note the increased scatter in the recovered lags at redshifts where the identity of the line-poor

Figure 9. $R_{BLR}(L)$ determination for $z = 0.01$ objects for several sampling patterns (upper panels), and recovered time-lag distributions with respect to the input lag (lower panels). Left column corresponds to DDF sampling with 120 day gaps (see Figure 5). The middle column is akin to UNS fields where we assume 200 visits per band, with seasonal gaps. Right panels correspond to UNS fields with 60 visits in one band and 200 visits in the other band over the LSST lifetime (the identity of the filters is unimportant, and contours are not shown for clarity). Clearly, as sampling becomes sparser, the scatter is increased, and the time-delay distributions around the input value become broader. It is possible, however, to narrow the distributions by rejecting nonphysical solutions based on prior knowledge of $\alpha$ (here we require that the recovered $\alpha$ is within $\pm 40\%$ of the input value). Such solutions and their respective distributions are shown as green points and curves in all panels, and the fraction of good solutions is denoted in percent in each of the upper panels. For the right panels we also show solutions and distributions focusing on intermediate luminosity objects, which do not suffer as much from finite sampling issues (magenta curves). Further, we consider a case in which the emission line is assumed to have a larger contribution to the band but with all other parameters fixed (cyan points and curves).

(A color version of this figure is available in the online journal.)
Figure 10. Lag determination, in relative units (O/I), as a function of redshift for different bands and for quasars with $L_{\text{opt}} = 10^{45.5} \text{ erg s}^{-1}$. DDF sampling with 15 s exposures and 120 day seasonal gaps are assumed. Black points mark all solutions, while green points constitute a subsample that agrees with our criterion for adequate $\alpha$ solutions (see the text). Clearly, there are broad redshift intervals where the recovered lag is in good agreement with the input lag up to a modest bias (see text). For a specific band, redshift gaps having no solutions mark intervals where the filter is used as the line-free band. The sharp limit on O/I for the $y$ band, at low z, results from an enforced time-delay cutoff in the phase space probed by the MCF, which corresponds to half of the LSST lifetime, and the dust component, which contributes to this band at those redshifts having $\sim 500$ days delay. The ability of the algorithm to recover the lag at high-redshifts is reduced by low S/N and the finite lifetime of the survey (a small cluster of green points for the $u$ band around $z \simeq 2$ corresponds to Ly$\alpha$ lag measurements, which are limited by S/N given the source luminosity; see also Section 4).

(A color version of this figure is available in the online journal.)

Figure 11. Statistics of time-delay measurements for a $L_{\text{opt}} = 10^{45.5} \text{ erg s}^{-1}$ source, as a function of redshift, for the different LSST bands. Red points mark the median O/I for the time delay, while the dashed line marks one standard deviation around this value (with a hard bound set at zero). The IDs of the most prominent emission features from Table 1, for a given band, and as a function of redshift, are denoted in different color bands (labeled by numbers in parentheses). All three cases shown correspond to DDF sampling with 120 days of seasonal gaps. Upper panel statistics are obtained from Figure 10. The middle row panels include the effect of finite redshift uncertainties (see the text). Whereas the median time delays are robust to finite redshift accuracies, the reliability of individual measurements at redshift ranges where filter switches take place, or when certain emission lines enter or leave the band in question, is considerably reduced. The lower panels show the effect of continuum time delays on the lag measurements. The median time delay is sensitive to the continuum time delays, and large biases may occur depending on the choice of line-poor and line-rich bands (see, e.g., the $u$-band results at $z < 0.4$ where the deduced lag may exceed the input lag by as much as a factor of 10; see the text).

(A color version of this figure is available in the online journal.)

3.3.1. Redshift Uncertainties

Redshift inaccuracies may lead to an erroneous identification of the line-poor and line-rich bands and to poor estimation of the relative contribution of emission lines to the flux, hence to an improper interpretation of the signal. We note that typical redshift uncertainties in photometric surveys are on the order of a few percent and incorporated such uncertainties in our simulations pipeline (a Gaussian distribution with a standard deviation, $\delta z = 0.05$, was assumed, and a hard lower bound of $z = 0$ was enforced).
Figure 11 (middle panels) portrays the effect of redshift uncertainties, where the standard deviation of the recovered lag distribution rapidly increases at band-specific redshift ranges. As expected, such intervals correspond to redshifts where the identity of the most prominent emission line at any given band is changed over narrow redshift intervals or in cases where the identity of the line-poor band is switched. Most importantly, whereas individual measurements are less reliable at such redshift intervals, the median of the recovered lag distribution does not show significant deviation from the ideal case where the redshift is precisely known. Clearly, provided that systematic effects are well controlled, large-number statistics wins.

Lastly, we mention a subtle effect having to do with the emission line contribution to the band across filter edges. Specifically, for relatively boxy filter throughput curves it is possible for only one of the extended line wings to contribute to the flux in the band. As has been shown in several previous works, the time delay associated with emission line wings could differ from that which characterizes the bulk of the emission line (Grier et al. 2013 and references therein). Such effects could lead to small biases in the median lag close to certain redshift intervals. However, under most circumstances pertaining to broadband data, the emission line contribution at the filter edge will be overwhelmed by that of another transition close to the peak sensitivity curve of the band. The full treatment of such cases is beyond the scope of the present work.

3.4. Continuum Time Delays

The presence of time delays between the continuum emission in different wave bands (Equation (2)) could considerably bias line-to-continuum time-delay measurements, as already discussed in Chelouche & Daniel (2012). Figure 11 (bottom panels) shows this effect when considering a quasar with an optical luminosity of $10^{45.5}$ erg s$^{-1}$ over a broad redshift range.

We find that, for much of the parameter space covered by our simulations, the effect of continuum time delays on the deduced (line-to-continuum) lag is modest. Nevertheless, there are particular filter combinations and redshift intervals where the deduced (median) lag can considerably deviate from the input value, which cannot be corrected by using priors on $\alpha$. For example, the emission-line time delays associated with the $g$ band appear to be highly biased (by an order of magnitude) compared to the input delay for $z < 0.4$ sources. This is due to the fact that the $i$ band is used as the line-poor band at this redshift interval and due to the continua time delay between the $i$ band and the $u$ band being $\sim 10$ days in our model, i.e., $\sim 6\%$ of the line-to-continuum time delay in this case (see also Chelouche & Daniel 2012). A similar bias, although somewhat smaller in amplitude, is noticeable when considering the $g$ and $r$ bands at $z \sim 0.2$.

There are two straightforward ways to mitigate the aforementioned complications: (1) use a line-poor band that is as adjacent as possible to the line-rich band probed, so that interband continuum time delays are minimized (Equation (2)), or (2) use a more comprehensive formalism, which is able to handle situations where two lagging emission components are present in the problem. The full treatment of such situations is naturally more complicated and may also lead to degenerate results (Chelouche & Zucker 2013).

Lastly, we mention the possibility of nonnegligible diffuse continuum emission from the BLR (Korista & Goad 2001, see their Figures 2 and 4). Whereas the quantitative treatment of this scenario is beyond the scope of the present work and is subject to model uncertainties, at the basic level the problem is akin to that of the continua time delays. Specifically, one should seek line-poor and line-rich filter combinations for which diffuse continuum emission from the BLR has similar characteristics (e.g., lag and relative contribution to the flux).

4. DISCUSSION

We have shown that photometric surveys with quasiregular sampling in several bands, and with characteristics similar to the LSST, can be used to measure the line-to-continuum time delay in major emission lines, line blends, and nonionizing continua from the BLR. Lag measurements show enhanced scatter when the time delay is a fair fraction of the survey lifetime or when the lag is comparable to the sampling period. Nevertheless, even in such cases, it is possible to reduce the scatter and reach statistically robust results if additional constraints on the value of $\alpha$ (e.g., from independent spectroscopic measurements or from knowledge of the quasar population as a whole) are incorporated in the MCF analysis. Probing line-to-continuum time delays on subsampling timescales is unreliable because photometry cannot disentangle line and continuum light curves on short timescales; an exception to this rule is in cases where the lagging signal dominates the flux in the band (Chelouche & Zucker 2013; Chelouche 2013), provided the light curves are well sampled.

Time series whose sampling pattern exhibits many different characteristic timescales lead to considerable scatter in individual lag measurements, especially on timescales comparable to the sampling periods and their harmonics. Here, too, it is possible to reject nonphysical solutions by employing priors on $\alpha$ so that a statistical measurement of the median lag, in properly defined quasar samples, provides a good estimator for the true lag. The degree to which such filtering can be effectively used depends on the strength of the emission feature probed. Generally, as with spectroscopic reverberation mapping campaigns, regular observing patterns should be sought to reduce the number of sampling timescales in the problem.

Good redshift determination leads to more robust lag measurement on a case-by-case basis because preferable filter combinations may be reliably selected and meaningful priors on $\alpha$ may be set. This also exemplifies the advantage of having follow-up (single-epoch) spectroscopy, which can secure the object identification and precisely determine its redshift. Moreover, spectroscopic follow-up can determine the velocity dispersion of the relevant emission lines, thereby providing critical information required for SMBH mass estimates.

We find that, even under ideal observing conditions, the recovered median lag may overestimate the true lag, i.e., the centroid of the line transfer function, by $\lesssim 20\%$. This is a direct consequence of the inability of photometric data to disentangle line and continuum light curves on short timescales, whose sum makes up the total signal. The exact value of the bias depends primarily on the line transfer function, which is rather loosely constrained by observations: for transfer functions with a large amplitude at zero time delays (e.g., when line emissivity close to our sightline is considerable, as in edge-on configurations) the bias is more significant. Consequently, the bias is smaller for face-on systems, which may be more relevant to type-I quasars (Maiolino et al. 2001). This implies that some statistical information concerning the line transfer function may be obtained using photometric means.

Our simulations indicate that photometric reverberation mapping is especially advantageous when large samples are
concerned, as the median time delay is less susceptible to sampling-induced noise, redshift uncertainties, and the underlying properties of the power-density spectrum of the quasar. Therefore, good control of systematic effects is essential, especially as far as redshift determination is concerned. Provided large-enough samples exist, statistical averaging would lead to BLR size–luminosity relations with unprecedented accuracy for large-enough samples exist, statistical averaging would lead to BLR size–luminosity relations with unprecedented accuracy for low S/N (either low source flux or small contribution of the emission line to the flux in the band), there is a tendency for a biased lag measurement, by up to 60%; see the second column of Figure 11. There is also a tendency to somewhat underestimate the lag, by typically 30%, in cases where it is comparable to the lifetime of the experiment. Discarding those regions near the envelope’s rims, the typical median lag determination is at the ∼±20% level for the Mg II line out to z ∼ 2.5. Taking into account the quasar luminosity function and the LSST selection criteria, some 5 × 10^4 lags may be determined over the LSST lifetime (see also Table 2), suggesting that Mg II may have a crucial role in constructing more reliable single-epoch BH mass estimations by cross-calibrating scaling relations used at different redshift ranges.

Our calculations imply that the expected scatter in individual Mg II λ2799 lag measurements is, typically, ∼40%, with a tendency for an increased scatter under low S/N conditions (see the middle panels of Figure 12). As noted above, these statistics were obtained after screening against erroneous α-solutions that, typically, results in only ∼10% of the objects being used (right panel of Figure 12). Nevertheless, there are regions in the parameter space (z < 1.2 and 45 < log(L_{opt}) < 46) that are characterized by good S/N and well-sampled light curves with respect to the BLR extent, for which ≥30% of the sources lead to robust solutions. We note that it may be possible to further narrow the scatter in individual measurements by testing the robustness of the solutions (Chelouche & Zucker 2013). This, however, is beyond the scope of the present work due to the prohibitively long computation time involved.

Reducing the exposure time per visit to 15 s instead of 60 s shrinks the parameter space over which reliable Mg II lag measurements are obtained while maintaining similar lag statistics in regions of the parameter space where such measurements are possible. Specifically, with the S/N reduced by a factor of two,

![Figure 12](https://example.com/figure12.png)

**Figure 12.** Lag determination for the Mg II λ2799 emission line in the luminosity–redshift plane. The top row corresponds to a 60 s exposure (obtained by combining four exposures of 15 s each, taken over an interval of 30 minutes), whereas the bottom row assumes 15 s exposure visits. Only objects for which α is recovered to within ±40% of the input value are considered in the presented statistics, which results in only a fraction of all objects being used. The blue-to-red colors (see color bar) mark the median output-to-input (O/I) lag ratio (left column) in each redshift–luminosity bin, the standard deviation (shown in the middle column as 10^{STD[log(O/I)]}, and the fraction of objects that pass our α-selection criterion (see the text; right column). DDF sampling is assumed in all cases.

(A color version of this figure is available in the online journal.)

| ID | UNS (60 s) | DDF^a (60 s) | DDF^a (15 s) |
|----|------------|--------------|--------------|
| Lyα | 64000 | 95000 | 7000 |
| Si IV λ1397 | 150 | 300 | 30 |
| Cr IV λ1549 | 8000 | 16000 | 1200 |
| CuII λ1909 | 21000 | 45000 | 6500 |
| Mg II λ2799 | 46000 | 48000 | 4300 |
| Hγ | 2000 | 6000 | 300 |
| Fe II λ4564^b | 9400 | 16000 | 900 |
| Hδ | 47000 | 110000 | 19000 |
| Fe II λ5305^b | 6500 | 27000 | 4800 |
| He I λ5877 | 0 | 700 | 40 |
| Hα | 28000 | 73000 | 25000 |
| Balmer cont. | 310000 | 310000 | 50000 |
| Paschen cont. | 14000 | 15000 | 4000 |

Total for all BLR features: 560000 760000 120000

**Table 2**

**Notes.** Number of time delays measured for individual emission features in quasars within the LSST footprint for DDF (using 15 s and 60 s exposure times) and UNS sampling (60 s exposure time). Features for which >100 lag measurements may be obtained are included in the table, as are measurements for which the measured lag agrees to better than 0.5 dex with the input value. Typical uncertainties on the quoted figures are at the 10% level given the model assumptions (but may be on the order of unity for those transitions with ≲100 detection statistics).

^a Full coverage of the LSST footprint by DDFs exceeds the LSST resources (see the text).

^b Approximate wavelengths are quoted for blends (Table 1).

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19 See http://www.lsst.org/files/docs/sciencebook/SB_2.pdf.
Mg II lag measurements are feasible up to a redshift of $\sim 1.7$ instead of 2.5, and only for the brighter sources, which reduces the number of reliable lag measurements by an order of magnitude for this transition (Table 2).

Figure 13 shows an analysis similar to the above for several additional major emission lines in quasar spectra and examines some of their statistical properties using DDF and UNS samplings (60 s exposure times are assumed throughout). Clearly, there exists a nonnegligible region in the redshift–luminosity plane in which time delays may be determined with good accuracy. For example, in low-luminosity, low-$z$ quasars, the lag–luminosity relation for Hα may be probed over $\sim 2$ orders of magnitude in luminosity with a total expected number of Hα lag measurements of $\geq 10^5$ (Table 2). For the C IV $\lambda 1549$ emission line, the parameter range probed extends to lower luminosities than probed by Kaspi et al. (2007) and is dominated by radio-quiet objects rather than radio-loud ones, as in their work. The small blue bump (Balmer continuum) has a similar role to the Mg II line in the sense that its lag may be quantified over a broad range of quasar luminosity and redshift. Obviously, this spectral feature is of limited use for directly estimating BH masses because there is no kinematic information associated with it. Interestingly, we find that Lyα lag measurements at the peak of quasar activity are facilitated by the effectively narrow and spiky throughput curve of the $u$ band and are feasible out to $z \sim 3$.

The fact that the lags of different emission lines may be determined in overlapping luminosity–redshift ranges means that a more reliable BLR-size ladder (in analogy with the cosmological distance ladder) may be obtained using LSST, allowing the cross-calibration of different prescriptions for SMBH mass estimation over cosmic time. In this respect, it is interesting to note that for an exponentially small (but finite) fraction of all quasars, simultaneous lag determination for several transitions may be possible. The number statistics in this case is less secure and may depend on the exponential tails of currently poorly determined quasar property distributions (e.g., the fraction of objects with extreme variability amplitude). Current predictions for the statistics of multi-time-lag measurements within the LSST footprint for different levels of accuracy and for UNS and DDF sampling (for the latter either 15 s or 60 s exposure times are considered) are shown in Figure 14. Clearly, an exponentially small (but finite) number of sources will have up to five time delays simultaneously determined. The number of such sources is very sensitive to sampling: e.g., the number of quasars with five lag measurements drops by more than an order of magnitude when switching from DDF to UNS sampling. The S/N has a smaller effect on the relative number of objects with multi-time-delay measurements.

Lastly, we consider the total number of reliable time-lag detections as a function of the number of DDFs covered assuming each field consumes 1% of the LSST resources. $^{20}$ The total sky coverage in $N$ DDFs is then $\approx 9N$ deg$^2$, and the remaining UNS coverage is then $\approx 2 \times 10^4(1 - N/100)$ deg$^2$. The total number of time-lag measurements as a function of $N$ is shown in the bottom-right panel of Figure 14, demonstrating that shear number statistics prefers UNS over DDF sampling with up to $\sim 500,000$ time-lag measurements possible for full UNS coverage of the sky. Note, however, that the sparser UNS will result in the loss of short time-delay information concerning, e.g., accretion disks or high-ionization optical emission lines, such as HeI $\lambda 5877$ (see Table 2), especially in low-$z$, low-luminosity sources.

$^{20}$ Assuming our definition of a DDF, each field, observed daily, will require four 15 s exposures, each with an overhead of 2 s of reading time, in six bands. Slewing between adjacent fields will take an additional 5 s. Together, this amounts to $\sim 400$ s per DDF, which is on the order of 1% of a full observing night.
Figure 14. Lag determination statistics with the LSST. Upper left panel shows the number of objects within the LSST footprint for which a given number of emission-line time delays may be simultaneously determined (using six filters a maximum of five lags are measurable using the formalism adopted here). A total exposure time of 60 s per visit is assumed and DDF sampling is considered. Different colors correspond to different lag measurement accuracies; for example, the blue line includes all objects for which the ratio between the absolute difference of the measured-to-input lag and the input lag is $< 0.7$ (see the legend). Upper right panel is for UNS sampling, whereas the lower left panel assumes DDF sampling but with a 15 s exposure time per visit. The bottom right panel is the total number of time-delay measurements as a function of the number of DDFs surveyed (see the text).

(A color version of this figure is available in the online journal.)

5. SUMMARY

We show that large time-domain photometric surveys, such as the LSST, are expected to transform the field of AGN reverberation mapping by increasing the number of objects with measured time delays by several orders of magnitude and by including sources at the epoch of peak quasar activity, at $z \sim 2$. Specifically, the LSST is expected to yield a total of $\gtrsim 10^5$ time-delay measurements, including all major emission lines, blends, and pseudocontinuum features out to $z \sim 3$. For a given exposure time per visit and finite survey resources, covering a larger area of the sky at the expense of sampling would result in additional time-lag measurements while inhibiting the study of short timescale phenomena. Spectroscopic follow-up of photometric quasars will lead to improved BLR lag-determination via the incorporation of priors in the MCF analysis. It will also facilitate BH mass estimations, thereby improving our understanding of BH demographics at high $z$ with implications for galaxy evolution, BH seeds, and gravitational wave detection.

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