Strobed imaging as a method for the determination and diagnosis of local seeing

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ABSTRACT
The image quality budget of many telescopes can have substantial contributions from local seeing, both ‘mirror’ and ‘dome’, which arise from turbulence and temperature variations that are difficult to quantify, measure directly, and ameliorate. We describe a method to determine the ‘local’ seeing degradation due to wavefront perturbations within the final few metres of the optical path from celestial sources to the focal plane of a ground-based telescope, using the primary instrument and along the same path taken by light from celestial sources. The concept involves placing strobed emitters along the light path to produce images on the main focal plane that ‘freeze’ different realizations of index perturbations. This method has the advantage of measuring directly the image motion and scintillation imparted by the dynamic spatial and temporal structure of local perturbations in the index of refraction along the light path, with a clean separation from seeing induced in the atmosphere above the dome. The strobed-source approach allows for rapid image motion and scintillation to be measured directly on the focal plane, even for large-aperture telescopes with wide-field instruments and slow shutters, such as that being constructed for the Rubin Observatory. A conceptual design is presented that uses the ‘guider’ CCDs in the Rubin telescope focal plane to make local-seeing measurements on demand, perhaps even during science exposures.

Key words: atmospheric effects – instrumentation: adaptive optics – telescopes.

1 INTRODUCTION
Ground-based optical and infrared telescopes suffer from sources of image quality degradation that typically preclude achieving the diffraction limit of $\theta \sim \lambda/D$. For $D = 10$ m class telescopes at optical wavelengths ($\lambda \sim 500$ nm), the typical achieved full width at half-maximum (FWHM) of 1 arcsec for a celestial point source (absent adaptive optics correction) is about 100 times worse than the diffraction limit.

A variety of factors contribute to this image degradation, including the following:

(i) index of refraction variations in the upper atmosphere;
(ii) ‘ground layer’ or ‘boundary layer’ turbulence due to the boundary condition of zero wind velocity at the Earth’s surface;
(iii) perturbations to laminar airflow due to local topography and structures;
(iv) turbulence within the enclosure, due to ambient and driven airflow through the slit and vents in the dome;
(v) thermally driven air currents due to power dissipation on the telescope top end, and other locations;
(vi) turbulence and thermal currents in the vicinity of the primary mirror due to temperature differences between the mirror and the adjacent air;
(vii) tracking errors and vibrations in the mirror support systems;
(viii) wind-driven oscillations and motions of the mirror support systems; and
(ix) quasi-static optical aberrations in the optical system.

The performance optimization of modern ground-based telescopes entails an iterative assessment of the image quality budget of the system and the suppression of the dominant sources of image degradation. Image quality is a major figure of merit for most observatories, and strongly determines the scientific utility of the system. The past few decades have seen considerable progress in both methodologies and understanding of this process, including active optical systems to adjust for quasi-static aberrations and adaptive optical systems to compensate for wavefront distortions due to the atmosphere. Reviews of astronomical seeing are given in Hickson (2014) and Hardy (1998). Papers that pertain specifically to the management of ‘local seeing’, arising from within the telescope enclosure, include Woolf (1979), Zago (1997), and Racine et al. (1991).

The design process for next-generation large-aperture ground-based telescopes (Rubin, GMT, TMT) typically includes detailed computational fluid dynamics simulations of airflow and turbulence within the enclosure (Sebag & Vogiatzis 2014; Vogiatzis et al. 2018a; Vogiatzis, Thompson & Roberts 2018b; Conane et al. 2019). The designers use this information as they strive to minimize local-seeing effects with appropriate systems engineering design choices.

Once these systems are built, we need to learn how to operate them, including airflow and thermal management within the enclosure, so as to maximize their scientific impact. An interesting machine-learning approach to image quality optimization, including the management of dome ventilation, is presented in Gilda et al. (2021).
intrafocal and extrafocal images of the pupil. These corner sensors provide displaced wavefront sensors, shown with black and white fill, that produce sensors. Each of the four corners contains a pair of guider CCDs with 10 Hz Layout of the focal plane for the Rubin Observatory. The imager Fig. 1. The off-axis guiders and wavefront sensors that occupy the need to identify and address in-dome sources of image degradation.

The process of identifying and suppressing sources of image degradation from within the telescope dome requires the discrimination between wavefront errors that are introduced by the upper atmosphere and the perturbations along the final few metres of the optical path, within the telescope dome. The illumination of the main imaging instrument with strobed collimated light is a potential method for achieving this discrimination. The comparison between centroid motion of the strobed artificial image, the FWHM of the images of stars on the focal plane, and measurements from external systems such as a differential image motion monitor (DIMM) will allow for the separation of various contributions to image degradation.

One major motivation for this paper is the upcoming commissioning phase for the Rubin Observatory (Ivezić et al. 2019), and the need to identify and address in-dome sources of image degradation. The layout of the Rubin focal plane (Riot et al. 2014) is shown in Fig. 1. The off-axis guiders and wavefront sensors that occupy the four corners of the focal plane present an opportunity to project strobed artificial stars for diagnostic purposes.

This paper presents the principle and possible implementations of strobed imaging as a method for determining local seeing. The examples are presented mainly in the context of the Rubin system, but are more broadly applicable. The advantage of this method over alternatives is the ability to probe directly the fluctuations in intensity and image centroid position due to in-dome optical path perturbations along the light path of the telescope. The short-pulse light allows us to take many realizations of the ‘frozen’ atmosphere, even with an instrument shutter that is slow compared to the millisecond characteristic time-scale.

2 PHENOMENOLOGY

Seeing produces both ray deflection and scintillation. The wavefront propagating through the system from a point source at infinity suffers from perturbations in both angle of arrival and surface brightness. The exposure-time-averaged intensity distribution on the focal plane determines the point spread function (PSF). The ratio of angular deflection to scintillation in an arriving wavefront is an indicator of where the wavefront degradation is occurring along the line of sight to the source.

The small-angle scattering and refraction that produce scintillation in a plane wave require a considerable propagation distance to accumulate enough multipath interference to generate substantial fluctuations in surface brightness. If a source is moved a distance $R$ into a scintillating medium, the intensity variance in the arriving flux increases as $R^6$. Moreover, the characteristic transverse spatial scale of scintillation is the geometric mean of the wavelength $\lambda$ and the distance $R$ to the index perturbation. This is the Fresnel length, $F = \sqrt{2R}$. For optical wavelengths and nearby scattering screens, $F(R = 20\text{ m}) = 3\text{ mm}$ and $F(R = 1\text{ m}) = 700\mu\text{m}$. Attempting to measure scintillation over apertures larger than $F$ will dilute the signature, due to ‘aperture averaging’. Another potential source of concern for near-field scintillation is whether the range-dependent Fresnel length-scale is smaller than the inner scale of the turbulent eddies. The phase shifts induced by optical path-length differences are wavelength-dependent, so scintillation is best probed using short wavelengths, with an optically-narrow-band source. Measuring the transverse spatial scale of scintillation to infer the distance to the perturbation is the principle behind the Full Aperture Scintillation Sensor (FASS) seeing diagnostic system (Guesalaga et al. 2021). The temporal coherence time-scale is another diagnostic observable, but is not typically exploited.

Beam deflection, by comparison, is not as suppressed by short-distance effects. Any wavefront tilt introduced in a plane wave produces the same image motion on the focal plane, regardless of where (upstream of the pupil) it arises. This suggests that image motion might be more effective for diagnosing local seeing than attempting to measure scintillation. Also, measuring wavefront tilt is a more direct path to determining the PSF on the focal plane, as opposed to inferring the refractive index structure constant $C_2^2(\bm{x}, y, z)$ from sparsely sampled data, obtained outside the beam of interest, and attempting to use that to compute beam deflection and image motion statistics. The focal plane centroid displacement due to local seeing has two contributions: one from before the pupil and the other from after the pupil where the beam is converging. An illustration of the complex nature of ‘dome seeing’ comes from comparing the effect of a screen of index of refraction perturbations placed above the top end of the telescope with one that lies between the primary and secondary mirrors. If the seeing layer is above the top end, each light ray passes through it once. The Rubin telescope is a three-mirror configuration, and if the seeing layer is instead placed between the mirrors, then each light ray passes through it not once but four times before striking the focal plane.

The focusing optical system of the telescope converts the angle of arrival at the pupil into focal plane position. Absent any perturbations beyond the pupil or optical aberrations, the rms fluctuations in angle of arrival at the pupil convert directly into the rms width of the PSF, with the conversion factor being the focal length of the system.

After passing through the telescope pupil, the rays start to converge, and from the seeing perspective, two things happen. First, the beamwidth shrinks, and so for a fixed transverse gradient in refractive index, the rays experience smaller differences in deflection. Secondly, the lever arm to convert from angular deflection into centroid displacement is reduced as the converging beam approaches the focal plane. An index variation just above the focal plane does not introduce much centroid motion at all. These effects combine to produce (Wheelon 2001) a weighting of $z^{-3}$ for how index perturbations induce centroid motion in a converging beam, where $z$ is the optical path distance upstream from the focal plane.

We can now place this in a more quantitative framework. If the index perturbations above and below the pupil are uncorrelated, the two resulting deflection variances add. For a sub-pupil of size $D$, a focal length $F$, a path-integrated distance $Z_p$ from the focal plane to
the pupil, a collimated source placed at a distance \( Z \) from the focal plane, and a spatially uniform \( C_n^2 \) index perturbation structure within the enclosure, the variance in image position is given by (Wheelon 2001)

\[
\langle p^2 \rangle = C_n^2 D^{-1/3} [1.092 Z_p^3 + 2.914 (Z_i - Z_p) F^2].
\]

The \( z \) coordinate in equation (1) runs from the focal plane outwards along the multireflected optical path traversed by a ray, and is not the vertical elevation in the dome. The first term in square brackets applies to the converging beam after the pupil, with a \( Z^3 \) path dependence that takes into account both the smaller turbulence scales spanned near the focus and the shorter level arm for angular deflections to produce image motion. The second term in square brackets arises from the column of air between the pupil and the output of the transmitting collimator, and depends only on the integrated path traversed by the collimated beam. The image motion does not depend on where the collimated light is deflected.

The temporal power spectrum of these centroid motions is dictated by the characteristic time-scale \( \tau \sim D_{\text{PVcal}} v \), where \( D_{\text{PVcal}} \) is the isoplanatic length-scale and \( v \) is the transverse wind speed.

### 3 MEASUREMENT OPTIONS

Once a telescope goes into operation, a variety of methods have been used to assess the local-seeing contributions within the telescope enclosure (Woolf 1979; Racine et al. 1991; Zago 1997; Lai et al. 2019). This work to date has predominantly involved indirect methods, such as (1) measuring the physical driving terms, through dome turbulence monitors or microthermometry of the ambient air, (2) correlating the delivered image FWHM with physical parameters such as mirror-to-ambient temperature differences, while attempting to distinguish local seeing from upper atmospheric effects, and (3) looking out through the slit with diagnostic instruments such as a DIMM, and comparing the observed image motion and scintillation statistics to those obtained from an identical system operated outside the dome. Lai et al. (2019) and Bustos & Tokovinin (2018) describe direct optical determinations of turbulence within a dome, but those measurements are not carried out along the same light path that is traversed by celestial sources and can miss, for example, the contribution from mirror seeing. Bridgeland & Jenkins (1997) describe time-resolved thermometry above the mirror of the William Herschel Telescope to assess mirror seeing, but converting from temperature gradients at a few points into a prediction of image degradation is difficult.

While much has been learned from the techniques described above, they are indirect methods. The ideal situation would be to monitor the local image quality perturbations along the same light path traversed by the celestial sources of interest, since this measures exactly what we care about. Using the primary astronomical instrument to assess local seeing is difficult for a number of reasons. Using celestial sources requires that we distinguish between upper atmosphere and local contributions to seeing. Another factor that limits the use of the main instrument is incompatibility of characteristic time-scales. DIMMs operate with millisecond exposure times, since in the frozen-screen approximation, the characteristic time-scale is \( \tau \sim r_c / V_{\text{wind}} \), where \( r_c \) is the Fried parameter, i.e. the length-scale over which induced phase errors are coherent. The resulting coherence time-scale is of the order of tens of milliseconds. Exposures longer than this average over the image motion we wish to characterize. The shutters on large instruments do not typically move fast enough to take images this short, even if illuminated from a collimated light source within the dome.

This paper presents a conceptual solution to these limitations, with a scheme that could allow the use of the primary instrument to diagnose local-seeing contributions.

### 4 CONCEPTUAL DESIGNS

We seek a configuration that can monitor image motion due to perturbations along the light path from the dome interior (or perhaps from just outside the enclosure slit) through the telescope and instrument optics and on to the main focal plane. Figs 2 and 3 show two implementations of the proposed concept that accomplishes this. Differential image motion is determined by looking at the variance in the distances between the centroids of the PSFs of the images of each collimated beam. This difference between pairs is a vector quantity, which allows for the computation of the image motion variance in \( \chi \).
The illuminated footprint on the focal plane is determined by the divergence of the laser emitter.

Scintillation conserves the energy in the beam that reaches the focal plane; it just rearranges where the photons land. Pulse-to-pulse variations in the light source can be compensated by looking at the excess variance in the surface brightness of the illuminated area, after normalizing each image to a common integrated flux.

4.1 Engineering parameter choices

In this section, we explore some of the factors that influence engineering design choices.

4.1.1 Optical wavelength and passband

The concept is to take a succession of images, each of which ‘freezes’ the instantaneous structure of the optical index of refraction along the various propagation paths. Shorter pulses allow for sensitivity to higher temporal frequencies in the transverse direction. The characteristic seeing correlation time $\tau$ can be as short as millisecond. Exposures longer than this smear out the image motion, so we seek a system capable of producing millisecond flashes. This is not technically challenging. The strobe duration is the effective exposure time, with a frame rate dictated by the shutter cycling and readout time of the system. We stress that the simultaneous-dual-slit sliding-curtain mode of obtaining short exposures on large cameras is inappropriate for this method. The shutter should be fully open before the strobe is triggered, to ensure that all the transient light makes it to the focal plane. The ability to generate varying durations of illumination ideally at a fixed total photon dose) will allow us to measure the correlation time of the local seeing, by mapping out $\sigma^2$ versus flash duration. It seems plausible that the power spectrum of image motion, probed by illuminating with pulses of varying duration, is different for mirror seeing versus convection in the upper parts of the dome, for example. This might help in discriminating the dominant contribution to local seeing. The exploration of this speculation could involve driving exaggerated signatures of the various local-seeing components, through intentionally large changes in ventilation and heat exchange.

4.1.2 Exposure times and optical pulse duration

The concept is to take a succession of images, each of which ‘freezes’ the instantaneous structure of the optical index of refraction along the various propagation paths. Shorter pulses allow for sensitivity to higher temporal frequencies in the transverse direction. The characteristic seeing correlation time $\tau$ can be as short as millisecond. Exposures longer than this smear out the image motion, so we seek a system capable of producing millisecond flashes. This is not technically challenging. The strobe duration is the effective exposure time, with a frame rate dictated by the shutter cycling and readout time of the system. We stress that the simultaneous-dual-slit sliding-curtain mode of obtaining short exposures on large cameras is inappropriate for this method. The shutter should be fully open before the strobe is triggered, to ensure that all the transient light makes it to the focal plane. The ability to generate varying durations of illumination ideally at a fixed total photon dose) will allow us to measure the correlation time of the local seeing, by mapping out $\sigma^2$ versus flash duration. It seems plausible that the power spectrum of image motion, probed by illuminating with pulses of varying duration, is different for mirror seeing versus convection in the upper parts of the dome, for example. This might help in discriminating the dominant contribution to local seeing. The exploration of this speculation could involve driving exaggerated signatures of the various local-seeing components, through intentionally large changes in ventilation and heat exchange.

4.1.3 Optical pulse energy and peak power

If we require 100 000 detected photoelectrons per pulse per PSF in the focal plane to achieve good statistics, after accounting for mirror reflections and detector quantum efficiency (QE) losses, we need of the order of $10^6$ collimated emitted photons per pulse, independent of pulse duration. As shown below, a reasonable collimator aperture is 100 mm, from which we desire a beam divergence of under an arcsecond. The $(A/\Omega)_{\text{coll}}$ product for the emitted beam is $\pi(0.1/2)^2 \times (5 \times 10^{-6})^2 = 2 \times 10^{-13}$ m$^2$ sr.

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The deflection of the rays is effectively achromatic, since the wavelength dependence of the index of air is small. This has the advantage that we can operate the image motion monitor in any wavelength or range of wavelengths that is advantageous. If the system performance is diffraction limited, there is merit to running sources at short wavelengths, with appropriate attention to ultraviolet safety issues.

For the scintillation monitor, there is merit to running sources at different wavelengths, to assess directly the wavelength dependence of the scintillation along the path. In general, the amplitude fluctuations are larger at shorter wavelengths.

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If we use a high-power LED, with a 5 mm × 5 mm source emitting π sr, the radiance is \((A−Ω)_{\text{LED}} \sim 8 \times 10^{-5} \text{ m}^2 \text{ sr}\). The LED-to-collimated-beam efficiency ratio is of the order of 10^{-9}.

This implies that we need to send a pulse of the order of 10^{15} photons down the fibre, to illuminate a few-μm pinhole at the collimator focus. For 500 nm light with 3 × 10^{-19} J photon^{-1}, this corresponds to sending 0.3 mJ per pulse into the fibre. Packing all these photons into a 1 ms pulse duration, the shortest we are likely to need, requires a modest peak optical power of 0.3 W.

Even feeding 10 or more fibres, this power level should be readily achievable with a xenon flash lamp or a pulsed LED. Driving LEDs in this regime is not challenging. A comparison of xenon flash lamps versus pulse-driven LED illuminators is provided by Wilson et al. (2015).

For the scintillation monitor, the beam footprint spans a focal plane area that is determined by the source’s beam divergence. A low-divergence laser diode typically has a divergence of 0.25 mrad, for an illuminated diameter on the focal plane of just under an arcminute. This encompasses 2.83 × 10^{3} arcsec^2 or 70 Kpixels on the Rubin focal plane. The energy impinging on the sensor for a 1 mW emitter is then roughly 1.5 μW pixel^{-1} or 10^{12} photons s^{-1} pixel^{-1}. If beam divergence is increased so that the beam spans the entire 3.5 × 3.5 focal plane, with 3.5 Gpixels, the flux per pixel becomes a more manageable 10^6 photons pixel^{-1} s^{-1} mW^{-1} emitted from the source. A 1 ms strobed full-field image would produce around 1000 photons pixel^{-1} for a very modest 1 mW laser diode, which seems adequate to determine scintillation by looking for excess variance in flux levels.

### 4.1.4 Collimator for image motion

The uncertainty in centroid position is well represented by \(\sigma_{\text{centroid}} = \text{FWHM}/(S/N)\), where the PSF is characterized by a width given by the FWHM and S/N is the Poisson-limited signal-to-noise ratio for the image of the source. Small PSFs and high photon S/N are favourable for measuring centroid displacements. To address the regime of interest, we should have FWHM < 1 arcsec. This requires that the collimated projector produce a beam with a divergence below 5 μrad. At the wavelengths of interest, the diffraction limit implies a collimator aperture \(D\) of at least 100 mm. A diffraction-limited collimator produces a centroid uncertainty \(\sigma_{\text{centroid}}\) that scales as \(D^{-1}\), at fixed photon flux.

Trading against this is aperture averaging of the beam deflection. The rms image motion (the signal of interest, see equation 1) scales as \(D^{-1/6}\).

These scalings with collimator aperture indicate that the diffraction factor wins, with the S/N for centroid motion scaling as \(D^{5/6}\), at fixed photon dose. This holds as long as larger collimator apertures produce smaller beam divergence, i.e. while collimator diffraction determines the FWHM on the focal plane.

The availability of high-quality achromatic reflectors in the 8–12 inch aperture range suggests that size might be a good choice for the collimators. Larger optics become increasingly unwieldy and expensive.

### 4.1.5 Scintillation source

The scintillation measurement favours a small aperture emitter, with \(D < \sqrt{\lambda L}\), where \(L\) is the optical path-length from the source to the focal plane. We can adjust both the size and the divergence of the source to meet different goals. A source with a diameter at the pupil of \(D_p\) and divergence of \(\theta = D_p/F\), where \(F\) is the focal length of the main telescope, will produce a spot on the focal plane of the same size, \(D_p\). This means the beam size stays essentially constant as it propagates through the focusing part of the optical system. That aside, mm beam sizes are readily available for low-divergence laser sources. As long as the speckle pattern arising from the source is temporally stable, frame subtraction of successive strobed images will suppress excess variance arising on the focal plane due to a fixed laser speckle.

### 4.2 Signal-to-noise and detectability estimates

Since the different contributions to the PSF are uncorrelated, their effects add in quadrature. The best-case seeing we expect at the Cerro Pachon site for Rubin is a PSF FWHM of the order of 0.6 arcsec. In order for local-seeing effects to have a significant deleterious impact on the PSF, the displacements of rays on the Rubin focal plane due to local seeing would have to exceed 0.3 arcsec rms.

With a local projector of the type shown in Fig. 2, a beam diameter of \(D = 100\) mm at optical wavelengths should produce a diffraction-limited spot with FWHM \(~\lambda D = 1\) arcsec. The uncertainty in the centroid separation for two beams is then \(\Delta \theta = \sqrt{2}\text{FWHM}/(S/N)\), where FWHM is the angular width of the image and S/N is the signal-to-noise ratio for each individual PSF. As long as the S/N exceeds 20, differential centroid motion of less than 0.1 arcsec is measurable. The light intensity levels described above far exceed the few hundred photons needed to achieve this, and so we conclude that the image displacements of interest should be readily detectable. The plate scale of the Rubin system, at 0.2 arcsec pixel^{-1}, is well suited to this determination of differential centroid motion.

### 5 OPERATIONAL CONCEPTS

The simplest implementation of strobed-source wavefront monitoring would involve the following sequence:

1. Open the instrument’s main shutter.
2. Enable either the image motion device or the scintillation source, or both.
3. Transmit optical pulses.
4. Close the instrument shutter.
5. Read out the focal plane array.
6. Repeat multiple times.
7. Compute centroids and aperture photometry, and compute standard statistics on image motion and scintillation. The scintillation analysis will benefit from using frame subtraction to suppress any quasi-static speckle pattern from the coherent source.

More sophisticated implementations could include constant-readout or shuttered row shifts with the shutter open, imaging a succession of multiple illumination strobes. This would generate multiple PSF realizations in each image, allowing for high data collection efficiency. A cruder version of this would entail offsetting the telescope, with the shutter open, between multiple strobes. One could extend this concept to multiple pinholes in the collimator focal plane along with multiple wedged apertures in its output pupil, which would allow one to do tomography as described in Hickson et al. (2019) and Beltramo-Martin et al. (2019).

### 5.1 Rubin guiders and wavefront sensors as local-seeing monitors

As shown in Fig. 1, each of the four corners of the Rubin Observatory focal plane contains 4K × 4K ‘guider’ CCDs, capable of reading out a sub-array at 10 Hz, as well as vertically offset wavefront sensors. Whether closed loop guiding will be implemented for the short (15–30 s) exposures anticipated for the Rubin system is an open question.
which is to be determined during the commissioning phase. The four
guiders lie 1.43 off the telescope boresight. These four detectors
could be used in conjunction with strobed sources to obtain high-
data-rate statistics on image motion, using a strobed reverse DIMM
as shown in Fig. 2. A pair of spatially separated beams could be
projected into the pupil, using a collimator mounted on the top end
of the telescope. An average off-axis angle of 1.43 for the two beams,
and the beams diverging from each other by a angle that spans the
guider (a few arcminutes), would provide a pair of in-focus centroids
on the guider chip. The collimated projector for this could be mounted
on the top end of the telescope in an area obscured by the camera
system and the secondary mirror. As long as the beams strike the
primary mirror at the correct angle and are unobscured, they will
land on the guider.

Another option would be to flash-illuminate the wavefront sensors
with one or more displaced beams, either instead of or in addition to
the guider chips. Since the wavefront sensors are only read out along
with the science frame, small tweaks of beam directions between
strobos could generate multiple realizations during a single science
image. Each of the Rubin wavefront sensors is displaced by 2 mm
from the nominal focus of the Rubin telescope. The outer diameter
of the full-pupil ‘doughnut’ on each sensor therefore spans 1.67 mm,
and this corresponds to a distance of 8.5 m at the input pupil. A
cylindrical collimated beam of diameter \( D \) entering the pupil will
therefore span a distance \( D_{\text{FWFS}} = 1.67 \text{ mm} \times (D/8.5 \text{ m}) = 20 \mu \text{m} \times (D/0.1 \text{ m}) = 2 \text{ pixels} \times (D/0.1 \text{ m}) \) on the wavefront sensor.
This should readily allow for the extraction of high-S/N centroids
from the resulting spots, even for a collimated illumination beam
100 mm in diameter.

This illuminate-the-focal-plane-from-the-top-end configuration
would allow for local-seeing diagnostics to be interleaved with
science observations, with no overhead for switchover. A more
sporty version would operate the strobed source even during science
integrations. While careful attention to stray and scattered light
and ghosting would be important, the strobed collimated artificial
source must have a brightness comparable to that of the guide stars
being contemplated, and should not produce any more scattered
background light than those celestial objects. Tracking-rotation of
the instrument can be compensated by rotating the collimator’s exit
pupil mask about the optical axis of the telescope, to continuously
direct the beam(s) to one or more guider or wavefront CCDs.

6 DISCUSSION AND NEXT STEPS
Strobed imaging for capturing transient events has a long history,
from the legendary work of Edgerton and his contemporaries to
modern studies of short-time-scale phenomena. Extensions of the
idea presented here, namely the use of strobed imaging to capture
local seeing, could include mast-mounted or drone-borne strobed
sources, to extend the method to investigate the boundary layer seeing
outside the dome.

The calibration plan for the Rubin Observatory includes (Coughlin
et al. 2016) a collimated beam projector for monochromatic flux
calibration. That device could readily be adapted to the scheme shown
in Fig. 2.

The explicit measurement of image motion, with the correct
weighting versus location along the line of sight, can be used to
explore the most advantageous ventilation configuration and thermal
management in the dome, without having to discriminate upper
atmosphere seeing or inferring image quality metrics from indirect
measurements of turbulence or temperatures. Taken in conjunction
with the determination of scintillation-induced variance as a function
of flash duration and wavelength, these are potentially useful tools
for characterizing the structure of the index of refraction within the
enclosure, along the light path of primary interest.

The airflow within a telescope enclosure strongly depends on the
wind speed as well as azimuth difference between the wind direction
and the enclosure slit. Wind-driven motion of the optical system
depends on many factors, including wind speed, relative direction,
and telescope elevation. An understanding of how these conditions
influence local seeing could inform image-quality-optimized and
condition-dependent scheduling of observations.

At a minimum, with a projector mounted on the enclosure, the
techniques described here should allow for daytime engineering tests
of thermal and ventilation management, using a direct comparison
of local-seeing diagnostic data to system configuration and operational
parameters. With a projector mounted on the telescope, this could be
extended to night-time tests with the slit open, perhaps even during
science operations.

Making the most of the substantial ongoing investments in ground-
based telescopes is a high priority. Given how strongly the delivered
image quality impacts scientific performance, we need to identify
and minimize local sources of image degradation. Strobed imaging
provides one potential means for doing so.

6.1 Next steps
We have initiated a staged programme to implement the ideas
presented here. Our initial tests will be conducted with a strobed LED
source at the focus of a collimated beam projector, to illuminate a
long-focal-length DIMM-like imaging system that produces multiple
images of the source on a DSLR camera. We will use the remote-
control flash function of the DSLR camera to trigger the strobed
LED source while the camera shutter is open. In a laboratory setting,
we can introduce turbulence into the beam between the telescopes.
Measuring the standard deviation of the separation between image
centroids as a function of wavefront distortion will serve as an initial
test bed for hardware and software development. This will also allow
us to validate the S/N estimates presented above, as a function of
source intensity.

Once the system is mature, we will install the strobed projector
to illuminate the Rubin auxiliary telescope, a 1.2 m diameter outrigger
telescope in Chile that is already in early operations (Ingraham et al.
2020). That will allow us to compare three things: (1) delivered image
quality for astronomical observations, (2) the local contribution to
seeing using the strobed emitter, and (3) DIMM data from the seeing
monitor that sits outside the dome. We can use this as a test bed for
optimizing dome thermal management.

The final stage of implementation will be to place strobed sources
within the dome of the main Rubin telescope, and illuminate the
guider and/or wavefront sensors that are shown in Fig. 1. The goal at
this stage will be to rapidly gain experience in operating the Rubin
thermal management system to maximize delivered image quality.

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DATA AVAILABILITY
No new data were generated or analysed in support of this research.

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