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Fighting the devil within: Improving image quality by thwarting local turbulence.

Olivier Lai^{1a}, Mark Chun^b, Kanoa Withington^c

^aUniversité Côte d’Azur, Obs. de la Côte d’Azur, Laboratoire Lagrange, CNRS, 06000 Nice, France;

^bInstitute for Astronomy, University of Hawaii, 640 N. A’ohoku Place, Hilo, HI 96720, USA;

^cCanada France Hawaii Telescope, 65-1238 Mamalahoa Hwy, Kamuela, HI 96743, USA.

ABSTRACT

Image quality is sensitive to temperature fluctuations on the optical path, even if these are not fully developed turbulence. Thus, it’s crucial to control the thermal environment, be it on a test bench in the laboratory, in instruments (e.g., entrance windows, near electronics), within domes and telescope structures. It is especially crucial where the beam is small (i.e., going through a focus) and the power spectrum of the refractive index can be anything from high frequencies to just tip-tilt.

We have used our optical turbulence sensor AIRFLOW to explore how a ΔT of a few degrees in the optical path can undo a lot of what an AO system can improve, and we are using our devices to study quantitative ways to minimize the image degradation induced by temperature fluctuations. These may include counterintuitive measures such as fans mixing the air at different temperatures, because mechanical turbulence with no ΔT doesn’t produce optical turbulence.

Keywords: Telescopes, image quality, optical turbulence, adaptive optics

1. INTRODUCTION

There exist numerous real-world examples to illustrate the importance of dome seeing in adaptive optics performance. The now infamous low wind effect (LWE) is caused by slight temperature differences between the secondary mirror support structure and the ambient air, but we also regularly find unusually strong ground layers, with odd power spectral densities, with an excess at low temporal frequency, or at high spatial frequencies, all of which point to local effects. Unfortunately accounting for and including all these sources of image degradation in our modeling seems intractable because these effects are often intermittent and rarely stationary. Furthermore, they depend on too many environmental parameters to be causally attributed or interpreted, parameters such as the wind speed, direction, the relative dome azimuth, heat sources, radiative cooling in the telescope structure with differential thermal inertias, natural air temperature variations and partial flushing with dome vents. Furthermore, turbulence is inherently stochastic and trying to pinpoint it is literally chasing wisps of hot air...

1.1 Dome Seeing

The strength of the problem should not be underestimated: the image degradation due to dome seeing can be a couple of tenths of an arcseconds (out of 0.6'' ~ 0.8'' in good telescopes), but in a volume which is many orders of magnitude smaller, thus the turbulence *density* is gigantically larger inside than outside the dome: small variations in internal environmental parameters can produce large, intermittent fluctuations of image quality. Including locally generated turbulence into adaptive optics simulations seems especially difficult because mechanical turbulence does not necessarily produce optical turbulence if there are no temperature differences in the fluid dynamics (the dependance of the index of refraction on pressure is orders of magnitude smaller). Furthermore, the term optical turbulence is misleading as any ΔT in the optical path will degrade the image quality (e.g., layers, diffusion, local convection). The spatial and temporal frequency spectrum can therefore be very different from the canonical Kolmogorov or von Karman PSD we generally expect. This means that methods using scintillation or tip-tilt to measure local turbulence are not sufficient to fully characterize the optical degradation of the beam because such methods rely on the Kolmogorov model to infer a value for C_n^2 from a variance; to properly include the local turbulence requires measuring the phase structure function which contains much more

¹ olivier.lai@oca.eu

information about the type of optical path difference and thus potentially the source that is generating the optical beam degradation. This is fundamentally harder to parametrize than a single scalar value, such as C_n^2 .

1.2 Altering reality

It therefore seems nearly impossible to estimate realistic AO performance from simulations that attempt to incorporate all these effects. So instead of trying to align our simulations to reality we propose to *align reality to our simulations*. Indeed, we do not have to incorporate all these effects in our simulations if we can prevent them from occurring in the first place, and fortunately these local effects can be relatively easily attenuated or averted at the source using intelligent dome design, cleverly positioned fans or precise real time thermal control including telescope structure heating. None of these are especially technologically challenging but the control systems need to be sensitive, active, and real time, which requires a means of accurately sensing optical turbulence inside the telescope and dome.

2. IN-SITU TURBULENCE MEASUREMENT

2.1 Heuristic approach

Hydrodynamic simulations in and around telescope domes are very helpful in designing systems that minimize turbulence. However, a telescope's environment is so complex that such modeling can only be useful in a representative sense. As an example, attempts to reduce or control the level of dome turbulence using vents have only been moderately successful because the complexity of the environment precludes analytic predictions. We therefore prefer a heuristic approach in which we perform in-situ measurements of optical turbulence and try to find correlations with image quality and relevant environmental parameters. Originally, we wanted to develop a "turbulence camera", akin to Schlieren photography or shadowgraphy but never found a method that could work on extended incoherent sources at low flux levels with sufficient sensitivity. These methods require some form of coherence (in the light sources, in the wavefronts, in the image structure), which is hard to obtain inside a dome and even more difficult outside. We therefore developed a localized optical turbulence sensor that can scan the required volume with the obvious drawback that any turbulence outside the measuring cell would be missed, as would any intermittent turbulence during a volume scan. Nevertheless, being able to establish a correlation between measured local turbulence and degraded image quality would certainly be useful for active control of dome vents and thermal stabilization.

2.2 AIRFLOW

AIRFLOW (Airborne Interferometric Recombiner: Fluctuations of Light at Optical Wavelengths) uses a non-redundant mask to generate several coherent beams traveling parallel to each other through a measurement cell (Lai et al., 2019). By recording many instantaneous PSFs, which are simply the convolution of each fringe pattern associated with a pair of holes of the mask and calculating their Fourier transforms, we can measure the optical phase variance as a function of separation, which is nothing but the Phase Structure Function; a very useful tool to characterize the type of turbulence present as well as its strength (Figure 1).

We use a single-mode fiber coupled to a laser-diode to illuminate the entrance focus of the instrument. A pair of plano-convex lenses form the parallel beam in the measuring cell and a non-redundant mask is placed on one end of it. The interferogram is formed with magnification 1:1 on a ZWO ASI178MM camera; chosen for its small pixel size (2.5 μ m), fast frame rate and low read noise. To obtain a proper sampling of the PSF in this configuration the focal length is fixed at 200mm which results in an instrument approximately 550mm long with a measurement cell of 100mmx25mm. The more compact the instrument the less sensitive it is to vibrations. Work is ongoing to use cameras with smaller 1.1 μ m pixels, which would reduce the instrument size by half or increase the size of the turbulence measurement cell: a longer cell would increase the signal strength which would improve the SNR (if the noise remains constant), or a larger diameter cell would allow to sample more deviation from Kolmogorov at low spatial frequency.

Early prototypes were built from Thorlab cages, but we have since built several instruments from carbon and flax fiber composites; these instruments are small and rugged enough to be able to be put in a suitcase when traveling for business or pleasure. We have also developed an IDL based data processing software with a graphical user interface, making it easy to use in the field. The software computes C_n^2 by fitting the measured Phase Structure Function with a Kolmogorov model ($=6.88(r/r_0)^{5/3}$) but can also perform a Von Karman or power law fit or a Kolmogorov 2 dimensional fit if the turbulence is suspected to be very anisotropic. We have also included a vibration filtering algorithm that can remove the tip tilt from the data and fit the residuals by the difference of a parabola (phase structure function of pure tip-tilt) from the Kolmogorov

$r^{5/3}$ power law. Because the instrument is capable of measuring Cn^2 down to $10^{-15} \text{m}^{-2/3}$ it is sensitive to environmental vibrations though great care has been taken to make the instrument as stiff as possible.

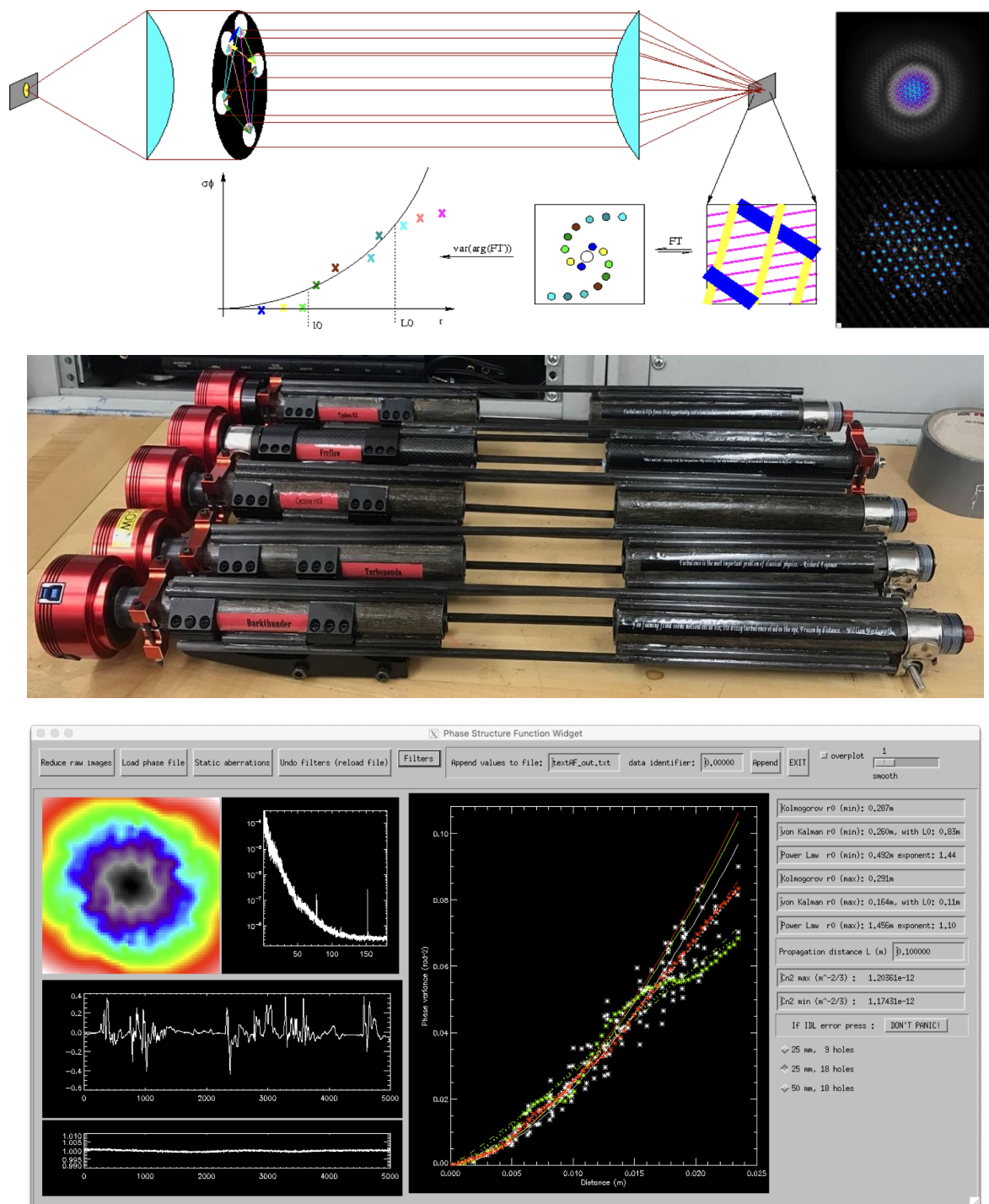


Figure 1. AIRFLOW concept: several parallel beams travel through the turbulence measurement cell in a non-redundant configuration. The PSF is the convolution of each fringe pattern, and its Fourier transform gives the optical phase variance as a function of separation, namely its Phase Structure Function. Middle: 5 units ready to be deployed. Bottom: Graphical User Interface showing the 2D phase structure function and Kolmogorov fit.

Interestingly, even with a smallest beam separation on the order of a few mm, we never see a drop of the variance to zero, as one might expect from an inner scale.

3. FIELD TESTS

3.1 CFHT

The first field tests were carried out at CFHT in October 2018. We mounted a prototype AIRFLOW instrument on one of the trusses of the Serrurier above the Caisson Central. We then proceeded to open the dome slit and vents, as shown in Figure 2. When the dome was closed, the environment was very quiet. With the slit open the environment remained calm but we could anecdotally feel buffeting as we see a few points of Cn^2 above the baseline. The East (windward) vents were then opened, and we see the turbulence jump by two orders of magnitude. The Cn^2 behavior then seemed to split, with one trend decreasing, as the dome thermalized and another branch remaining at the $10^{-13} \text{m}^{-2/3}$ level, most likely due to outside turbulence entering the dome (these tests were carried out in daytime, with the dark ground being radiatively heated by sunlight). When the West vents were open and the air could flow freely through the dome, this second pattern became prominent. Then, the East vents were closed while the West vents remained open and the turbulence decreased by an order of magnitude, suggesting that operating with only the leeward vents open in certain cases is a better strategy than opening all the vents.

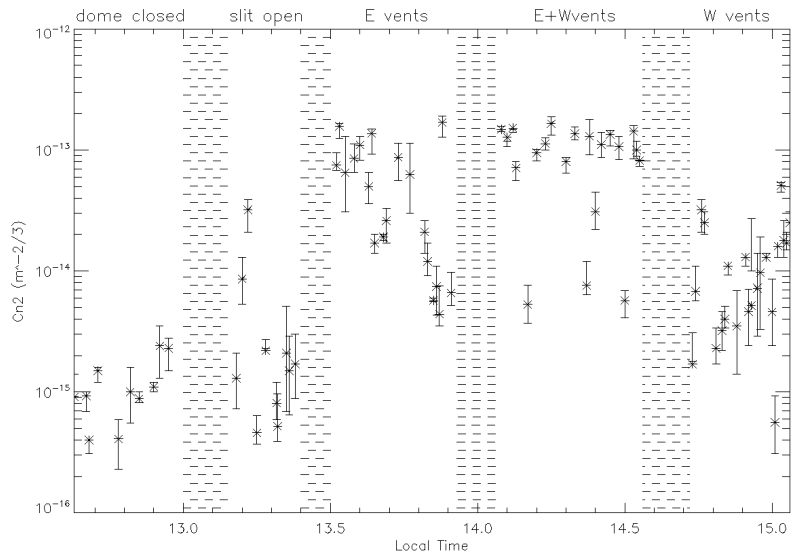


Figure 2: AIRFLOW testing at CFHT, opening and closing vents during daytime. See text for details.

3.2 UH88

The UH88 telescope has a closed tube which we have long suspected as a source of image degradation if heat gets trapped in the tube due to the thermal lag of the primary mirror. We tried lowering the optical turbulence sensor up and down the tube (again during daytime in October 2018) and found that the value of Cn^2 increased inside the tube compared to the opening. However, we also found that the *temporal* behavior was very different inside the tube from the outside fully developed turbulence. The temporal power law appears to follow a f^4 power law, which appears consistent with mostly tip-tilt, which could be due to “sloshing” or layers of air at different temperatures, moving around but not mixing.

During an imaka ground layer AO observing run, we implemented an extra-focal camera imaging the pupil while we had two AIRFLOW sensors mounted to the south side of the telescope, one just over the primary mirror and the other attached to the secondary mirror spider. These revealed a plume of air on the North side that our localized optical turbulence sensors completely missed, revealing one of the shortcomings of our approach with a small number of sensors.

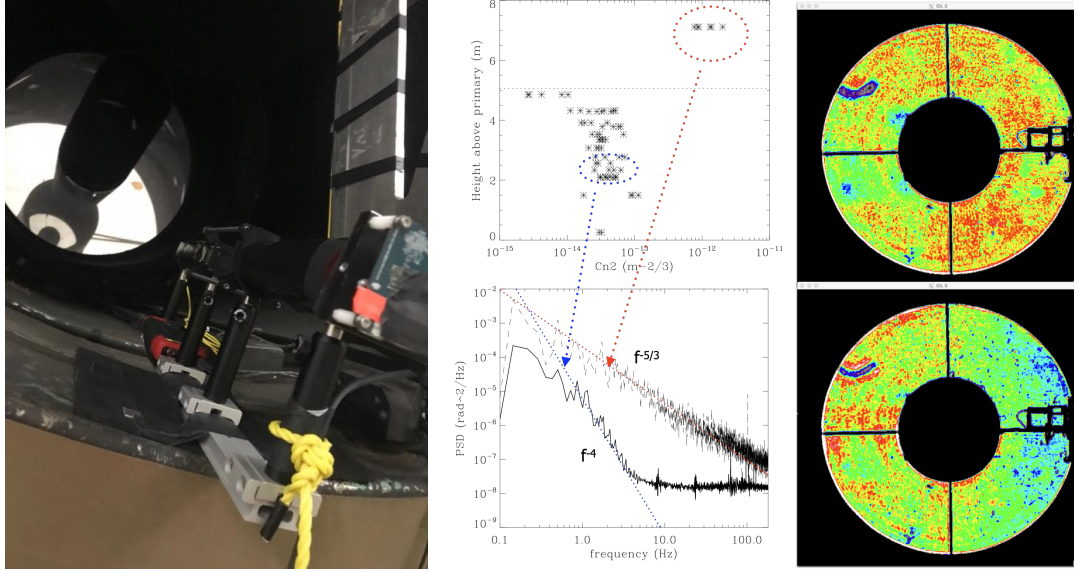


Figure 3: Turbulence inside the tube of the UH88". Lowering the optical turbulence sensor in the (enclosed) telescope tube (left) revealed a higher C_n^2 close to the mirror than at the opening, although with a very different temporal spectrum (middle). However, imaging of pupil extra-focal images (right) revealed a plume in the opposite quadrant to which we had our sensors, showing one of the limitations of localized optical turbulence sensing: turbulence outside of the measurement cell is not seen; however, these extra-focal images also illustrate that the instrument itself does not contribute to the local turbulence.

3.3 LBT

In June 2019 we were invited to test out our sensors at the Large Binocular Telescope on Mount Graham in Arizona. The dome of the telescope is like a cathedral yet will be dwarfed by ELT domes, giving a good sense of the challenge of turbulence control on these future telescopes.

We used two sensors during this three-day exploratory campaign: one was fixed to the outer edge of the primary and the other used to explore the volume inside the dome, as we found that differential measurements are always more reliable or at least credible. For example, during the last night as shown on Figure 4, we had put the second sensor on the inside edge of the primary mirror near the secondary support structure, thinking perhaps its thermal inertia would show a differential effect with the outer edge sensor. Instead, what we found was that a slight repointing of the telescope in the middle of the night exposed the outer edge sensor to increased turbulence. The source is unknown but the heightened level of turbulence at the outer edge of the primary was persistent.

This illustrated a further difficulty of using localized optical turbulence sensors, namely that to transform local C_n^2 into a phase variance on the beam, it must be integrated, and if the C_n^2 distribution across the primary mirror is not uniform, this becomes very complicated.

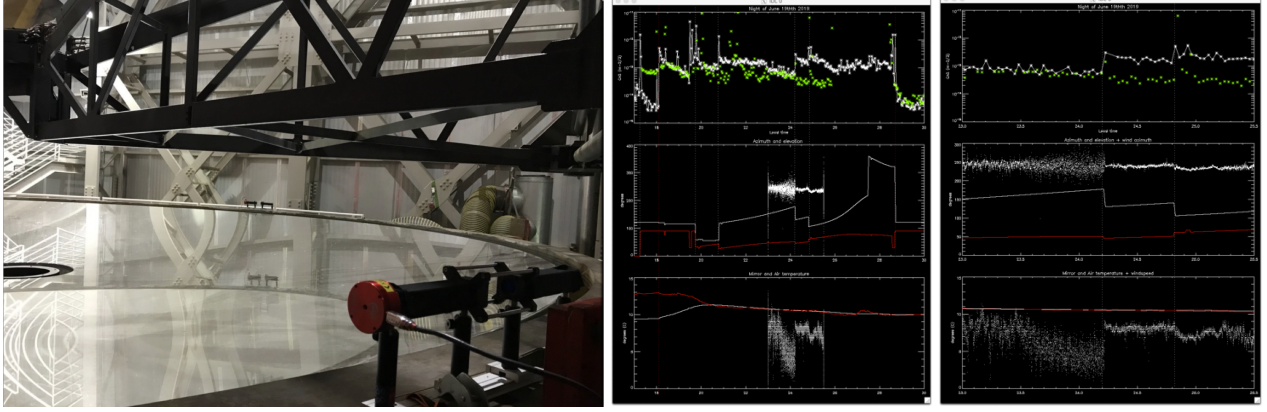


Figure 4: Left, one sensor was on the outer edge of the primary, while the other was near the secondary support structure. In the middle of the night a repointing of the telescope changed its azimuth by less than 40 degrees but increased the C_n^2 on the outer edge sensor (in white on top middle and right plots, the green shows the measurements from the inner edge sensor). The middle plots show the telescope elevation (in red), azimuth (in white) and the wind azimuth (white dots). In the bottom plot, red is the ambient air temperature, white is the primary mirror temperature, and the white dots show the wind speed which also registered this change.

3.4 ASTEP

ASTEP (Antarctica Search for Transiting ExoPlanets) is a 40 cm Newtonian telescope at Dome C (3300m) in Antarctica for long transit confirmation and characterization (Abe et al, 2022). The image quality in this case is not as critical for photometry but due to the extreme environment (temperatures can reach -85°C in winter), it is necessary to heat the primary and second mirrors as well as the camera box to prevent frosting (see Figure 5). Because AIRFLOW is so compact and sturdy, it was easy to bring an instrument in a suitcase along this epic journey to the White Continent and carry out some preliminary measurements. Again, daytime testing meant that the thermal driving of the sun on the structure would introduce different turbulence than at night. We tried some tests with the dome closed to prevent this thermal bias, but the dome was unduly quiet and not representative of the nighttime observing environment, so we also conducted some tests with the dome open to evaluate the effects of natural venting.

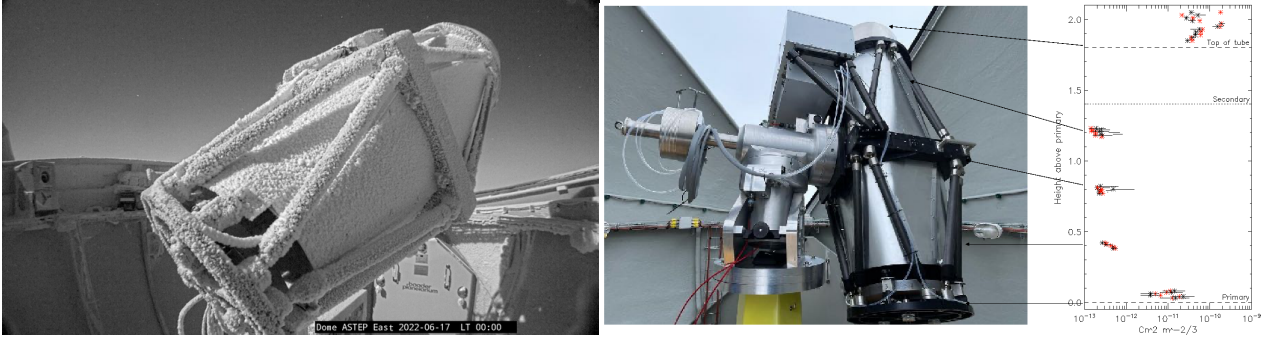


Figure 5: Left, ASTEP telescope at night near the solstice, illustrating why it is necessary to heat the primary and secondary mirrors. Right, daytime measurements of C_n^2 inside the tube; note the small opening at the base of the tube which allows for mixing, thus higher C_n^2 . These measurements were obtained with no heating on the mirrors.

To test the effects of heating the primary mirror, we placed the AIRFLOW sensor right above it and ran the temperature up and down with the dome open and closed. When the dome was closed, we got exquisite sensitivity, and an almost perfectly linear (in log scale) relationship between C_n^2 and ΔT . However, when we repeated the measurements with the dome open, we noticed that the onset of turbulence was more abrupt near $\Delta T \sim 3^\circ\text{C}$, which can be explained by flushing through the opening near the base of the tube if the difference in temperature between the ambient air and the primary mirror remains below a certain level which almost certainly depends on the wind speed inside the dome. The results are shown on Figure 6. In the analysis we attempted to take into account the thermal lag by introducing a constant time offset to minimize the difference between the measured temperatures and the temporal C_n^2 sequence.

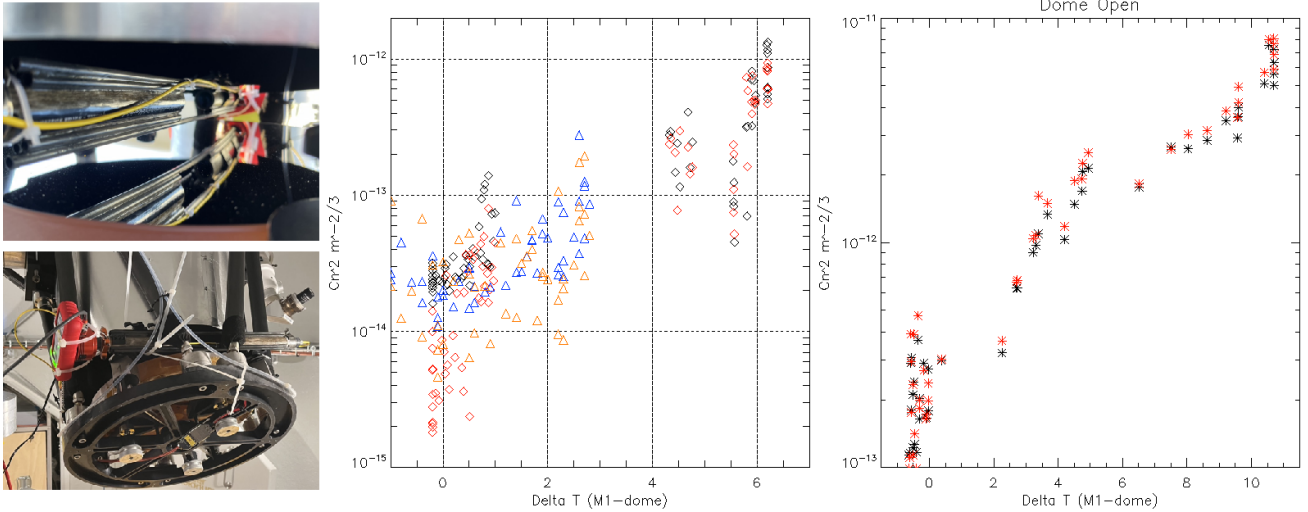


Figure 6: Left, the AIRFLOW sensor above the primary mirror of ASTEP. Middle, C_n^2 as a function of ΔT between the mirror and the ambient air with the dome closed on two different days and for two different sensor configurations (red and black, compared to orange and blue). Right, same but with the dome open: there is an abrupt onset of turbulence near $\Delta T \sim 3^\circ\text{C}$ and note the much higher levels of turbulence than with the dome closed, due to thermal driving by the sun with the dome open.

We ran some further tests with AIRFLOW placed above the camera box and near the camera box entrance window, but these were less conclusive in terms of detecting a signal as a function of heating the elements. One interesting but not completely unexpected result was that when the sensor was too close to a surface (in our case the camera box), the power law index of the phase structure function fit was always close to 1, indicative of diffusive mixing, a random walk of phase variations as the turbulent cells do not have enough time and volume to fully develop.

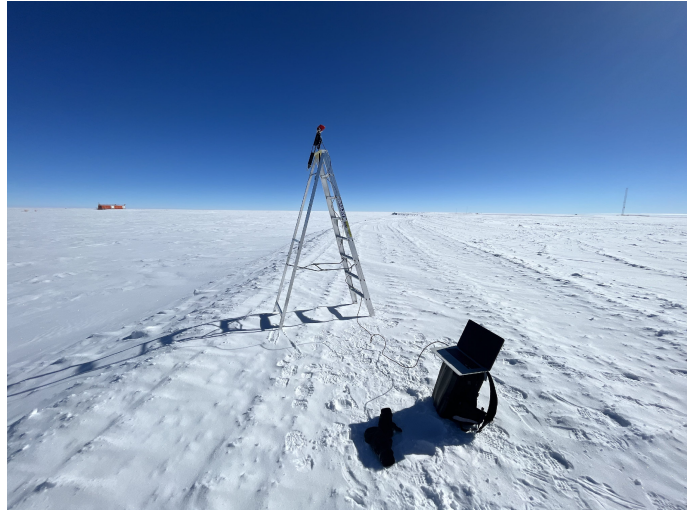
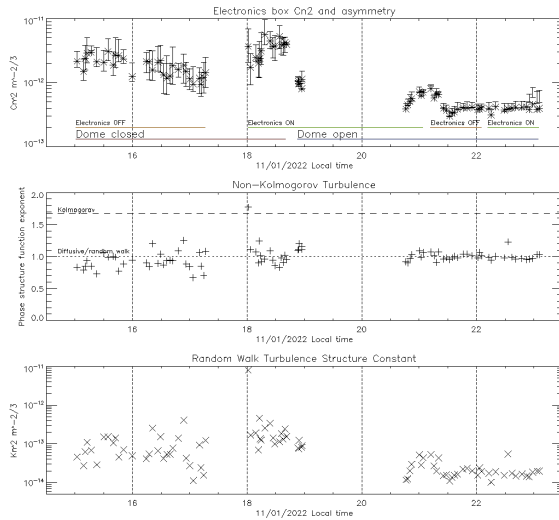


Figure 7: Left, trying to detect the effect of turning on the electronics of the camera box with the dome closed and open.

When the dome is closed, the effect is more notable, but opening the dome flushes it and the self-generated turbulence vanishes. However, the most notable point is the power law index, equal to unity, indicative of diffusive, random walk turbulence. Right, trying to measure the free air turbulence at Dome C sometimes led to absurd situations... “Accroche toi à la turbulence, j’enlève l’échelle”, to paraphrase Gotlib (<http://victoire.b.free.fr/Paris20/fant/gotlib.html>)

4. CONCLUSION AND LESSONS LEARNT (SO FAR)

4.1 Optical turbulence is intermittent, stochastic, and impossible to model accurately

The examples of Section 3 show that optical turbulence inside a beam is difficult to predict from theory; wind plays an enormously important role in flushing as was previously illustrated by the low wind effect (LWE), due to a slight temperature difference between the telescope's (VLT and Subaru's) secondary mirror support structure and the ambient air. But as we measured in the LBT dome, the flushing can change dramatically even with only a small change between the dome azimuth and wind direction or at CFHT, with the improvement of using only the leeward vents. Furthermore, these measurements showed the sudden onset of turbulence, illustrating that it is intermittent and not linear with environmental parameters. However, too much flushing can also generate or import outside turbulence into the beam. Additionally, we often see high values of C_n^2 inside a dome when the slit is open and warm air inside the dome mixes with colder outside air. Besides, the turbulence can be highly localized (plume inside the UH88 tube, differential C_n^2 on either side of the LBT primary) and have an anomalous frequency content compared to models and simulations as shown in the UH88 tube and above the ASTEP camera box.

4.2 Integrating optical locally measured C_n^2 is viciously difficult

The biggest difficulty, however, lies in relating the locally measured C_n^2 to image quality which requires integrating it along the optical path to obtain the total phase variance introduced to the optical beam. It seems hopeless to carry out this integration analytically due to the presence of hot spots which illustrate that there is no reason for the distribution of C_n^2 to be continuous. Also, in a Cassegrain telescope if there is a hot spot inside the tube, the beam will encounter it three times with different beam sizes each time (possibly even missing it altogether after reflection on the secondary mirror (see Figure 8).

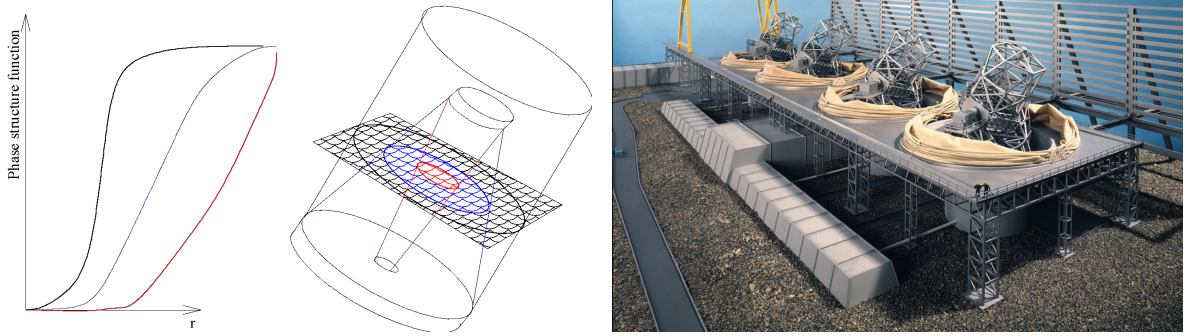


Figure 8, left: a single layer with a small outer scale inside the tube will be seen three times by the beam in a Cassegrain (or Gregorian) configuration, but with a different phase structure function each time, making it extremely difficult to integrate analytically unless the outer scale and the height of the layer are known with extreme accuracy. Right: early models of the VLT recognized the detrimental of dome seeing but were also aware of boundary layer turbulence and wind shake, both of which would be attenuated by the use of “hedges”, increasing the mixing of air at different temperatures, so that mechanical turbulence would not necessarily translate into optical turbulence.

If analytical integration seems hopeless then it seems the best we can hope for is finding empirical correlations between an estimate of the dome seeing (for example, given by the measured focal plane image quality minus the externally measured DIMM) with a linear (or more likely non-linear) combination of multiple localized turbulence sensors placed at strategic locations. We need not be completely blind however as we have strong *a priori* information from the focal plane PSF morphology. For example, we know that an excess of high spatial frequencies will flatten the phase structure function and produce stronger wings on the PSF, lowering the beta index of a Moffat fit. The correlation between IQ and turbulence and environmental sensors could take the form of a principal component analysis, but we suspect that due to the non-linear onset of turbulence this may be a task best performed by machine learning which may be better able to account for turbulence step functions and sudden onset of the turbulent regime (Gilda et al., 2022).

4.3 Need for in-situ optical turbulence control

We hope to have shown that to accurately predict when and where dome seeing will occur and with what power spectrum seems like an intractable problem. It is even difficult from a statistical point of view as the distribution of turbulent behavior is not linear (e.g., a median or a mean is not meaningful), and that to include all the potential cases into adaptive optics

simulations is prohibitive. What to do? The best approach is to prevent this unpredictable and detrimental behavior from occurring in the first place so that we don't even have to include it in our simulations, as a bonus it would improve the absolute image quality. What can we do to prevent this turbulence from occurring in the first place? Fortunately, the dome is the only place where we stand a chance of attenuating all these local effects or averting them right at the source, using intelligent dome design, cleverly positioned fans or precise real time thermal control including telescope structure heating. None of these are technologically challenging, as shown on Figure 8, right. However, if we wish to go beyond a passive control, we need to be able to measure the turbulence in strategic locations around the dome, and such measurements need to be reliable, sensitive, active, and real time. Until we have developed a wide field "turbulence camera", we will keep trying to accurately sense and map the turbulence inside the telescopes and domes and correlate such measurements to focal plane image quality as a guide.

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