Simulation and laboratory demonstration of measurement and mitigation of dome seeing

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Abstract. Ground layer turbulence is seen to be dominant at most telescope sites. Some fraction of this is caused by the interaction of the telescope dome and structure with the surrounding environment, leading to mixing of air at different temperatures, and hence, optical perturbations. Here we investigate the use of laminar air flow in the form of air curtains to reduce this mixing. We provide laboratory measurements of the effect of mixing and its mitigation, and detail the steps that can be taken to reduce this effect. Application for telescope dome structures is developed.

1. Introduction
Atmospherically induced perturbations form the major performance limitation for ground-based optical telescopes. Mixing of air of different temperatures in the atmosphere between telescope and target lead to changes in refractive index, and hence differential delays in the wavefronts of light incident along different lines of sight. These variations in wavefront phase limit effective telescope resolution, and mean that, if unmitigated, the largest optical telescopes have only the effective resolution of a large hand-held telescope, albeit with a larger light collecting area.

At most astronomical sites, the large majority of atmospheric perturbations are introduced in the atmosphere close to the ground, where the free flow of air is restricted both by the surrounding environment, and the telescope structure itself. We investigate the effect of air flow around a telescope dome using both compute simulation and laboratory bench models, and study the use of air curtains to provide a laminar air flow to isolate air within the dome from air outside, thus reducing mixing of air at different temperatures. In §2 we present our method and discuss our findings. In §3 we provide details of future work, and we conclude in §4.

2. Introduction
Air curtains, which produce a laminar flow of air are used in many application to separate different regions of air. In supermarkets, the are used to prevent cold exterior air from mixing with warm air in the shop (or in warmer climates, to prevent hot exterior air from mixing with cooler interior air). Air curtains are also used in refrigerated displays to retain chilled air without necessitating a physical barrier. Operating theatres within hospitals also use air curtains to provide a sterile operating space similarly to a clean-tent, but without a physical barrier. Warehouses sometimes use air curtains across wide entrances to allow free access for vehicles, whilst retaining and maintaining interior air temperature.
2.1. Dome seeing
Mixing of air within and around a telescope dome structure can lead to significant optical aberrations caused by the differing refractive indices when air of different temperatures is mixed. This effect, called dome seeing, is situation dependent, and unsensed by external atmospheric profilers, such as DIMMS, Slodar and Scidar systems. A reduction of this dome seeing, by reducing the mixing of interior and exterior air, can have a positive impact on astronomical image quality.

Placing a large glass screen across the telescope dome opening is impractical. The surface quality would have to be maintained at the ten-nm-level, and transmissive losses would impact telescope sensitivity. The alternative approach is to use an air curtain.

2.2. Air curtain design
The design of an air curtain involves the optimisation of several different parameters, in addition to a consideration of the purpose of the curtain. In the case considered here, we are aiming to reduce turbulence, and so a curtain with a laminar air flow is highly desirable (turbulent air flows are sometimes used for shop entrances to reduce the number of insects passing through the curtain).

The air curtain velocity is an important consideration, as the air within the curtain need to have ample momentum to traverse the gap. The volume of air within the curtain (i.e. its thickness) also requires consideration, as this affects the momentum of the curtain, the dispersion of air leaving the source, and the length over which laminar flow can be achieved.

The laminarity of air leaving the source should also be considered: if air flow is not linear at this point, quality of the air flow will be reduced. The introduction of flow shaping within the source can aid this, e.g. smaller tubes of air prior to the source exit.

The use of an air sink should also be considered, to provide a negative pressure across the aperture aiding the laminar flow by maintaining momentum within the curtain. This will aid the laminarity of the airflow, channelling the air from source to sink.

2.3. Optical perturbations due to airflow
It is important to note that moving air itself does not cause optical perturbations. Rather, it is the mixing of air with different temperatures that cause this, leading to refractive index differences which then move across the field of view. Turbulent eddies can facilitate this air mixing, thus increasing optical perturbations.

The key concept under investigation here is whether laminar air flow can be used to reduce this mixing, by separating air within a telescope dome from external air, which will be at a different temperature.

Mixing of air above a telescope can be caused by incident wind, a chimney effect within the telescope (air being sucked up from ground level and out of the dome), and heating effects such as mirror heating (the primary mirror of most telescopes having a large thermal mass) which will cause convection above the mirror. Telescope domes are not usually conducive for smooth airflow: obstructions, sharp corners and sudden surface gradient changes will cause eddies to form as air flows past the telescope. Introduction of an air curtain will help to smooth these eddies.

3. Air curtain modelling and testing
We have used a commercial computational fluid dynamics software package to model a telescope dome, internal and external air mass, and an air curtain across the dome aperture. The model is based on the dimensions for the dome of the 4.2 m William Herschel Telescope on La Palma, and as such has a 6 m open aperture.
Figure 1. A figure showing mixing of interior and exterior air with wind propagating past a telescope dome, both with and without an air curtain, and with wind directions coming from behind the telescope, and from the side relative to the dome opening. The first two columns show air blowing from behind the dome (from left to right), without and with an air curtain respectively. The last two columns show air blowing across the dome aperture (again from left to right), without and with an air curtain respectively. The rows represent increasing time in 2.5 s intervals, from 2.5 to 10 s.

We assume a 5 m/s wind speed, and a 10 m/s air curtain speed in our models, and include an initial condition with a region of warmer air away from the telescope, but travelling towards it, as shown in Fig. 1. We then propagate the model for 10 s to show how this warmer air will mix with cooler air, both with and without air curtains. The initial temperature difference is 1 °C, and is necessary so that we can clearly identify the mixing of interior and exterior air. We assume warmer exterior air, though this is immaterial: it is simply so that we can identify the mixing.

Fig. 1 shows that the air curtain is able to prevent mixing of interior and exterior air within the dome, and that eddies are significantly reduced.

3.1. Qualitative laboratory measurements
We have set up a laboratory air curtain across free space, and use Schlieren imaging to observe hot air flow from a heater both with and without the air curtain, as shown in Fig. 2. It is evident that the air curtain is able to reduce turbulent eddies.

3.2. Quantitative analysis
Schlieren imaging is generally a qualitative observation tool, and so to perform a quantitative analysis of the reduction in optical perturbation using air curtains, we use a Shack-Hartmann sensor, passing a collimated beam of light through the region of turbulence under investigation. Initial tests were performed using a cuboid dome geometry, i.e. the dome aperture was a slit within a planar surface, across which the air curtain was set up, and turbulent air blown.

The air curtain source used a honeycomb arrangement of tubes and piping to linearise the
airflow upon exit of the source. Pressure for the air curtain was generated using a fan, and the velocity, source width and length were chosen to give a low Reynolds number.

Initial modelling of this configuration (Fig. 3 suggested that a reduction in turbulent mixing would be achieved. Shack-Hartmann slopes were reconstructed into an incident wavefront using the CuReD algorithm ([1]), and a Zernike decomposition of the time-varying incident phase obtained (Fig 4(a)). This was found to follow a generalised turbulence model power spectrum:

$$\phi_n(\kappa) = 0.033C_n^2(z)|\kappa|^{-\beta}$$

with $\beta = 2.7$ rather than the $\frac{11}{3}$ expected for pure Kolmogorov turbulence.

The RMS phase perturbation was found to be significantly reduced by the air curtain. As shown in Fig. 4(a), the variance of turbulence with the air curtain is significantly reduced from that without. It is also interesting to note that free-space turbulence, i.e. without a dome aperture to contend with, results in even lower variance. This may have application for dome-free telescopes, though even the presence of the telescope itself is likely to increase phase variance, and so we do not discuss this further here.

In our measurements, we find that the air curtain reduces variance by close to a factor of three compared to the case without an air curtain, across a planar aperture. In free-space, the variance is found to be a factor of two lower. Ambient air, and the air curtain alone (at ambient temperature) result in very low, almost identical phase variance, i.e. the air curtain alone is not introducing significant phase perturbations.
3.3. Laboratory investigation of a conventional dome
We developed our laboratory air curtain model to use a conventional shaped dome, with an aperture cut into a hemispherical shell. The outlet width was adjustable, and a honeycomb mesh was used to linearise the airflow before exit. An optional air curtain sink was also installed, with the ability to provide a negative pressure on the opposite side of the dome aperture from the source. The use of this sink was investigated.

The angle of arrival of the incident turbulent air was varied, from zero (being parallel to the air curtain), through to 180° (opposing the air curtain). Fig. 4(b) shows turbulence strength (measured as phase variance) as a function of angle of arrival of the perturbing wind. It can be seen that the air curtain significantly reduces the phase variance compared to the case without an air curtain. It can also be seen that the use of a sink improves performance significantly when the wind direction is opposing the air curtain direction, though for other incidence angles, there is little difference in performance regardless of whether a sink is used or not.

The effectiveness of a sink when used with opposing incident air can be explained by the sink giving additional momentum to the curtain allowing it to propagate the aperture even when significantly perturbed by the wind.

3.4. Baffles for air curtain initialisation
When air curtains are used within the mining industry to direct airflow within mines, baffles are used to initially direct the air. Once the airflow has been set up, these baffles can then be removed, and the airflow pattern is sustained. Without baffles for initialisation, airflow is undirected, and follows all paths throughout the mine. In a similar way, we have investigated the use of baffles across the telescope dome aperture during air curtain initialisation. Here, the dome aperture is initially blocked when the air curtain is switched on. Then, after a few minutes of operation, once a steady state flow has been initiated, the baffle is slid up over the
dome, revealing the aperture, whilst maintaining the steady state flow. Our investigations show that a 10% performance improvement is achieved using baffles, reducing the phase variance. We therefore recommend that baffles should be designed into any operational telescope system.

4. Future work
We have clearly demonstrated, both through laboratory testing, and computer modelling that the use of an air curtain across a telescope dome aperture can significantly reduce dome turbulence, improving the quality of astronomical images. We are now seeking to test this concept on 0.5 m class telescopes both on the roof of the Physics department at Durham University, and on a nearby observatory. This will involve the development and deployment of a portable air curtain system, complete with fan, source and sink, and optical components for testing the reduction in atmospheric perturbation, based on a Shack-Hartmann sensor to be installed on the telescopes in question.

The use of an air curtain reduces ground layer seeing, and hence can reduce the demands placed on an adaptive optics system (or, depending on scientific goals, remove the need entirely). Reduced adaptive optics system demands also feeds through into reduced requirements for real-time control systems ([2]), thus reducing instrument costs.

5. Conclusions
Dome seeing is known to have a significant turbulence contribution, something which we have demonstrated using modelling and laboratory testing. In particular, the interaction of a telescope dome with flowing air causes mixing of interior and exterior air, and hence optical aberrations. This mixing of air can be reduced using air curtains across the telescope dome aperture, leading to significantly improved astronomical seeing. The use of an air curtain sink is beneficial, further strengthening the air curtain effect, particularly when incident wind is not aligned to the air curtain.

6. References
[1] Rosensteiner M 2011 J. Opt. Soc. Am.A 28 2132
[2] Basden A, Geng D, Myers R and Younger E 2010 Appl. Optics 49 6354–6363