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Processing of external SLODAR turbulence profile measurements to support adaptive optics performance predictions

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ABSTRACT

The Adaptive Optics Facility (AOF) at the Very Large Telescope (VLT) will have two ground layer adaptive optics (GLAO) modes of operation. To make the best use of these modes, information about the ground layer turbulence profile up to 500 m will be important. External turbulence profiling support will be provided by a robotic slope detection and ranging (SLODAR) instrument with 8 resolution elements and a maximum sensing altitude of 100-500 m. When profiling at the higher end of this range the surface layer of turbulence is not resolved so the fraction observed by the Unit Telescopes (UTs) is ambiguous. Here we present a method of estimating the surface layer contribution seen by the UTs by assuming an exponential decay model for the surface layer. Older, higher resolution, profiles from the prototype surface layer SLODAR instrument (from 2011-2012) have been used to determine the most appropriate scale height for the model. By incorporating the model, a better estimate of the integrated turbulence strength from the UT dome height upwards can be achieved.

Keywords: SLODAR, optical turbulence, adaptive optics

1. INTRODUCTION

Slope Detection and Ranging (SLODAR)[1,2] is a two-star turbulence profiling technique that can be implemented on a small (50 cm) telescope. Durham University developed such an instrument under contract from the European Southern Observatory (ESO) to support adaptive optics (AO) at the Very Large Telescope (VLT).

This paper describes recent work on how make the best use of data from the SLODAR instrument at Paranal. Section 2 introduces the Adaptive Optics Facility and its turbulence profiling requirements, section 3 describes the SLODAR instrument, section 4 describes the new data processing pipeline and section 5 contains the conclusion.

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2. VLT ADAPTIVE OPTICS FACILITY

The Adaptive Optics Facility (AOF)[3] upgrades one of the 8 metre unit telescopes (UTs) to include an adaptive secondary mirror, 4 laser guide stars (LGSs) and 2 AO modules:

GRAAL – A ground layer AO module for the Hawk-I infrared wide-field imager, with a science field of $7.5' \times 7.5'$.

GALACSI – This will increase the performance of the Multi-Unit Spectroscopic Explorer (MUSE) instrument. MUSE has two modes:

- Wide Field Mode, $1' \times 1'$ field of view, ground layer AO correction.
- Narrow Field Mode, $7.5'' \times 7.5''$ field of view, tomographic AO correction.

2.1 Profiling requirements

In GLAO mode, the AOF requires information on the ground layer turbulence profile up to 500 m. This will be provided by SLODAR.

Earlier surface-layer (SL) SLODAR measurements have shown that the surface layer is strong and much of it occurs at a lower height than the top of the UT domes (which are approximately 30 m in height).[4] Some turbulence will therefore not be seen by the UTs and this must be taken into account when estimating the profile.

Two of the most useful parameters for predicting GRAAL and GALACSI performance are the relative turbulence strengths below 300 m and 500 m. These can be calculated from estimates of the integrated C_n^2 from the UT dome height up to 300 m, 500 m and the top of the atmosphere.

3. THE VLT FACILITY SLODAR INSTRUMENT

The robotic SLODAR instrument (figure 1), installed in 2013, consists of a pair of 8×8 subaperture Shack-Hartmann wavefront sensors that can observe pairs of stars with separations ranging from 2 arcmin to 12 arcmin. The turbulence profile is recovered from the spatial cross-covariance of wavefront slope measurements from the two stars. The instrument delivers 8-layer profiles of the surface layer of turbulence. The vertical resolution and maximum sensing altitude depend on the separation of the target stars and the zenith angle, up to approximately 500 m for the narrowest targets. Wider targets yield higher resolution profiles but do not profile as high. The total integrated turbulence strength is always measured. The SLODAR instrument is 2 m above the ground – turbulence below this height is not measured.

Much of the time, especially when the instrument is observing the narrow targets required to reach a maximum altitude of 300-500 m, the surface layer of turbulence is too thin to be resolved. The SL is therefore usually observed entirely in the first resolution element and the instrument is unable to determine what fraction of the SL turbulence is observed by the UTs.

The prototype surface-layer SLODAR (operated 2011–2012) used wider targets (typically 13-15 arcmin) and was able to resolve the SL. This period is therefore a source of statistical information that can be used to construct an average model of the surface layer. This model, scaled by the total turbulence strength in the first resolution element, can be used as our best estimate of the SL profile when it is not resolved. This is described in section 4.

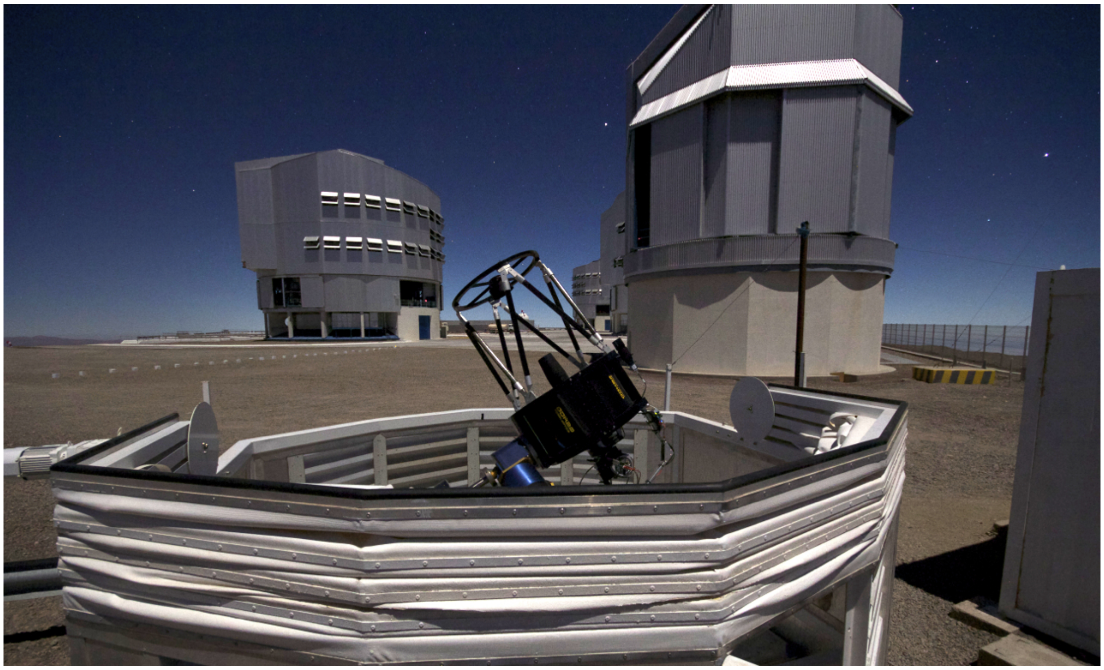

Figure 1. The Paranal robotic SLODAR instrument.

4. REVISED DATA PROCESSING PIPELINE

A new pipeline was developed to provide an estimate of the turbulence above the height of the UT domes even when the surface layer is not resolved.

1. To find an appropriate model for the surface layer turbulence, the data from the prototype SL-SLODAR were used. That instrument operated with wide target angular separations and hence gave higher vertical resolution of the surface layer. The data with the largest target separations and for relatively low target elevations were selected, in order to resolve the surface layer turbulence as much as possible.

2. The prototype SL-SLODAR data were then fitted using an exponential model of the form

$$C_n^2(h) = A \exp\left(\frac{-h}{h_0}\right), \tag{1}$$

   where h is the height above the ground and h_0 and A are constants. A combination of two such exponential components has previously been used to model the turbulence profile at Cerro Pachón.[5] The older, higher resolution, data from the prototype SL-SLODAR was used to establish the best scale-height for the exponential model; this was found to be $h_0 = 5.0$ m.

3. The data for the new SLODAR data (2014 – present) were then re-cast onto a regular vertical grid, as follows:

   (a) The original SLODAR analysis (8 sensed layers, variable altitude, example in Figure 3) was repeated using a non-negative least squares fit.

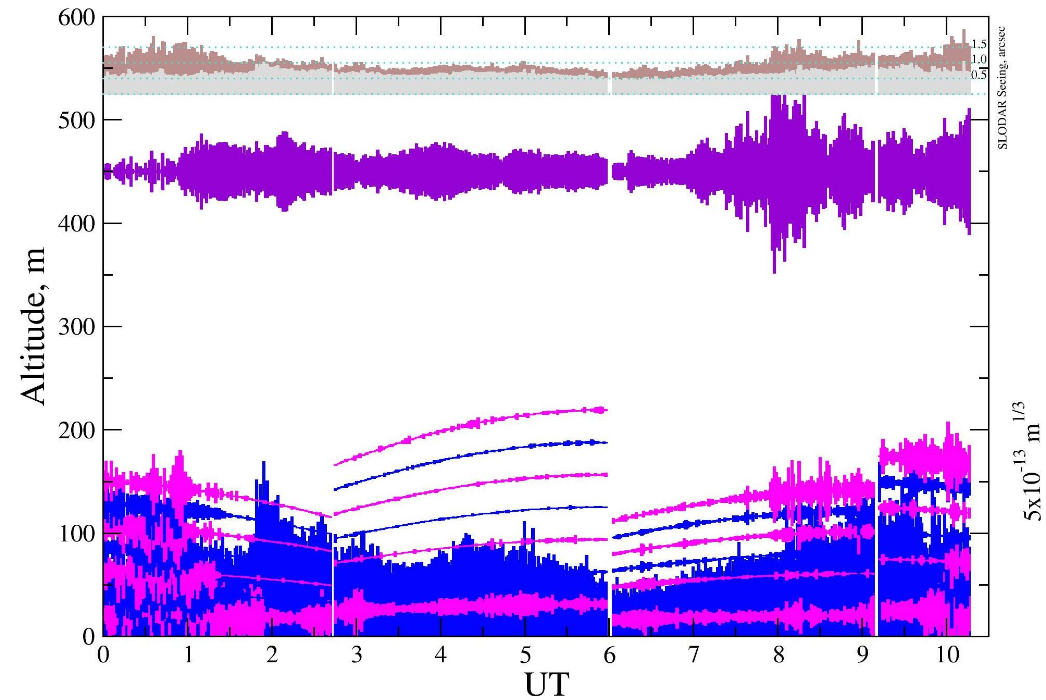

Figure 2. Example turbulence profile data (night starting 22 April 2014).

(b) A surface-layer component was calculated using the model defined from steps 1 and 2. This was re-binned onto the actual vertical resolution of the SLODAR observation. It was then scaled in strength according to the Cn2 value of the first SLODAR bin. (In fact this SL component strength was "capped" if it would produce a value in the higher altitude SLODAR bins that was larger than that which was actually observed).

(c) The SL component, as calculated in (b) was subtracted from the original SLODAR profile. The remainder of the SLODAR profile was re-binned onto a 1 m vertical profile using the known (triangular) SLODAR response/weighting functions centred at the altitude of each original SLODAR vertical bin.

(d) The final C_n^2 profile, on a regular 1 m vertical grid, was the sum of the SL component from (b) plus the result of (c). See Figure 4.

5. CONCLUSION

The Paranal robotic SLODAR instrument provides surface layer turbulence profiles up to a maximum altitude that ranges between 100 m and 500 m, with 8 resolution elements. It is desirable to make integrated C_n^2 estimates from the top of the VLT dome up to 300 m and 500 m available for AOF. The surface layer of turbulence is not usually resolved, so we have fitted an exponential model to the surface layer model to allow the fraction of the surface layer that is below the top of the UT domes to be estimated.

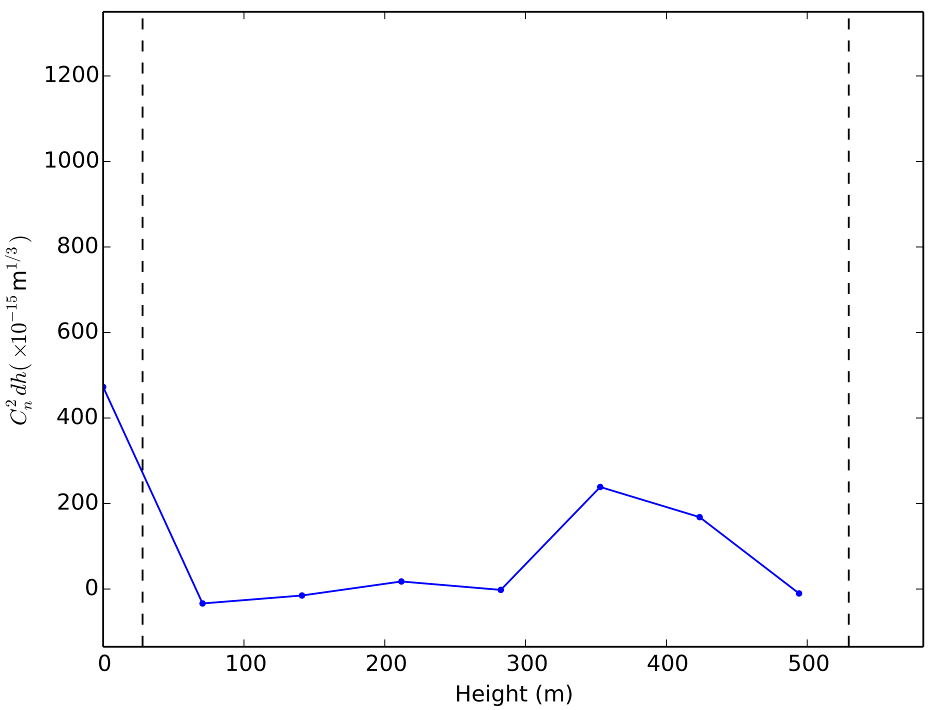

Figure 3. Example of a “raw” 8-layer SLODAR profile. The broken lines indicate the UT dome height and maximum profiling height.

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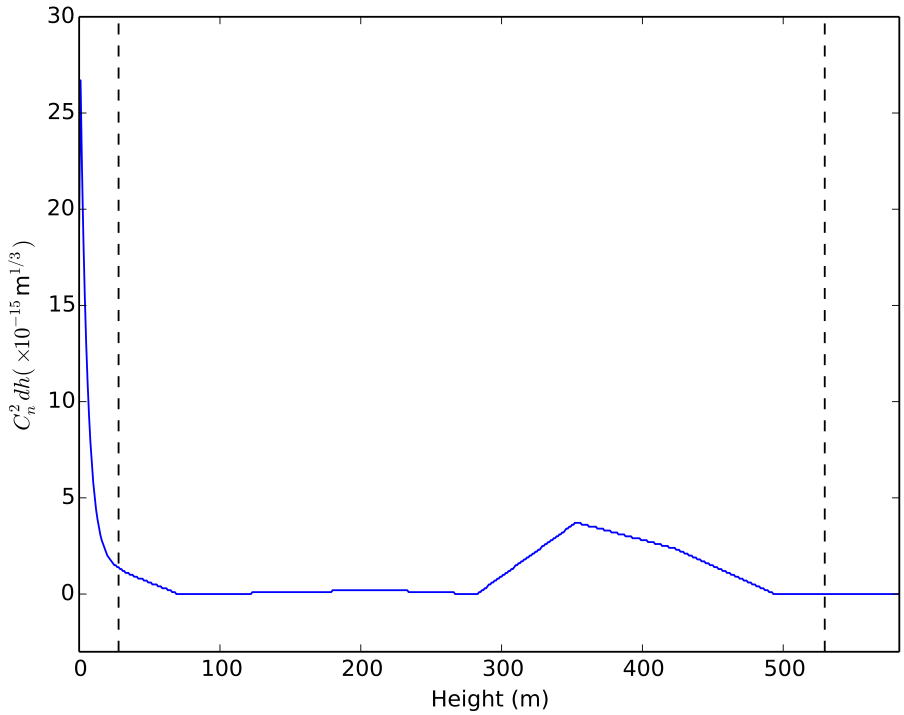

Figure 4. Example of a corrected profile with samples every 1 m. The exponential-model surface layer yields a better estimate of the SL contribution below the dome height. The broken lines indicate the UT dome height and maximum profiling height.

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