Beyond conventional G-SCIDAR – the Ground-Layer in high vertical resolution

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ABSTRACT

By using the SCIDAR instrument at the VATT on the top of Mt. Graham and a very wide binary star with a separtion of 35", the vertical structure of the turbulence in the first few hundred meters above the telescope was measured. When using such a binary and analysing the cross-correlation images, a vertical resolution for the turbulence profile of a few tens of meters can be achieved near the ground. This permits to determine the inner structure and the wind sheer of the single turbulent layers inside the ground-layer. We present the principles and the data-reduction process of this method and show first results obtained with this method at Mt. Graham. As an application, we estimate the fraction of the turbulence between the dome of the VATT and the primary mirror of the LBT.

Keywords: Atmospheric Turbulence, SCIDAR, site-testing, MCAO

1. INTRODUCTION

The SCIDAR (SCIntillation Detection And Ranging) technique was first proposed by Rocca et al.[1] to measured the atmospheric turbulence structure function $C_N^2(h)$ above astronomical observatories. It is based on the analysis of the spatial auto-correlation of the intensity fluctuations in the pupil plane image generated by a binary star. The value of the auto-correlation is related to the refractive-index structure function $C_N^2(h)$, which is a measure for the strength of the optical turbulence. For a more detailed description of the SCIDAR technique and the data-reduction process, see e.g. Avila et al.[2,3]

The original SCIDAR method was insensitive to the turbulence near the ground or inside the dome. With the extension proposed by Fuchs et al.,[4] to place the detector to a conjugated plane below the ground, this so-called Generalized SCIDAR (GS) is able to measure the $C_N^2(h)$ profile of the whole atmosphere. In the last few years, the GS technique was implemented in a number of instruments and extensive observation campaigns were performed at various astronomical observatories.[5–9] Thus today the SCIDAR technique can be considered as an established method to measure routinely the C_N^2-profiles, with a vertical resolution Δh_S, which is given by:[9]

$$\Delta h_S(h) \;\approx\; \frac{0.78\,\sqrt{\lambda\;|h\,-\,h_{GS}|}}{\vartheta}. \tag{1}$$

This vertical resolution depends on the wavelength λ, the angular separation of the binary ϑ, the height h of the turbulent layer above the ground and the height h_S of the conjugation plane of the detector. The vertical resolution is limited due to the fact that the peak in the auto-correlation image produced by a single layer has a certain size. If the vertical separation of two turbulent layers is too small, their respective peaks in the auto-correlation profile overlap, and it is no longer possible to discern the two layers. For typical values ($\lambda = 0.5\mu m$, $\vartheta = 7"$, $h_{GS} = -3.8$km and $h = 0$km), the resulting vertical resolution at the ground is $\Delta h_S \approx 1000$m. This limitation of the vertical resolution can be seen in figure 1, which shows the median C_N^2-profile for one night as measured with the GS. No information on structures smaller than 1km can be extracted from this C_N^2-profile.

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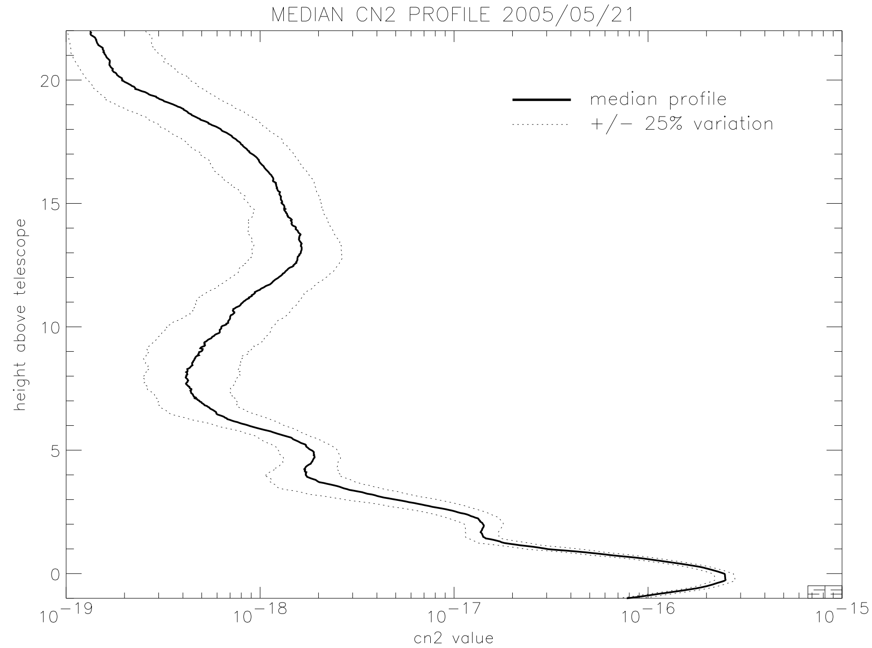

Figure 1. The median C_N^2-profile as measured with a Generalized SCIDAR in standard configuration for one night. The turbulence profile has a vertical resolution of around 1km, and no inner structure of e.g. the ground-layer peak can be seen.

For comparison, the vertical size Δh_p corresponding to one pixel on the detector in the auto-correlation image and along the axis of the binary can be calculated from simple geometry and is given by:

$$\Delta h_p = \frac{\Delta X}{\sin \vartheta} \tag{2}$$

which depends on the size of the detector pixel projected onto the telescope pupil ΔX. Usually ΔX is choosen in a way that Δh_p is similar to Δh_S, which can be accomplished, among others, by binning the CCD. Binning the CCD also helps to reduce the image processing requirements and to keep the read-noise of the CCD smaller than the photon-noise, but it does not result in a loss of vertical resolution, as long as Δh_p is smaller than Δh_S.

The vertical resolution $\Delta h_S(0)$ at the ground due to scintillation and the vertical size of one pixel Δh_p as a function of the separation of the used binary star is summarized in figure 2. With the diameter of the VATT of 1.75m, the optimal separation (resulting in a vertical resolution of better than 1km at the ground and a maximum attainable height of more than 20km) of the binary used for the SCIDAR is between 6" and 10". It can also be seen that in our case (CCD with 256×256 pixel), the vertical size Δh_p corresponding to one pixel is much smaller than the intrinsic vertical resolution $\Delta h_S(0)$ of the SCIDAR.

In spite of the fact that the GS delivers turbulence profiles with a typical vertical resolution of $\Delta h_S(0) \approx$ 1km, it would be highly desirable to obtain C_N^2-profiles with a much higher vertical resolution. This would be particularly useful for the design and development of the next-generation Adaptive Optics Systems (e.g. Ground-Layer AO or Multi-Conjugated AO), which correct single turbulent layers. To achieve optimal performance, it is therefore essential to know the location and the strength of these layers and especially the inner structure of the Ground-Layer, which usually contains most of the turbulence. Several methods were proposed (SODAR (SOund Detection And Ranging), meteorology masts, High-resolution SCIDAR,[10] etc.) to measure the turbulence in the Ground-Layer with high vertical resolution. However, all these methods either do not directly measure the optical effects of the turbulence, making the obtained data difficult to calibrate and interpret, or cannot be done with an exisiting SCIDAR instrument.

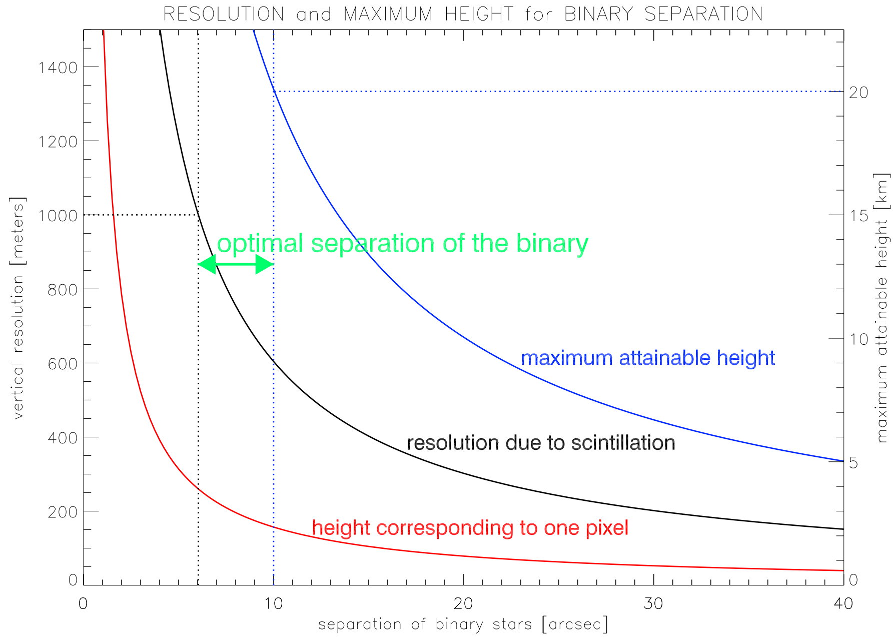

Figure 2. The achievable vertical resolution at the ground and the maximum attainable height above the conjugation plane of the detector versus the separation of the binary used for the SCIDAR observations. By choosing reasonable numbers for the desirable resolution at the ground and the maximum altitude, the range for the optimal separation of the binary for normal operation of the Generalized SCIDAR is for a telescope of 1.75m diameter between 6 and 10 arcsec.

In the next section we will present a new way to employ an already existing GS, which can provide a vertical resolution of the order of some tens of meters in the first few hundred meters above the ground.

2. HIGH VERTICAL RESOLUTION METHOD (HVR-GS)

As explained in the introduction, the vertical resolution of the SCIDAR is limited by the size of the correlation peaks. If the peaks associated to different turbulent layers could be somehow separated, the vertical resolution might be improved. Such a possibility is given by analysing – instead of the auto-correlation images – the temporal cross-correlation images for the calculation of the $C_N^2(h)$ profiles. When the wind-speed in two layers is different, their corresponding peaks in the cross-correlation images are no longer only separated by their different heights, but also by their different wind-speed & -direction. Under favorable conditions, the correlation triplets associated to two different layers are no longer only displaced along the axis of the binary, but shifted in a different direction, corresponding to the wind-speed $\mathbf{v}_{\mathrm{wind}}$ of the two layers (see e.g. fig. 3).

The shift $\Delta\mathbf{s}$ of the correlation triplets with respect to the center of the image is given by

$$\Delta\mathbf{s} = \mathbf{v}_{\mathrm{wind}} \cdot \Delta T_{cc}, \tag{3}$$

where $\mathbf{v}_{\mathrm{wind}}$ is the wind-speed and ΔT_{cc} the temporal lag used for the calculation of the cross-correlation image. The separation d_{triplet} in pixel of the lateral peaks for each triplet is related to the height h_{layer} of the turbulent layer can be derived from eqn. 2 via:

$$h_{\mathrm{layer}} = \frac{\Delta X}{\sin\vartheta} \cdot \frac{d_{\mathrm{triplet}}}{2} \tag{4}$$

Since for a given star, all the quantities in the first term are fixed, the vertical resolution is then only limited by the accuracy to determine the distance d_{triplet} of the lateral peaks for each triplet. For a peak sampled with at least a few pixels across, the center position can usually be determined with an uncertainty which is much smaller then the FWHM of the peak. Since – as explained in the introduction – the FWHM of the correlation peaks is the limiting factor for the vertical resolution in the conventional operation of the SCIDAR (i.e. by analysing the auto-correlation images), this new method which relies on the center position of the peaks offers the prospect to increase the vertical resolution by a significant factor. In the next section we will explain how this increase in accuracy translates into an increase in the vertical resolution of the C_N^2-profile.

With this high-vertical resolution (HVR-GS) method, the height h_i of the single layers can thus be determined very precisely. However, it is not possible to get from the intensities of the correlation peaks in the cross-correlation images directly the absolute C_N^2 value of the corresponding turbulent layer. However, the absolute values of the C_N^2 for the turbulent layers from the cross-correlation images $C_{N,cc}^2(h_i)$ can be determined from scaling the measured triplet intensities $I_{i,\mathrm{outside}}$ in the cross-correlation images with a common factor f_{scale} (assuming a the same temporal decorrelation of all the layers) to get the same total amount of turbulence as in the dome-seeing corrected $C_{N,ac}^{2*}(h)$ profiles (as determined from the auto-correlation images):

$$\int_{-\Delta h_S(0)/2}^{h_{GL}} C_{N,ac}^{2*}(h)\, dh \;=\; f_{\mathrm{scale}} \cdot \sum_i I_{i,\mathrm{outside}} \cdot h_i^{-5/6}, \tag{5}$$

where h_{GL} is the height of the highest layer identified in the cross-correlation images. The intensity $I_{i,\mathrm{outside}}$ of the central peaks of the triplets (in the absence of smearing due to wind shear) depends on the height h of the turbulent layer above the telescope[11] with $h^{5/6}$. To correct for this effect, the intensities of the central peaks of the triplets $I_{i,\mathrm{outside}}$ are scaled with $h_i^{-5/6}$. Furthermore, the thickness Δh_i of all the turbulent layers was assumed to be the same for all layers, which seems to be valid for our observations (see below).

In eqn. 5, the $C_{N,ac}^{2*}$ is calculated from the auto-correlation images, h_i is determined from the separation d_i of the lateral peaks for each triplet and $I_{i,\mathrm{outside}}$ is the measured intensity of the central peak for each triplet. Using these inputs, the scaling factor f_{scale} can be determined via eqn. 5 for each correlation frame. The value of $C_{N,cc}^2(h_i)$ for the single turbulent layers is then given by

$$C_{N,cc}^2(h_i) \;=\; f_{\mathrm{scale}} \cdot I_{i,\mathrm{outside}} \cdot h_i^{-5/6}. \tag{6}$$

In a similar way, the seeing in the single layers can be determined via

$$\epsilon_i \;=\; \left[\frac{0.409 \cdot (2\pi)^2}{\lambda^{1/3}} \cdot f_{\mathrm{scale}} \cdot I_{i,\mathrm{outside}} \cdot h_i^{-5/6}\right]^{3/5}. \tag{7}$$

In the following, we will discuss how this new high vertical resolution method can be used with an already existing SCIDAR instrument to retrieve high-resolution turbulence profiles near the ground and show some first results obtained at Mt. Graham.

3. ON-SKY METHOD VALIDATION

The SCIDAR observations to validate the HVR-GS method were conducted at the VATT observatory,[12] which is located on Mt. Graham in Arizona, the site of the LBT. A more detailed description of the LBT/GS can be found in Ref. 13 (this proceeding). Contrary to normal SCIDAR operation where usually 6000 frames (corresponding to 1 minute) were averaged to get one auto- & cross-correlation image, for the HVR-GS method, only 500 frames were used. The reason was to limit the smearing of the correlation peaks in the cross-correlation due to a variation in the wind-speed & -direction during the averaging time.

In order to test the HVR-GS method described above, a wide binary was observed for roughly 1 hour per night for a total of 5 nights during our SCIDAR measurement campaigns in May and December 2005. The observed binary star was in May β Cyg and in December ψ Psc, with a separation of 35" and 30" (see tab. 1), respectively. By using such a wide binary, the achievable vertical resolution can be improved by a factor of 5, as compared to a standard binary with a separation of 7". The conjugation height h_{GS} was set -3800 meters and a projected pixel size on the pupil of $\Delta X \approx 7$mm. For this configuration, the resolution $\Delta h_S(0)$ of the SCIDAR

Star	Separation [arcsec]	Brightness [$\text{mag}_1/\text{mag}_2$]
ψ Psc	30.0	5.27 / 5.45
β Cyg	34.7	3.37 / 4.68

Table 1. The observed binary stars for the on-ksy validation of the HVR-GS method.

in normal operation is around 200 – 230 meters (see eqn. 1), whereas one pixel on the detector corresponds to a vertical range Δh_p of 45 and 52 meters (see eqn. 2), respectively.

As a first step in the data reduction process, from all the measured cross-correlation images, we selected only frames in which the cross-correlation peaks have a circular shape. The other frames were discarded, because in these cases it would be not possible to distinguish between a vertical extend of the turbulent layer and a variation of the wind-speed &-direction during the averaging time. Furthermore, the total intensities of the single correlation peaks would be impossible to determine precisely. Then all peaks in the selected cross-correlation images were fitted with a 2-dimensional Gaussian to determine their central position. The accuracy of this procedure was determined by using the correlation triplet associated to the dome. This triplet is always at the same altitude and not shifted due to the wind and should thus always give the same center positions of the three peaks. When repeating the fitting procedure for different cross-correlation images, the standard deviation of the peaks' center positions was determined to be around 0.4 pixel. According to eqn. 4, this accuracy in determining the center position of the lateral peaks limits the achievable vertical resolution of the HVR-GS method. Using eqn. 2, the vertical resolution $h_{\text{HVR-GS}}$ can be calculated via

$$\Delta h_{\text{HVR-GS}} \;=\; 0.4\,\sqrt{2}\cdot\Delta h_p \tag{8}$$

For a binary separation of 35" and a $\Delta X \approx$ 7mm, this results in a vertical resolution $\Delta h_{\text{HVR-GS}} \approx$ 25m. This vertical resolution is thus a factor of 40 better than the one achievable with the SCIDAR in the standard configuration, which is around 1000m (see eq. 1).

From the cross-correlation images, we then calculated the intensity I_i of the central peak of each triplet. As explained above, to reconstruct the C_N^2-profiles, we used the $C_{N,ac}^2(h)$ profile as calculated from the auto-correlation images. The $C_{N,ac}^2(h)$ profile has of course a lower vertical resolution of only a few hundred meters, and also contains the dome-seeing. We therefore corrected for the dome-seeing in the $C_{N,ac}^2(h)$-profile with the method as described by Avila et al.[2] and Egner et al.[13] It relies on the analysis of the intensities of the central peaks of all the triplets $I_{i,\text{outside}}$ and I_{dome} in the cross-correlation image within the first resolution element $\Delta h_S(0)$ of the $C_{N,ac}^2(h)$ profile as determined from the auto-correlation images. Depending on their position in the cross-correlation image and thus their respective wind speed, the single triplets are associated with the ground-layer and the dome, respectively. The $C_{N,ac}^2(h)$ in the first resolution element $\Delta h_S(0)$ can then be corrected according to:

$$C_{N,ac}^{2*}\,(h < \Delta h_S(0)/2) \;=\; C_{N,ac}^2\,(h < \Delta h_S(0)/2)\;\cdot\;\frac{\sum I_{i,\text{outside}}/\alpha}{\sum I_{i,\text{outside}}/\alpha \;+\; I_{\text{dome}}}. \tag{9}$$

Where α corrects for the faster temporal de-correlation of the turbulence in the ground-layer compared to the turbulence inside the dome. For our observation[13] we found $\alpha \approx 0.82$.

With the dome-seeing corrected $C_{N,ac}^{2*}(h)$ profile, the scaling factor f_{scale} can then be calculated according to eqn. 5. The highest turbulent layer visible in the measured cross-correlation images was at around 600m, we thus chose $h_{GL} = 600\text{m}$ as the upper limit for the integration in eqn. 5. Finally, by using eqn. 6 and eqn. 7, the $C_{N,cc}^2(h_i)$ profile and the seeing ϵ_i in the single turbulent layers can be calculated.

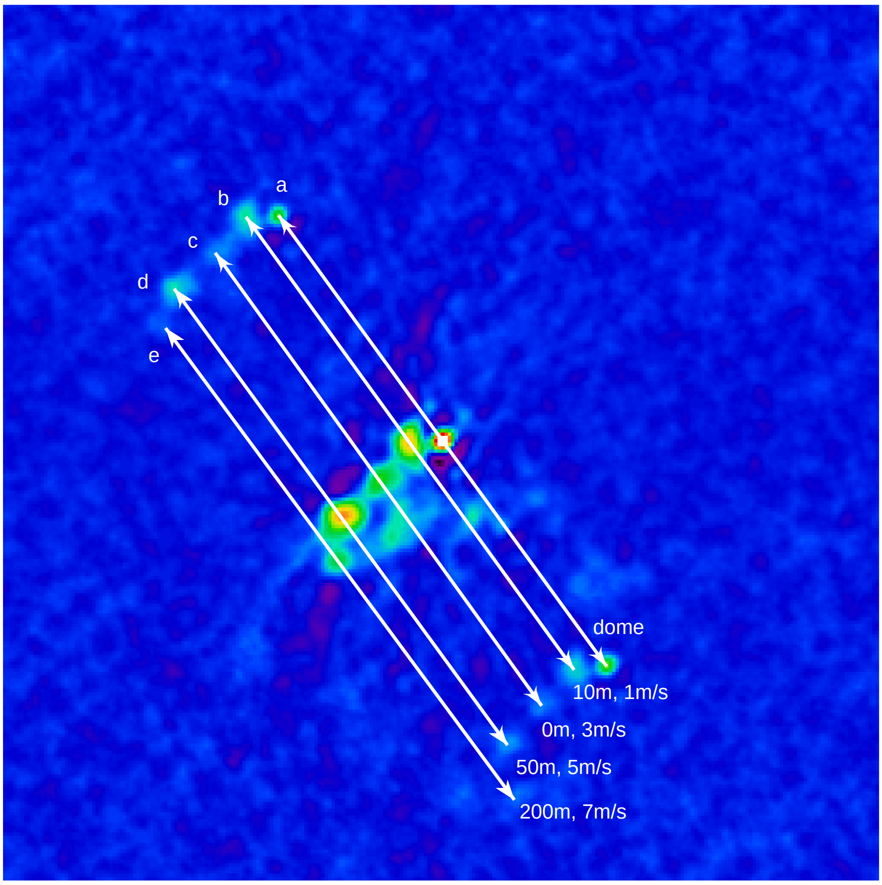

Figure 3. Sample cross-correlation image of β Cyg. For the detected triplets, the retrieved heights above the telescope and the wind speeds are indicated. The uncertainty in the height of the single layers is around 25 meters.

4. RESULTS

From the data taken with the wide binary, the $C^{2*}_{N,ac}(h)$ profiles can be retrieved from the auto-correlation images, just like in normal operation mode of the SCIDAR. Figure 4 shows the temporal evolution of the $C^{2}_{N,ac}(h)$ profile during ≈ 45 minutes in the night of 21 May 2005. When using such a wide binary, the vertical resolution $\Delta h_S(0)$ is improves from around 1 km (as in fig. 1) to around 200 meters.

Figure 3 shows a typical cross-correlation image and the identified triplets. Next to each triplet, the retrieved height and wind speed in indicated. The triplets (a) and (c) are associated to turbulent layers placed at the ground, but with different wind-speeds. The triplets (b), (d) and (e) are associated to layers placed at 10, 50 and 200m above the ground, respectively. From the determined heights and intensities of the triplets, the C^2_N-profile and the seeing in the single layers can be calculated with eqn. 6 and 7. A plot showing the equivalent seeing in the single layers for all the measured profiles for one night is shown in figure 5. In all profiles, a weak layer at the height of the VATT is visible and the strongest turbulent layer is located at ≈ 50m above the ground. As can be seen from the schematic topography shown in figure 6, the primary mirror of the LBT is ≈ 35m above the VATT and thus above the first weak layer, but still below the strong layer at ≈ 50m above the ground. Above the strong layer at around 50 meters, the strength of the turbulence drops down rapidly, with only one more distinct turbulent layer at around 350 meters. The height of this layer matches well with the layer seen in the $C^{2*}_{N,ac}(h)$ profiles as determined from the auto-correlation images (see fig. 4). This provides us a further confirmation of the reliability of the HVR-GS method.

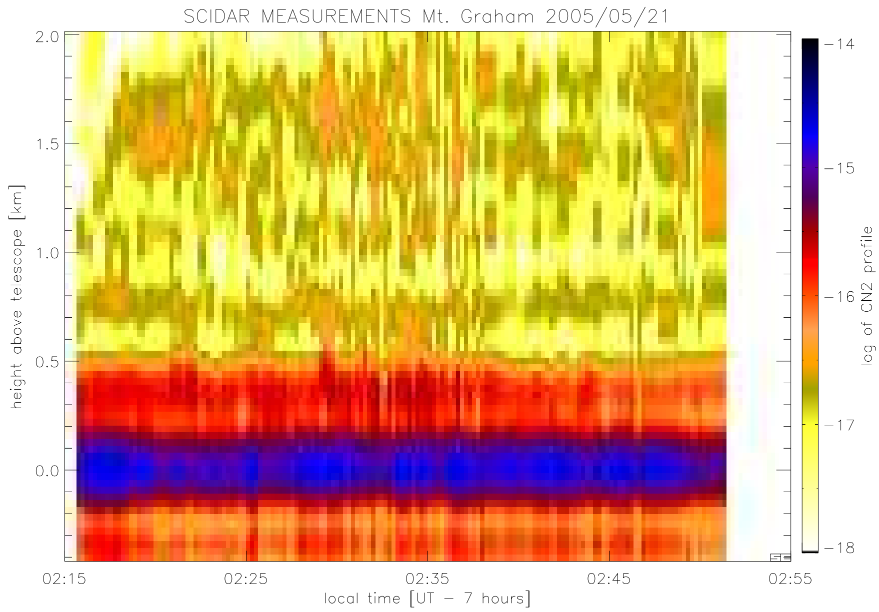

Figure 4. The temporal evolution of the $C_{N,ac}^{2*}(h)$ profile as determined from the auto-correlation images when using a wide binary with a separation of 35". According to figure 2, the maximum attainable height above the telescope is limited to around 2 km, and the vertical resolution is around 200 meters (as can be seen in the thickness of ground-layer turbulence).

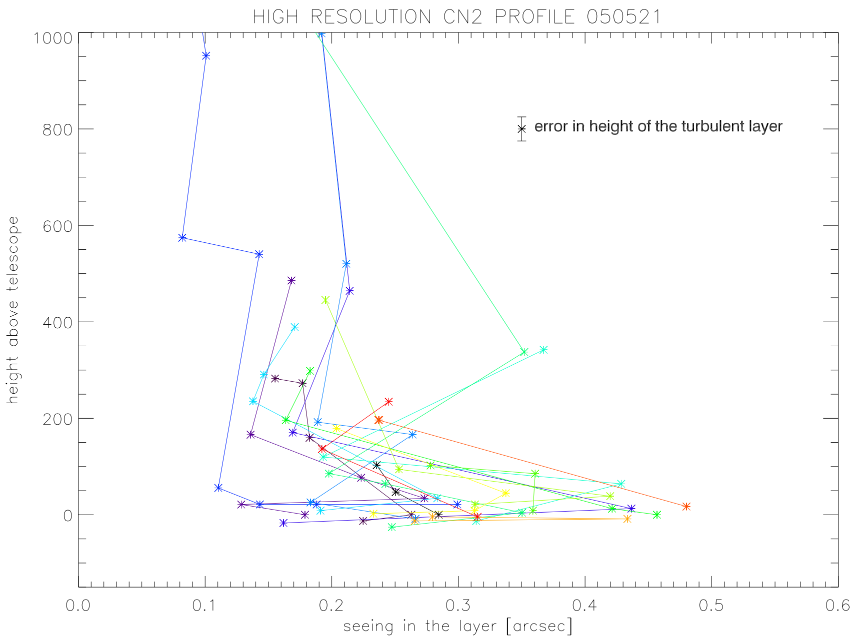

Figure 5. The seeing in the single layers as retrieved from the data of 21 May 2005. The vertical resolution is ≈ 25m (as indicated by the error bar). A weak layer is located just above the VATT, and the two major layers are located at 50m (by far the strongest layer) and 350m above the ground. The colors corresponds to different cross-correlation images taken during this night.

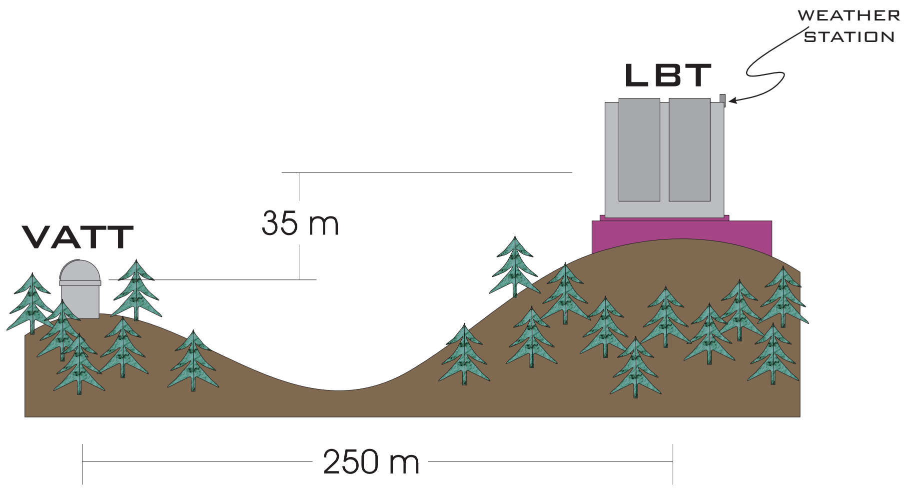

Figure 6. The topography and location of the telescopes on the peak of Mt. Graham. The VATT is as high as the trees, the LBT is placed on the top of the mountain. The primary mirror of the LBT is around 35 meters above the VATT.

Using the average C_N^2-profiles retrieved from the HVR-GS, the average seeing in the layer between the ground and the primary mirror of the LBT can be estimated. From the high-resolution profiles $C_{N,cc}^2(h_i)$, it is found that around 27% of the C_N^2 in the first 600m is below the primary mirror of the LBT, when assuming that the turbulence profile at the LBT is the same as measured at the VATT. For a total seeing of around 0.6" at the VATT for this night, and a seeing of 0.55" in the first 600m, this translates into a seeing of 0.52" above the primary mirror of the LBT. The turbulence profiles shown in figure 5 stress the impotance of the actual position of a telescope on a mountain and the height of the telescope above the ground, because 50m difference in height could make a large difference in the resulting seeing and thus image quality.

An anemometer placed on the roof of the LBT (see fig. 6), which is thus $\approx$ 50m above the VATT, measured at the time of the cross-correlation image shown in figure 3 a wind-speed of between 5 and 7 m/s. It thus matches very well the derived wind-speed of the turbulent layer at $\approx$ 50 meters above the VATT, as determined with the HVR-GS method.

5. CONCLUSION

A new method to determine the C_N^2-profile in the first 2km above the telescope with a vertical resolution of around 25m is presented. This high-vertical resolution method (HVR-GS) is based on the Generalized SCIDAR (GS) technique, but contrary to normal GS operation, it relies on the analysis of the cross-correlation images instead of the auto-correlation images and on using a wide binary star (with a separation of around 30"). With this method, the achievable vertical resolution can be increased by a factor of around 40, as compared to the one achievable with a SCIDAR in standard configuration. We showed the basic concept of this method and how to retrieve the C_N^2-profiles and the equivalent seeing in the single layers.

First results of this technique obtained with the existing GS/LBT instrument at the VATT on top of Mt. Graham are shown. The observed turbulent layers are rather thin ($<$ 25 meters), with a weak layer just outside the dome of the VATT and the strongest layer being located at around 50m above the ground. Since the primary mirror of the LBT is around 35m above the ground, it is below this strongest turbulent layer, and only the very first turbulent layer is below the LBT. For a total seeing, as measured at the VATT, of 0.6" for this night, the seeing above the primary mirror of the LBT is estimated to be around 0.52". The observed inner structure of the ground-layer turbulence underline the sensitivity of the achievable image quality on the actual position of the telescope on a mountain, because 50m difference in height above the ground can have a large impact.

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