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Scintillation Noise in Exoplanet Transit Photometry

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Abstract. Transit photometry is a powerful technique for studying exoplanets. Transit observations from the ground of targets of magnitude $V = 10$ or brighter, however, are limited by scintillation noise due to Earth's atmosphere. Through turbulence profiling using instruments such as the stereo-SCIDAR, we have shown to be able to accurately model scintillation noise, which is essential in order to fully account for the error budget of the observation. Through numerical modelling we find that employing scintillation reducing techniques enables an improvement of a factor between $1.36 - 1.6$ on the astrophysical parameters.

1. Introduction

Time series photometry is a powerful technique widely used in all areas of astronomy, including in the study of X-ray binaries (e.g. [1]), pulsars (e.g. [2]), white dwarfs (e.g. [3]), asteroseismology (e.g. [4]), brown dwarfs (e.g. [5]), exoplanets (e.g. [6, 7, 8]), as well as Kuiper Belt and Oort Cloud objects via occultations (e.g. [9]). In particular for exoplanet science, transit photometry provides a vast wealth of information not obtainable through other methods. Quantities obtained through transit photometry include the absolute dimensions of planetary and stellar radii, inclination and semi-major axis, when combined with an extra constraint. Photometry of the secondary eclipse allows the inference of unseen planets from timing, enables the measure of planets dayside flux emission and gives constraints on the planet's orbital eccentricity.

Ground-based photometric observations play an important role in the field of exoplanet science as they are three orders of magnitudes less costly than space-based observations. For this reason, the availability of observing time from the ground is far higher than that in space. However, observations from the ground have the major drawback of suffering from the degrading effects of the Earth's atmosphere. For time-series photometry, scintillation arising from the Earth's atmosphere is a major source of noise on observations which causes the quality of data from the ground to be significantly worse compared to that obtained from space.

Scintillation arises due to high altitude optical turbulence in the Earth's atmosphere. As opposed to *seeing*, which arises from perturbations in phase, scintillation is a result of interference during propagation, and cannot be corrected by most adaptive optics techniques.

2. When is Scintillation a Problem?

The effects of scintillation have been well studied in the past [10] [11][12][13]. For exposure times t_{exp} of typical for exoplanet photometry (of a few seconds) and typical telescope diameters D ,



the noise due to scintillation can be calculated via [14],

$$\sigma_I^2 = 10.7 \cos(Z)^{-3} \int_0^\infty \frac{C_n^2(h)h^2}{V_\perp(h)} dh D^{-4/3} t_{\text{exp}}^{-1}, \quad (1)$$

which is a function of the integrated sum of the turbulence strength, $C_n^2(h)$, the horizontal windspeed, $V_\perp(h)$ and the height of each layer h . Because of this, in order to accurately model scintillation effects in long exposures, we require measurements of the wind speed $V_\perp(h)$ in addition to the turbulence profile. We note that since transit observations are performed during the course of several hours, the effect of changing airmass, arising from the change zenith angle Z , also has an observable effect on the quality of the transit data (see [15]).

For the average turbulence profile for La Palma, this equates to a magnitude of $V = 10.36$, below which scintillation noise is the dominant source of noise on photometry. While this was calculated for a small, $D = 0.5\text{m}$ telescope, this value only has a weak, $D^{-1/3}$ dependence and is independent of the exposure time used.

3. Measurements of Scintillation

Between 2014-03-13 and 2014-03-17 we ran a campaign on the Isaac Newton Telescope on La Palma using the stereo-SCIDAR instrument for turbulence profiling [16]. From data we were able to produce estimates of the expected amount of scintillation over the course of the night. Figure 1 shows an example of the calculation of the atmospheric parameter $\sum C_n^2(h)h^2/V_\perp$ obtained from the stereo-SCIDAR profile for the night of 2014-03-15. The perpendicular wind velocity V_\perp was obtained by interpolating the velocity vectors obtained from stereo-SCIDAR to the whole atmosphere.

The scintillation measurements were compared to the actual variance on simultaneous transit observations made using ULTRACAM on the 4.2m William Herschel Telescope and the 0.5m *pt6m*. Figure 2 shows an example of a comparison for two stars of brightness around 13.2 Vmag (see [17]). As the night progressed, the scatter on the ULTRACAM measured data was found to improve, coinciding with the scintillation prediction from stereo-SCIDAR, indicating that the noise additional to the known photon and instrument noise is caused by scintillation. The 3 nights of comparisons yielded a total of 390 data points which were found to have a Pearson correlation coefficient of 0.9, indicating a good agreement.

4. Correcting for Scintillation and Improvements on Astrophysical Parameters

Previous results for scintillation correction using conjugate-plane photometry (see [18]) have shown that, depending on the atmospheric conditions, we can obtain an improvement of a factor of 2 on transit photometry. Using Markov-chain Monte-Carlo methods, we found that this would enable an improvement in the range of 1.36 - 1.6 on the scatter on all astrophysical parameters.

5. Conclusions

Scintillation is a limiting source of noise for ground-based observations of bright targets. We have shown that we can obtain an accurate measure of photometric scintillation noise through the measurement of the atmospheric turbulence profile. We are currently working on techniques for scintillation reduction, one of which is conjugate plane photometry, which has been shown to be capable of reducing scintillation noise to the level of photon noise. Modelling has shown that such an improvement would result in a measurement improvement of a factor of ~ 1.5 on all astrophysical parameters.

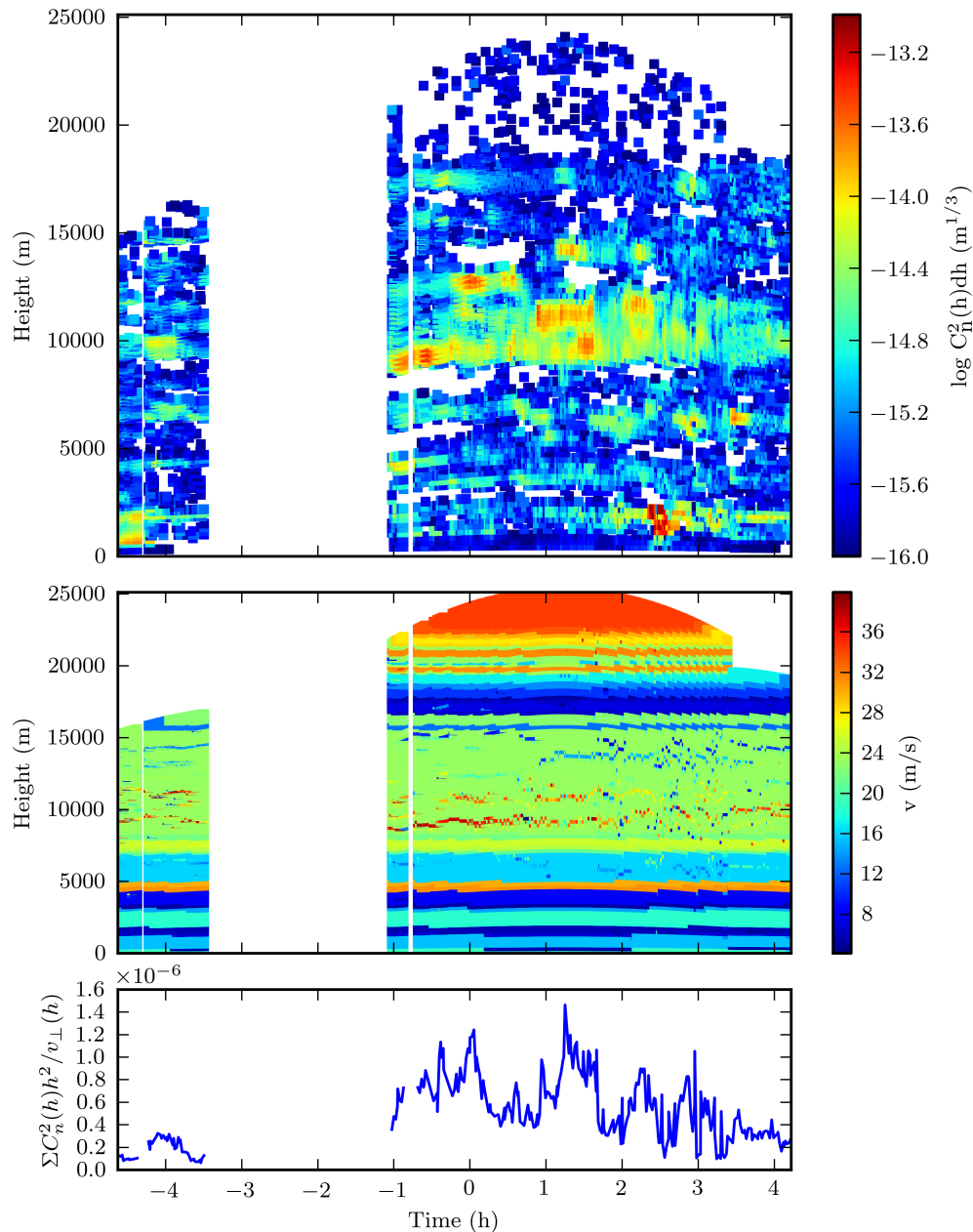


Figure 1. Atmospheric data for the night of 2014-03-15 obtained using Stereo-SCIDAR on the 2m Isaac Newton Telescope Telescope. The top panel shows the measured C_n^2 profile with height. Data points with C_n^2 weaker than $10^{-16} \text{ m}^2/3$ have been removed for clarity. The middle panel shows the determined average wind velocity for the layers for each night. The bottom panel shows the calculated sum of $C_n^2(h) h^2 / V_{\perp}$ from the information in the top two panels.

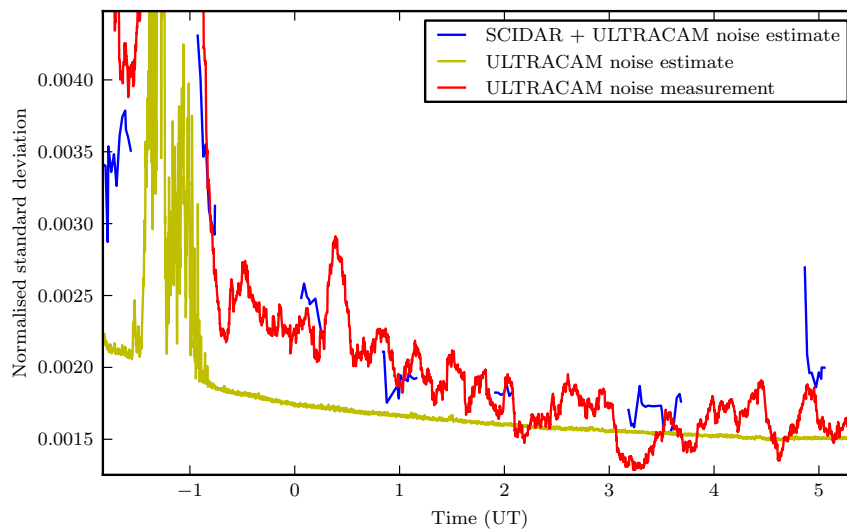


Figure 2. Comparison between predicted and measured scintillation from ULTRACAM on 2014-03-16 in the g' band. The red line shows the normalised standard deviation of the measured flux from ULTRACAM. The prediction from SCIDAR (blue) takes into account scintillation, which is scaled according exposure time, telescope diameter and airmass of the observation, and the predicted noise from ULTRACAM. The predicted ULTRACAM noise includes photon noise and the small amount of system noise in ULTRACAM, shown in yellow. The sharp spikes in the yellow line are caused by the transparency variations and the gradual curve in the line is due to the changing extinction due to changing airmass.

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