

Characterization of optical turbulence at the solar observatory at the Mount Teide, Tenerife

Detlev Sprung, Erik Sucher

Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, Gutleuthausstr. 1,
76275 Ettlingen, Germany

ABSTRACT

Optical turbulence represented by the structure function parameter of the refractive index C_n^2 is regarded as one of the chief causes of image degradation of ground-based astronomical telescopes operating in visible or infrared wavebands. Especially, it affects the attainable spatial resolution. Therefore since the middle of September 2012 the optical turbulence has been monitored between two German solar telescopes at the Observatory in Tenerife /Canary Islands /Spain. It comprises the solar telescope GREGOR and the vacuum tower telescope VTT mounted on two 30 m high towers. Between the two towers at the level of the telescopes, C_n^2 was measured using a Laser-Scintillometer SLS40 (Scintec, Rottenburg, Germany). The horizontal distance of the measurement path was 75 m. The first results of the measurements starting from the 15th September 2012 up to the end of December 2012 are presented and analyzed using simultaneous measured meteorological data of wind, temperature and humidity. Daily and seasonal variations are shown and discussed.

Keywords: scintillometry, optical turbulence, turbulence at astronomical telescopes.

1. INTRODUCTION

Observations with ground based telescopes suffer from atmospheric turbulence. Fluctuations in the refractive index, caused by temperature and humidity variations, are responsible for image degradation and reduction of the attainable resolution. These turbulent fluctuations are called optical turbulence and are quantified by the intensity of the structure function of the refractive index C_n^2 . Especially astronomical telescopes operating with visible or infrared wavebands are affected. The maximum telescope resolution is called “astronomical seeing”. It is defined as the integral of C_n^2 over the propagation path and describes the turbulent state of the atmosphere.

Some important parameters characterizing the quality of seeing and the telescope design are dependent on the integral of the vertical distribution of optical turbulence. For example one is the atmospheric coherence length or Fried parameter r_0 ¹, that is an upper bound for the aperture diameter in maximizing the normalized signal-to-noise ratio (SNR) and is a measure for the attainable resolution. Another parameter is the Greenwood time constant that specifies the time interval over which Taylor’s theorem of frozen turbulence will be considered as fulfilled¹.

Most telescopes are used in nighttime observation of stars. So many methods have been developed to derive the vertical profile of C_n^2 from star or double star observations at the observatory site. These include techniques using the scintillation of the star light, like different SCIDAR (Scintillation Detection and Ranging) methods^{2,3,4} or the MASS (Multiaperture scintillation sensor) technique^{2,5}. Other methods like SLODAR (Slope Detection and Ranging)⁶ analyze the beam wander (Angle-of-Arrival technique) of the light of an observed star. The investigation of the boundary layer is pronounced in these methods very different. Therefore responsible is vertical resolution of the invented profiles and the detection ability at the lowest levels of the atmosphere.

Meteorological techniques (SODAR (Sound Detection and Ranging) or ultrasonic anemometers) for the characterization of the optical turbulence of atmospheric boundary layer were only be reported published for site investigations^{7,8}.

Investigations of the vertical profile of C_n^2 during the day, interesting for solar observatories, have been performed very rarely at telescope sites. One used technique is SHABAR (Shadow Band Ranger) method^{9,10} that uses the properties of

solar scintillations. An array of solar scintillometers measures the vertical profile of optical turbulence in the lower atmosphere.

Two methods for the investigation of the vertical profile of C_n^2 during the day from solar observations have been developed at the Kiepenheuer Institute of Solar Physics (KIS) /Freiburg /Germany using the Shack-Hartmann wave front sensor¹¹ or the Foucault-technique¹². During the day the atmosphere at telescope level and a few meters above is expected to provide an important contribution on the vertical profile of optical turbulence¹³.

For the new GREGOR observatory built up 75 meters aside from the older VTT (Vacuum tower telescope) at the German solar observatory on the mountain ridge of Mount Teide at Tenerife /Canary Islands /Spain, we installed in Co-operation with the KIS a laser scintillometer SLS40 to investigate the optical turbulence at telescope level continuously with a high temporal resolution. The location close below the mountain ridge let classical theories of boundary layer meteorology fail. The turbulence is more influenced by orographic effects and mesoscale flow patterns.

The effect of the telescope on the optical turbulence should be investigated. Also the portion on the integrated turbulence of the total vertical profile retrieved and analyzed at the solar observatory with the methods mentioned before, should be estimated.

In this article we present the first measurement on C_n^2 of this experiment started in the middle of September 2012. Additionally some meteorological data are displayed to describe the atmospheric conditions at the location of the solar observatory at Mount Teide.

2. EXPERIMENTAL SETUP

The challenge of this atmospheric research is to characterize the optical turbulence at telescope level for the German solar observatory on the mountain ridge of Mount Teide on Tenerife at the Canary Islands / Spain. The mountain ridge is orientated from southwest to towards northeast. The geographical coordinates are given with $16^{\circ}30'35.70''W$, $28^{\circ}18'8.83''N$ and it has an elevation of 2384 m a.s.l.. The German / European observatory consists of two towers with the telescopes GREGOR and VTT (Vacuum Tower Telescope). They are part of the international Mount Teide Observatory. A picture of the observatory with the two telescope towers is presented in figure 1. The GREGOR observatory is at the left (northeast) end, the VTT on the right) The telescope level is at about 30 m above ground. The horizontal distance between the two telescopes is about 75 m. A detailed description of the operation of the two telescopes is given in a publication of this proceedings by Soltau et al. (2013)¹⁴.



Figure 1. The German telescopes GREGOR (left) and VTT (Vacuum Tower Telescope) at the mountain ridge of Mount Teide / Tenerife /Canary Islands /Spain.

For the determination of the deep optical turbulence between the two telescopes, a surface layer laser scintillometer (SLS40, Scintec, Rottenburg / Germany) was installed at the observatory.

This instrument is often used as ground truth device for the determination of the optical turbulence close to the ground (e.g. Sprung et al. (2011))¹⁵. The SLS40 consists of a transmitter, sending out two locally separated laser beams with a wavelength of 670 nm. The two beams are vertically and accordingly horizontally polarized and their scintillations are monitored with 2 Si-detectors at the receiver. From the covariance and variances of the scintillation signals of the two beams, C_n^2 can be inferred. The time period of the averaged C_n^2 was permanently set to one minute. It was tried to run the device continuously.

For this experiment the receiver of the SLS40 was installed on the top of the GREGOR-tower, shown in figure 2. The transmitter was set at the top of the VTT. So the integrated turbulence between the two telescopes could be measured at an average height of about 30 m above ground. According to the weighting function of the Laser-scintillometer, the major contribution of the optical turbulence signal comes from the middle of the horizontal line between the two towers.



Figure 2. Receiver of laser-scintillometer SLS40 on top of the GREGOR tower, viewing towards the transmitter on the VTT at telescope level 30 m above ground.

Additionally, close to the SLS40 meteorological instruments have been installed on top of the GREGOR-tower. These include a Reinhardt-weather station (Reinhardt System und Messelectronic GmbH, Germany) with wind vane and anemometer as well as 4 thermocouples measuring the temperature at the surface of the platform of the GREGOR-tower and in the heights of 0.3 m, 1.3 m, and 1.6 m above it. Also the relative humidity and pressure were measured. The meteorological data were also collected every minute. All data could be downloaded remote from our institute.

3. RESULTS AND DISCUSSION

Results of the measurements are presented here, for a period from 15th September 2012 will be presented here for a time period up to the end of the year 2012. An instrumental failure in January led to an interruption in the measurements. The results are split off in to meteorological data characterizing the measurement site and in results on optical turbulence.

3.1. Site characterization

First the wind situation for the observatory is regarded. Tenerife belongs to the region of the prevailing north-easterly trade winds in the lower atmosphere close to ground level. They are caused by an often met surface anticyclone.

Figure 3 displays the wind rose our total set of 1-min-wind data of 2012. The main wind direction was from the north-west up to the north. The reason for this is the counterclockwise turn of wind direction with height (Ekman-layer)¹⁶. The wind direction is also affected by the mountain ridge and the building themselves. Therefore all wind directions could be found. Southwesterly and westerly flows are attributed to Atlantic low pressure perturbations. The highest wind speeds could be found in the north and west-southwesterly directions with more than 25 m/s. The whole wind situation is can be regarded as stable by the prevailing north-northwesterly winds.

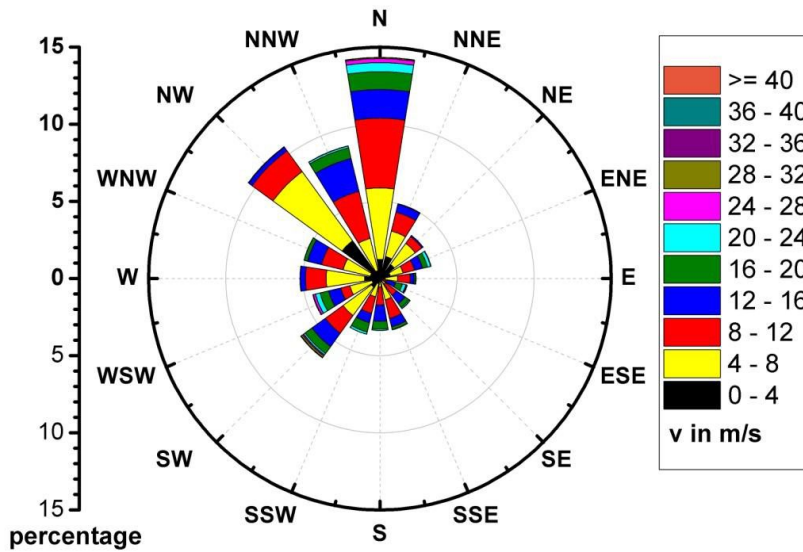


Figure 3. Wind-rose of the percentage frequency of all wind data from 15th September 2012 to 31st December 2012. The color indicates the frequency of monitored wind speeds.

Figure 4 displays as an example the time series of the data for September 2012 of the 4 temperatures at different height level at and above the platform (a) and the relative humidity (b) at the receiver level 1.3 m above the platform. The four temperatures of the vertical distribution between platform surface and 1.6 m height exhibit strong daily variations. In fine weather situations the amplitude between daily maximum and early morning minimum was about more than 12 K. Especially the cooling and heating of the platform surface on some days is very evident (black line). A strong temperature layering is build up in the lowest 1.6 meters above the platform.

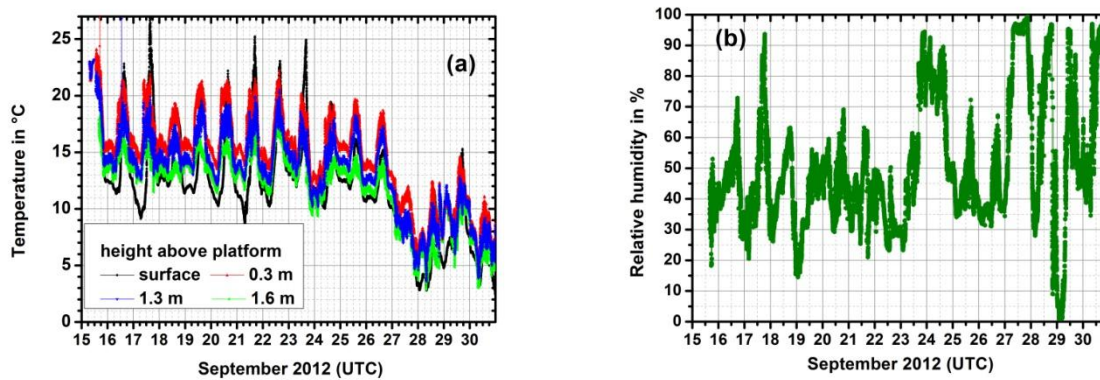


Figure 4. time series of 4 temperature measurements for September 2012 (a) at the ground of the platform (black), 0.3 m above it (red), 1.3 m above ground (height of receiver, blue), and 1.6 m above platform (green) and relative humidity (b).

The relative humidity in figure (4b) demonstrates the different air masses. Strong humidity with up to 100% relative humidity can be found. At this time fog or clouds are expected at the telescope level, constraining the sight line of the scintillometer or solar observations. But also very dry conditions with less than 20% relative humidity could be

observed. The weather situations with high relative humidity increase during the months October and November and became a little bit more favorable again in December (not shown here).

These measurements describe very well the conditions affecting the results of the optical turbulence.

3.2. Optical turbulence

Temperature fluctuations and gradients as well as the influence of the mechanical forces of wind stress affect the optical turbulence directly. The dynamical turbulence processes of heating respectively cooling, and wind shear are responsible for the optical turbulence, that we measured directly with the laser-scintillometer. Therefore the timeseries of C_n^2 is presented for the 3.5 months of measurements at the end of 2012 in figure 5. It is very obvious that the nighttime values are often missing. This is attributed to a problem of the SLS40 instrument that shows a slight drift in the position of the laser-beam with temperature. Strong cooling could lead to the lack in data during the night. The daily cycle with maxima around noon are very evident for September. During October and November more and more data got lost with increase situations of bad weather and clouds prohibiting good measurements of C_n^2 . Nevertheless the solar observatory is not so affected, because no solar measurements were performed during that time. Depending on the weather situation the diurnal cycle is more evident. Then minima in optical turbulence at the neutral conditions of the atmosphere could be observed. The daily maxima in optical turbulence were about $2 \cdot 10^{-13} \text{ m}^{-2/3}$.

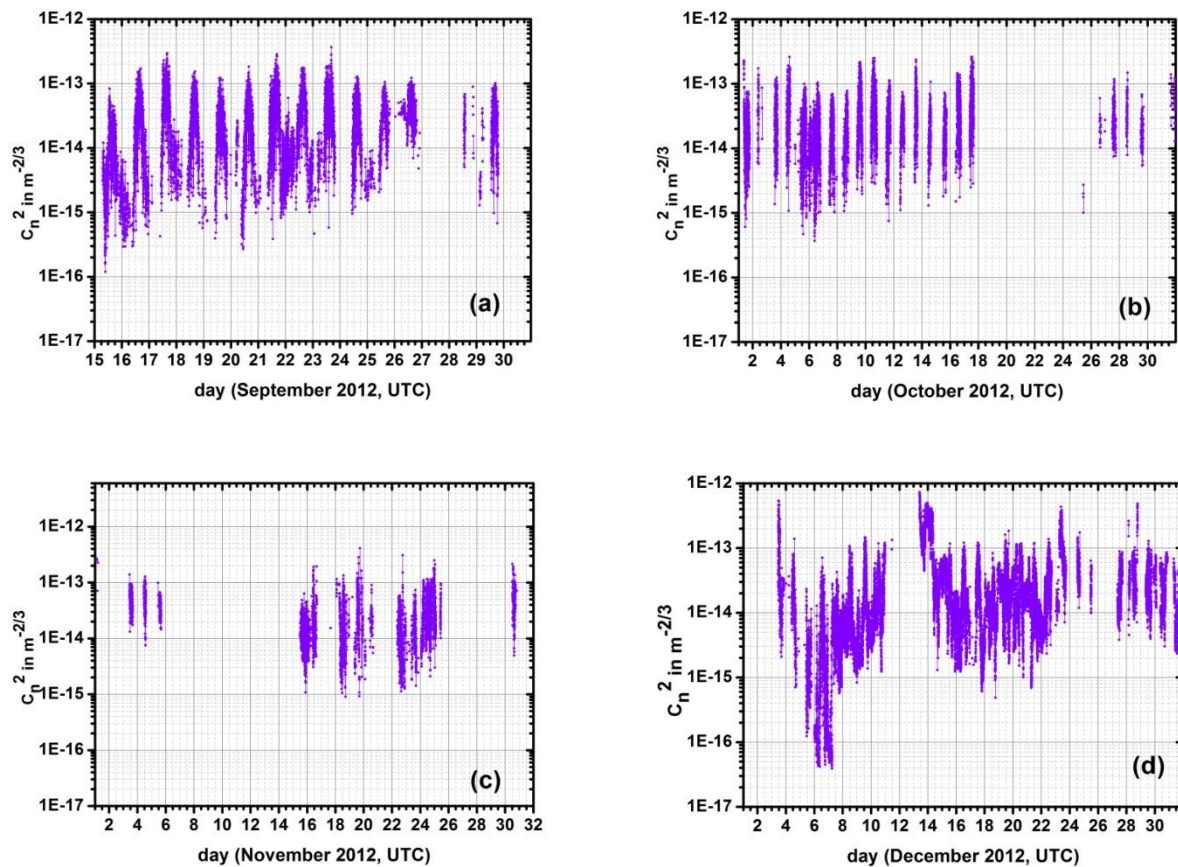


Figure 5. Time series (given in UTC) of C_n^2 for 4 months from 15th September to 31st December 2012, (a) September, (b) October, (c) November, and (d) December.

In December the data availability increases. The variability of the values of C_n^2 was more evident, too. Trusting in our data, the highest and lowest values of optical turbulence occurred during this month. The cloud events were less frequent.

From the time series data in figure 6, diurnal cycle of C_n^2 are plotted for the 4 months. In September the diurnal cycle is very clear with minima at the neural condition during sunrise and sunset as about 9:00 UTC and 20:00 UTC. The maxima reach values of $2 \times 10^{-13} \text{ m}^{-2/3}$. At October and November the variability during daylight increases. The diurnal cycle shows more noise. The trend also develops that the nighttime values were of the same order as the daytime values for November but even more clear for December. For December an estimated percentage of above 90% would lie in the range between $1 \times 10^{-15} \text{ m}^{-2/3}$ and $1 \times 10^{-13} \text{ m}^{-2/3}$ showing a variation of two orders of magnitude. Very low value of about $1 \times 10^{-16} \text{ m}^{-2/3}$ are attributed to a very calm weather conditions.

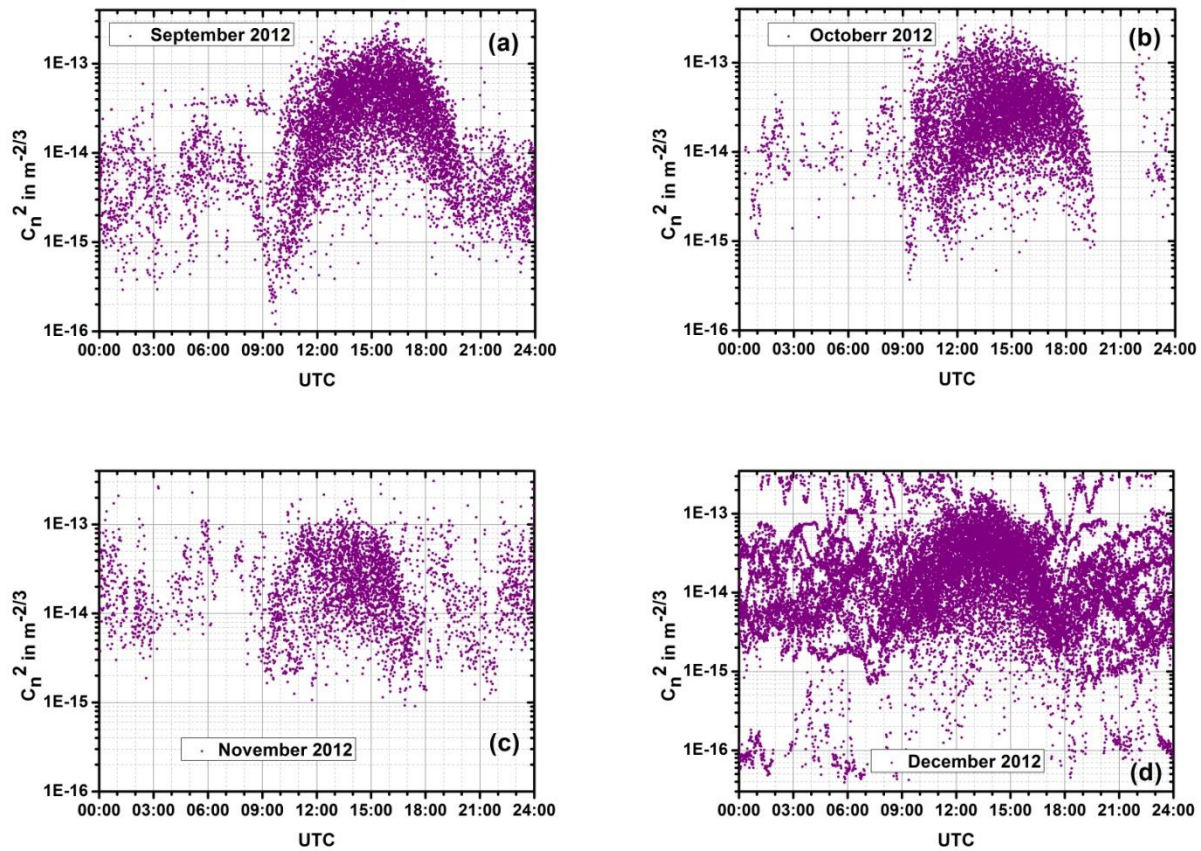


Figure 6. Diurnal cycle of C_n^2 for (a) September, (b) October, (c), November, and (d) December 2012.

In figure 7 the frequency distribution for the intensity of the optical turbulence for the 4 months is presented. It becomes evident that for all four month the maximum intensity of optical turbulence is about $3 \times 10^{-14} \text{ m}^{-2/3}$. Also in this picture the stronger diurnal amplitude can be seen for September. Very low values seem to be missed during October and November due to the bad weather conditions with missing data. In figure 7 the nighttime values are excluded. This figure shows the conditions typically to be met for the solar observations of the specific month.

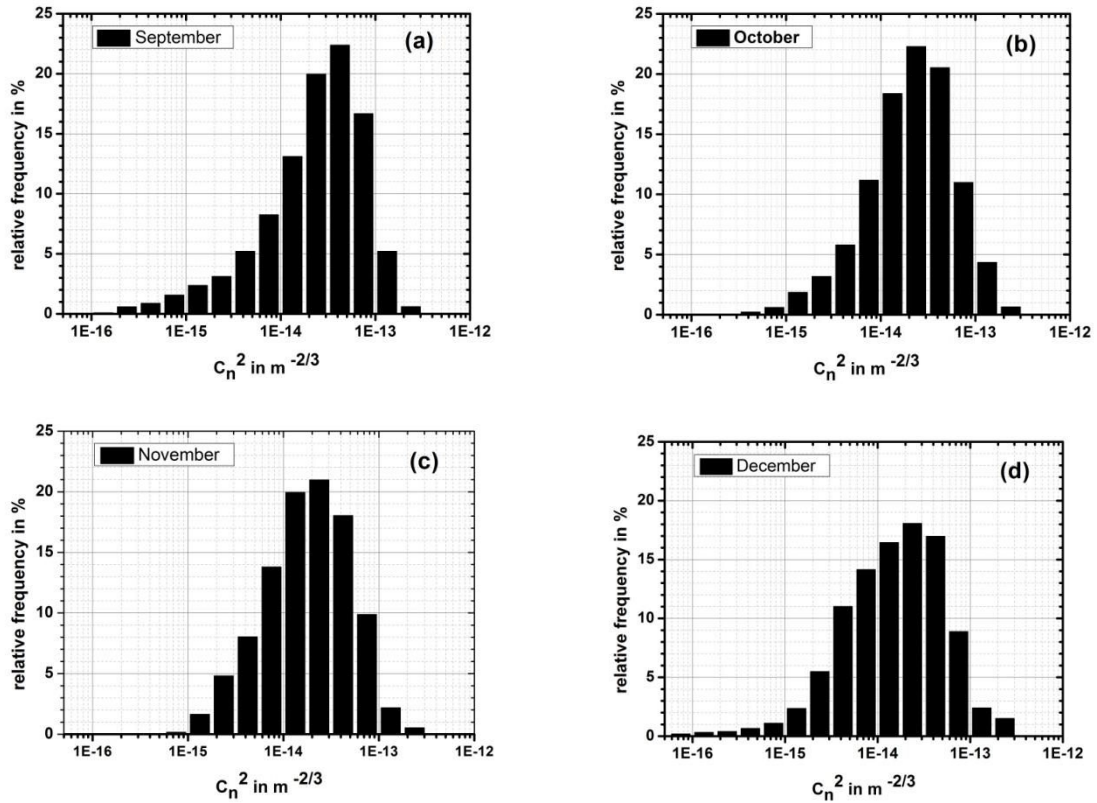


Figure 7. Frequency distribution of the daytime values (9:00-19:00 UTC) of C_n^2 for September (a), October (b), November (c), and December (d) 2012.

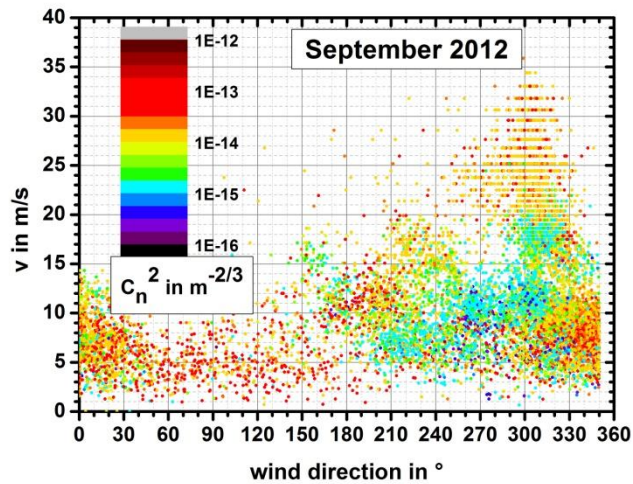


Figure 8. 1-min mean values of C_n^2 of September 2012 dependent on wind direction and wind speed. The color coding displays the intensity of C_n^2 in $m^{-2/3}$.

According to figure 8 we try to find a dependency of optical turbulence on the wind influence. Here the intensity of C_n^2 is displayed in colors referring to wind direction and wind speed. For southwesterly and westerly wind directions there seems to be a minimum in the strength C_n^2 . The minimum correspond to wind speeds between 5 m/s and 15 m/s increasing when the wind turns to the west. But very high wind speeds continued by decreasing C_n^2 are only measured for the north-westerly to north directions. But this could so far not be ascertained because references are missing. The other months did not show such a behavior. Besides of September the last 3 months of 2012 are not favorable for an analysis of optical turbulence by the prevailing weather conditions.

4. SUMMARY, CONCLUSIONS, AND OUTLOOK

First data analysis of optical turbulence measured at the telescope level of the German observatory at Tenerife is presented. The meteorological data and especially the wind data are dominated by the general circulation, the altitude above sea level and the mountain ridge. The heating of the tower surface could also influence the optical turbulence close to the opening of the telescope. At all there seemed to be an effect on the scintillometer measurements by fluctuations in the position and intensity of the laser beam. This resulted in data lost mainly at night. The observed diurnal cycle of C_n^2 observed in September disappears in the following months. High relative humidity fog and clouds prohibited the scintillometer measurements. In December more measurements were performed. But the variability in optical turbulence seemed to be very high. The reason for this could not be investigated, yet. It might be attributed to instrumental problems or it might be even realistic. In January an error in the measurement system arose.

Maximum values of optical turbulence were about $2 \cdot 10^{-13} \text{ m}^{-2/3}$ for all the four month. Minimum values were about $1 \cdot 10^{-16} \text{ m}^{-2/3}$. A dependency on wind conditions seems to be evident for September. There seems to be a situation of wind speeds increasing from 5 m/s to 15 m/s by turning from southwesterly to westerly directions, at which the optical turbulence exhibits a minimum.

Monthly mean values of the vertical distribution during nighttime of C_n^2 up to the height of the tropopause have been published^{3,4,17}. The monthly nighttime mean values for the level of the telescope were about $5 \cdot 10^{-16} \text{ m}^{-2/3}$ and so in the range our lowest measured nighttime values of December. The nighttime values as indicated in figure 6 are highly variable. So it is difficult to compare them to with monthly averages. To our knowledge for the daytime situation no data of optical turbulence were published until now. So these are the first measurements direct at telescope level of Mount Teide. Also daytime values of optical turbulence measurements at telescope level of other observatories are not known, but should exist^{7,9,10}.

We hope to extend the measurements for other months. Especially the summer months are expected to be very exciting. The optical turbulence gave much higher values than indicated by other methods in the literature before. That must be also assured. The difficulty by data loss during night due to an outside temperature drift, should be overcome in future measurements by stabilizing the system housing of the SLS40 instrument. Additional turbulence measurements are planned by using ultra-sonic anemometer to provide direct optical turbulence measurements above the telescope. These could ascertain the high values of optical turbulence and show how representative deep turbulence is between the towers, i.e. how the measured C_n^2 values have to be considered with respect to the influence of optical turbulence on the imaging quality of the solar observation. The measurements could also provide a good comparison to measurements of the vertical profile of optical turbulence using methods developed at the Kiepenheuer Institute for Solar Research¹².

ACKNOWLEDGEMENTS

We thank German armed forces of the WTD91 for the financial support of these measurements. We thank the staff from the Kiepenheuer-Institute for Solar Physics Freiburg /Germany for their technical support at Tenerife.

REFERENCES

- [1] Andrews, L.C., "Field guide to atmospheric optics", J.E. Greivenkamp (series ed.), SPIE press, Bellingham/USA, 2004.
- [2] Tokovinin, A., J. Vernin, A. Ziad, M. Chun, "Optical turbulence profiles at Mauna Kea Measured by MASS and SCIDAR", Publications of the Astronomical Society of the Pacific, 117, 395-400, 2005.
- [3] Fuensalida, J.J., B. Garcia-Lorenzo, J.M. Delgado, M.A.C. Rodriguez-Hernandez, and J. Vernin, "Sampling and characterization of the turbulence vertical distribution, statistics of SCIDAR profiling", *RevMexAA*, 31, 84-90, 2007.
- [4] Garcia-Lorenzo, B., J.J. Fuensalida, J.A. Castro-Almazan, and M.A.C. Rodriguez-Hernandez, "Statistical behaviour of atmospheric turbulence at the Teide Observatory", *Optics in Atmospheric Propagation and Adaptive Systems XII*, Proc. SPIE 7476, doi.10.1117/12.830236, 2009.
- [5] Wilson, R.W., SLODAR: measuring optical turbulence altitude with a Shack-Hartmann wavefront sensor, *Mon. Not. R. Astron. Soc.* 337, 103-108, (2002).
- [6] Vernin, J., and m.o., "European Extremely Large Telescope Site Characterization I: Overview", Publications of the Astronomical Society of the Pacific, 123, 1334-1346.
- [7] Skidmore, W., T. Travouillon, and R. Riddle, "Evaluation of sonic anemometers as highly sensitive optical turbulence measuring devices for the thirty meter telescope sit testing campaign", Proc. SPIE 6267, 62671Z, doi: 10.1117/12.671518, 2006.
- [8] Riddle, R.L., W. Skidmore, T. Travouillon, M. Schöck, and S. Els, "TMT site testing survey: instrument, methods and operations", in [Optical Turbulence – Astronomy meets Meteorology], Proceedings of the Optical Turbulence for Astronomical Applications, eds E. Masciadri and M. Sarazin, Imperial College Press, London, p. 90-97, 2009.
- [9] Beckers, J.M., "Seeing Monitor for Solar and other extended object observations, *Experimental Astronomy* 12,1 (2001).
- [10] Hill, F., and m.o., "Solar site testing for the advanced technology solar telescope", Proc. SPIE 5489; 122, doi:10.1117/12.551812, 2004.
- [11] Waldmann, T.F., "Untersuchung der Turbulenzstruktur der Atmosphäre mithilfe von Hartmann-Shack Wellenfrontensordaten", diploma thesis, Albert-Ludwigs-University of Freiburg, 2007.
- [12] Thomann, M., "Bestimmung des Turbulenzhöhenprofils der Erdatmosphäre mit der Focault-Methode", diploma thesis, Albert-Ludwigs-University of Freiburg, 2011.
- [13] Racine, R. "An astronomer's view of optical turbulence", in [Optical Turbulence – Astronomy meets Meteorology], Proceedings of the Optical Turbulence for Astronomical Applications, eds E. Masciadri and M. Sarazin, Imperial College Press, London, p. 13-22, 2009.
- [14] Soltau, D., T. Berkefeld, D. Schmidt, and O. Von der Lühe, "Solar adaptive optics at the Observatorio del Teide, Tenerife", Proc. SPIE 8890-50, 2013.
- [15] Sprung, D., P. Grossmann, E. Sucher, K. Weiss-Wrana, and K. Stein, "Stability and height dependant variations of the structure function parameters in the lower atmospheric boundary layer investigated from measurements of the long-term experiment VerTurM (vertical turbulence measurements)," *Optics in Atmospheric Propagation and Adaptive Systems XIV* 8178(1), 817809, SPIE (2011).
- [16] Stull, R.B., [An introduction to boundary layer meteorology], Kluwer Academic Publishers, Dordrecht, 1988.
- [17] Garcia-Lorenzo, B., A.Eff-Darwich, J.J. Fuensalida, and J.A. Castro-Almazan, "Estimation of adaptive optics parameters from wind speed: Results for the Teide Observatory", *Optics in Atmospheric Propagation and Adaptive Systems XII*, Proc. SPIE 7476, 74760F doi.10.1117/12.830390, 2009.