Optical Turbulence Model for Laser Propagation and Imaging Applications

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ABSTRACT

We evaluate a simple model for predicting and understanding the structural behavior of C_n^2 for a specific location, date, time, and given environmental parameters. This model is compared with C_n^2 data taken at the Chesapeake Bay Detachment of the Naval Research Laboratory in Chesapeake Beach, Maryland. This simplified model predicts and explains the fluctuation in C_n^2 reasonably well, and also shows that C_n^2 is a strong function of solar irradiation.

1. INTRODUCTION

Several complicated similarity-based optical turbulence models [1,2] have been proposed to estimate the value of C_n^2 for a given location, date, time of day, and set of environmental parameters. The values of C_n^2 predicted by these models were found to compare reasonably well with experimental data taken at three different sites with widely varying environment conditions [3].

Here we consider a simplified version of [1] that depends primarily on insolation and wind speed during the day, and wind speed alone at night. To describe the location of interest, the model requires as inputs: the latitude, longitude, date, time of day, percent cloud cover, and terrain type, as well as a single measurement of atmospheric temperature, pressure and wind speed at the height of the C_n^2 estimate.

In the experiments reported here, we measured C_n^2 using a scintillometer at the Chesapeake Bay Detachment (CBD) of the Naval Research Laboratory. We simultaneously collected all of the required environmental and cloud cover data. Solar insolation was also measured in order to compare solar insolation estimated by the model with direct solar insolation measurements.

2. EXPERIMENTAL SET-UP

2.1 Procedure for Taking C_n^2 data at CBD

We chose to take C_n^2 data at the Chesapeake Bay Detachment of the Naval Research Laboratory for several reasons; the base offers minimal human interference, data collected at this site is shared by other projects, and we have an existing weather station with a solar radiation sensor. We used a commercially available scintillometer from Optical Scientific, Inc. model LOA-004. The scintillometer system consisted of a transmitter and a receiver system set up 100 meters apart in the grassy area as shown in Fig. 1. The weather conditions for the months of May, June, and July 2003 in the East Coast of the United States were excessively wet, raining 90% of the time. Despite such unfavorable conditions, we were able to collect some solid sets of 24-hour data during 23-30 June 2003 for a period of 24 hour cycles (in 10 sec intervals), along with cloud coverage data (pictures of the sky) on a daily basis. Since weather has the tendency to change abruptly, such as clear skies in the morning turning to dark rainy clouds by the

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afternoon, a single photo of the sky is not a good representation for the whole day. We noted such changes in the lab notebook on a daily basis.

The Davis Vantage Pro weather station was positioned about 200 feet from the receiver and collected weather data such as temperature, humidity, pressure, solar insolation, and about 30 other weather parameters. These were logged on a 5-minute basis.

Figure 1. Scintillometer set-up

3. EXPERIMENTAL RESULTS

Two distinct sets of results are presented here: (1) a model using the predicted solar insolation based on date, time of day, location, and cloud cover; and (2) a model that uses the measured solar insolation data to calculate C_n^2. Here we refer to the first model as the "theoretical" C_n^2 model and the second as the "solar" C_n^2 model. Using measured solar insolation data will allow us to evaluate the performance of the solar insolation model, and to more accurately estimate the effect of solar insolation on the estimated value for C_n^2.

Table 2 lists the parameters used as inputs for the model. For all cases, the longitude was 76.56 degrees, the latitude was 39.04 degrees, and the Greenwich mean time offset was five hours. Five days of data is presented here. Four graphs are included which summarize the data for each of the five days. For each day, the first graph compares the measured solar insolation with the predicted solar insolation (the smooth curve indicates the predicted solar insolation). The second graph shows the diurnal variation in temperature (solid line), humidity (dashed line), and wind speed (dotted line). In the third graph the theoretical (modeled solar insolation) C_n^2 estimates are compared to the measured values for C_n^2. The fourth graph compares the solar (measured solar insolation) C_n^2 model with the measured values for C_n^2

Table 2. Parameters used for modeling.

Date	Day #	Cloud cover (/8)	Average wind (m/s)	Terrain Roughness (m)	Height (m)	Pressure (mbar)	Temperature (F)	Comments
June 23	174	0	2.30	0.075	2	1017	90	clear
June 26	177	0	2.17	0.075	2	1018	95	sunny
June 27	178	6	1.94	0.075	2	1010	90	rain
June 28	179	6	1.70	0.075	2	1018	83	some cloud
June 30	181	6	1.41	0.075	2	1018	92	some cloud

3.1 Data for 26 June 2003

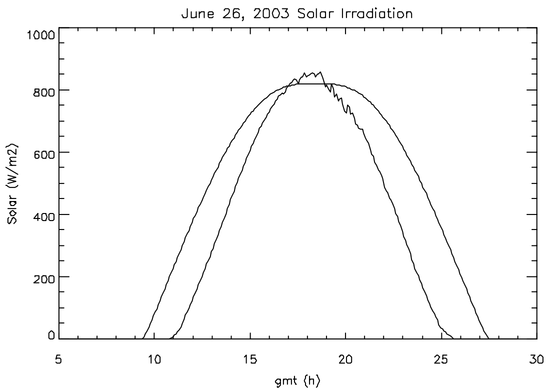

Figure 2. Modeled solar insolation vs. measured.

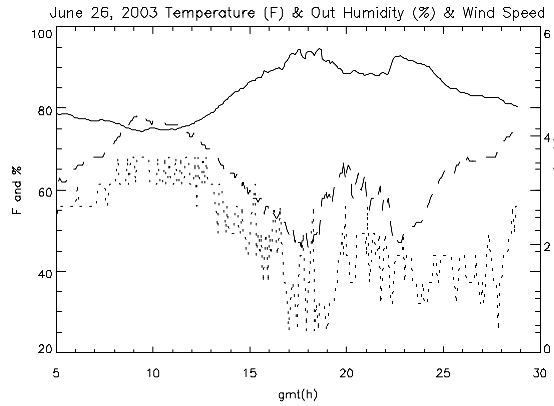

Figure 3. Weather data.

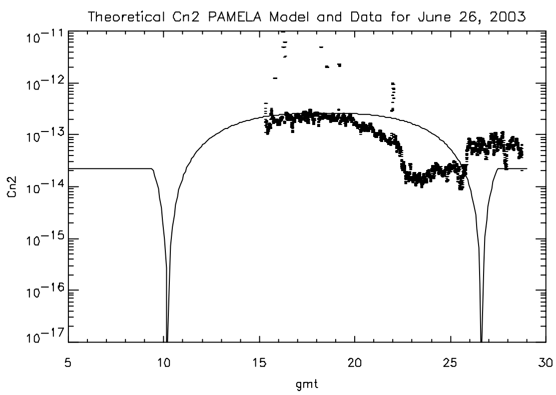

Figure 4. Theoretical C_n^2 model compared with data.

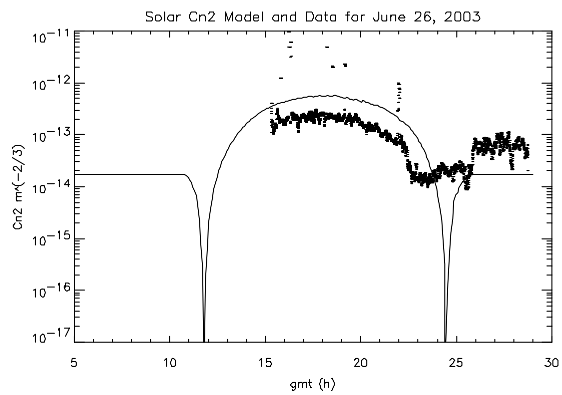

Figure 5. Solar C_n^2 model compared with data.

In Fig. 2, while the model estimate for solar insolation closely follows the shape and has about the same maximum value as the measured value for solar insolation, the model predicts that the received solar insolation begins and ends about one hour after and one hour before the measured values—the theoretical curve is wider than the measured curve. It is possible that our location was affected by shade from the nearby trees (see Fig. 1) and that this in turn affected the received insolation. Note that time is given in terms of Greenwich mean time (GMT). Fig. 3 shows the temperature (solid line), humidity (dashed line), and wind speed (dotted line) for this day.

The theoretical C_n^2 model results are compared with measured values of C_n^2 in Fig. 4. The estimated value for C_n^2 reaches its maximum value in the mid afternoon as expected, and stays flat at a lower C_n^2 value for the night (we assumed a constant value for wind speed). The model indicates two dips in the value for C_n^2 at about the time of sunrise and sunset. These two dips are the neutral events, where the atmosphere maintains a calm and steady state for a short period of time. The sensitivity of our scintillometer was not sufficient to accurately measure the full extent of the neutral events

Comparing the theoretical C_n^2 model to the data, we note some similarities as well as some differences. First, we are missing data in the morning as the computer had been shut down for some unknown reason soon after midnight. However, it is possible to extrapolate what the diurnal shape of the C_n^2 curve may have looked like for the entire day. The timing of the evening neutral event as predicted by the theoretical model is not in close agreement, but is weakly visible at about 22.5 hours GMT. Again, it is possible that our data was affected by shade from the nearby trees, which in turn affected actual insolation and the timing of the neutral event. Since we used a single average value for wind speed and temperature, the theoretical C_n^2 model predicts that the nighttime value for C_n^2 is constant.

Despite these differences, the theoretical C_n^2 model seems to be a reasonably good predictor and compares fairly well, but does not explain the fine structural variation in the C_n^2 data.

Now consider the comparison between the solar C_n^2 model and scintillometer data shown in Fig. 5. Referring to the solar insolation data in Fig. 2, this day was characterized by sunshine all day without any cloud attenuation. When we use the measured solar insolation data in the C_n^2 model, we receive closer agreement with the measured C_n^2 data. The predicted dip corresponding to the neutral event more closely corresponds to the measured value.

3.2 Data for 27 June 2003

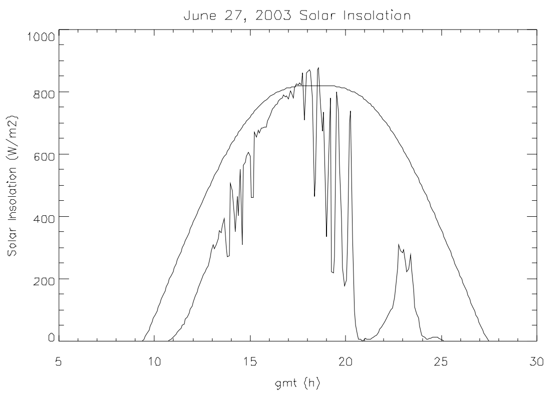

Figure 6. Modeled solar insolation vs. measured.

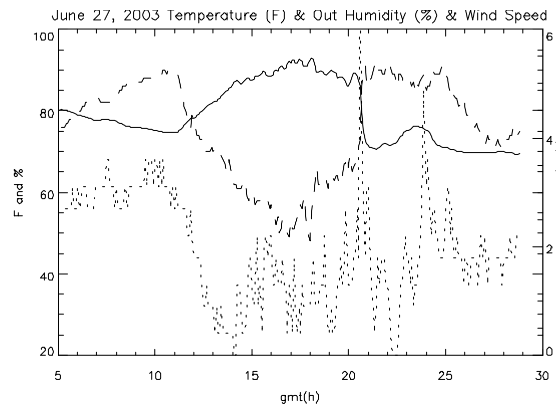

Figure 7. Weather data.

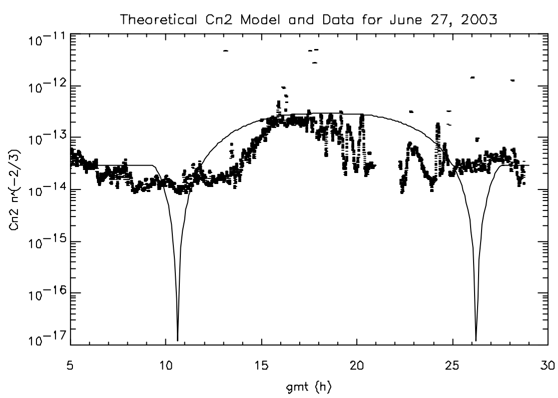

Figure 8. Theoretical C_n^2 model compared with data.

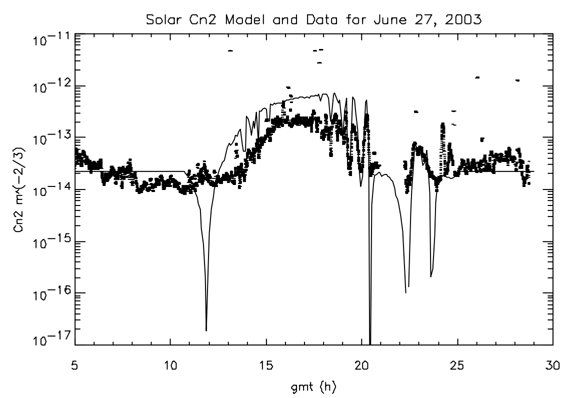

Figure 9. Solar C_n^2 model compared with data.

This was a very interesting day and fairly well depicts the type of weather that occurred on the East Coast over the months of May, June, and July 2003. Fig. 6 shows that the day started with a clear sky. By mid morning there were some clouds, but soon the clouds disappeared and it was clear again. By mid afternoon, however, dark clouds moved in and the weather changed abruptly. There were thunderstorms with lightning for several hours with a downpour of rain. Shortly before nightfall, the sun came out again. Such spontaneous events are not well accounted for in the solar insolation model and one can see the difference this makes in the theoretical C_n^2 result. Although the general shape of the C_n^2 prediction is correct, it does not include oscillations caused by such changes in the weather. This may be due to random clouds in the sky which cause attenuation in the solar insolation received. Note that shortly after 20 hours GMT, the lightening caused the Navy Base to shut down the power. When we went back to check on the system, the computer was turned off. We turned the system back on but were missing about 2 hours of data. Also note that neutral events were not detected for this data set.

Figs. 9 and 10 illustrate the remarkably good agreement we achieved between the modeled and measured results when the measured solar insolation date was used. Incorporating solar insolation data into our model helps to illustrate how the refractive index structure parameter C_n^2 varies with given parameters. The oscillations in the solar data translate proportionally to the solar C_n^2 model. Based on these results, changes in the solar insolation are instantaneously reflected in C_n^2. Since the scintillometer and the weather station are not synchronized (off by about 30 seconds) and the weather station records data only every 5 minutes, we were surprised to obtain such a close fit between the measured and estimated values of C_n^2 (see Fig. 10).

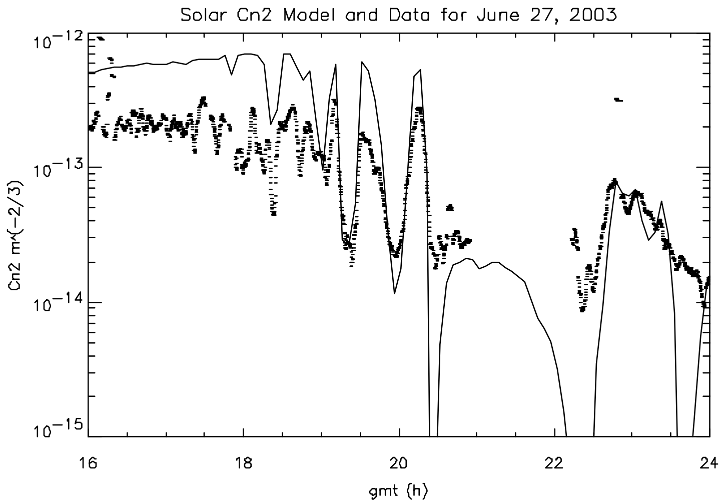

Figure 10. Detailed view from Fig. 9.

3.3 Data for 28 June 2003

As seen in Fig. 11, the sky was cloudy for most of this day with the sun randomly appearing and disappearing throughout the day. For the solar insolation and theoretical C_n^2 models, we used a cloud attenuation factor of 75% (6/8). The theoretical C_n^2 model result shown in Fig. 13 predicts the general shape of the C_n^2 curve for the day. Although some signs of the neutral events are noticeable, it is not shown conclusively. We lost some data due to lawn mowing activity from 15–18 hours GMT. When solar data is included, the comparison between measured and predicted values for C_n^2 improves dramatically (see Fig. 14). In the early hours of the day there are some unexplained "jumps" in the C_n^2 data which are not well understood.

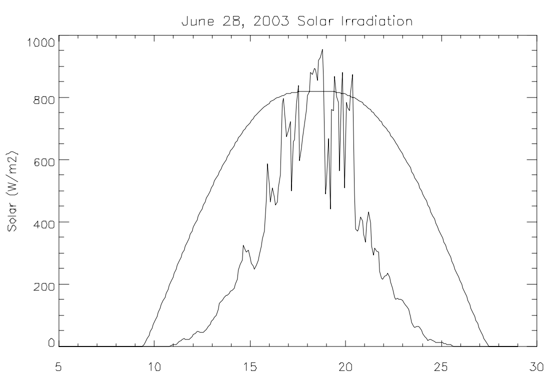

Figure 11. Modeled solar insolation vs. measured.

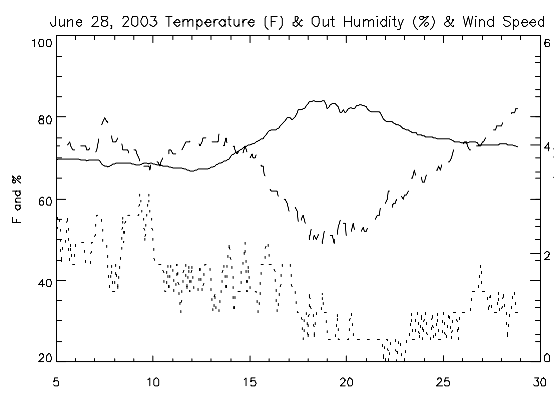

Figure 12. Weather data.

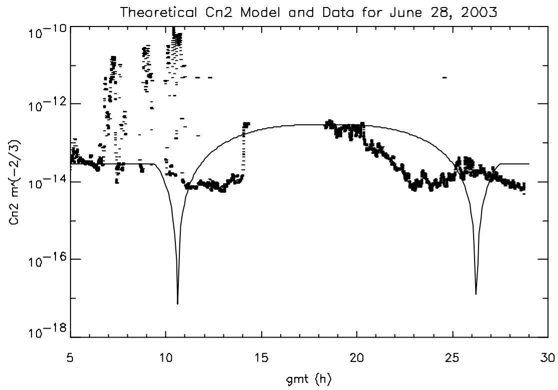

Figure 13. Theoretical C_n^2 model compared with data.

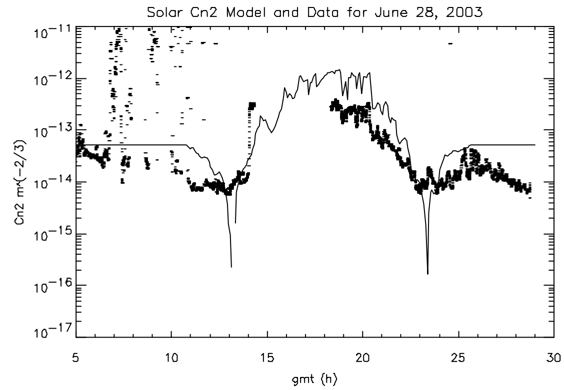

Figure 14. Solar C_n^2 model compared with data.

3.4 Data for 30 June 2003

For this day we were able to record a complete twenty-four hour block of data. As shown in Fig. 15, attenuation in solar insolation due to cloud cover was a factor, but not to the same extent as on 27 June 2003. Referring to Fig. 17, the theoretically predicted values for C_n^2 follow the measured values rather closely. It is possible to discern where the neutral events occurred. In Fig. 18 we see that the behavior of C_n^2 predicted by the solar model and the measured behavior of C_n^2 are in good agreement. The simplified optical turbulence model used here to predict C_n^2 is clearly dominated by solar insolation to a large extent.

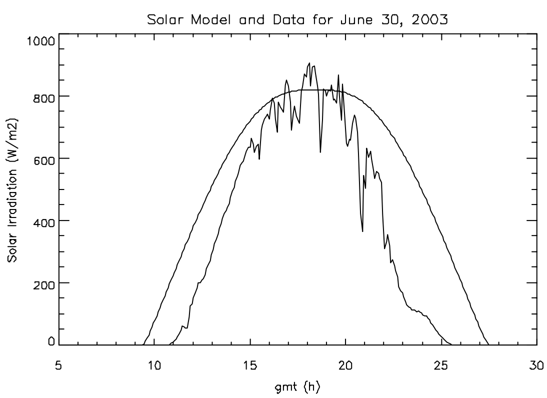

Figure 15. Modeled solar insolation vs. measured.

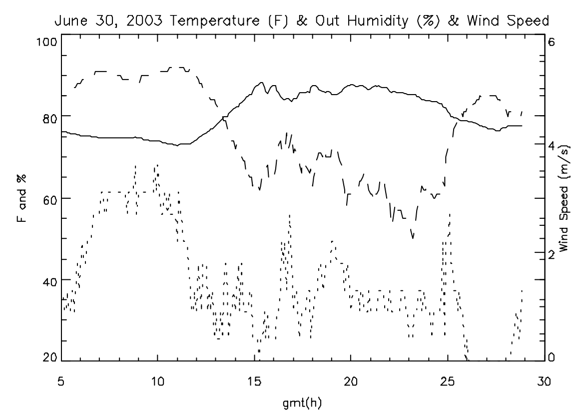

Figure 16. Weather data.

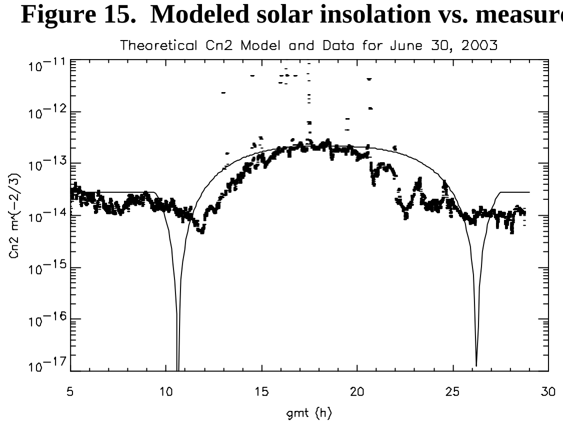

Figure 17. Theoretical C_n^2 model compared with data.

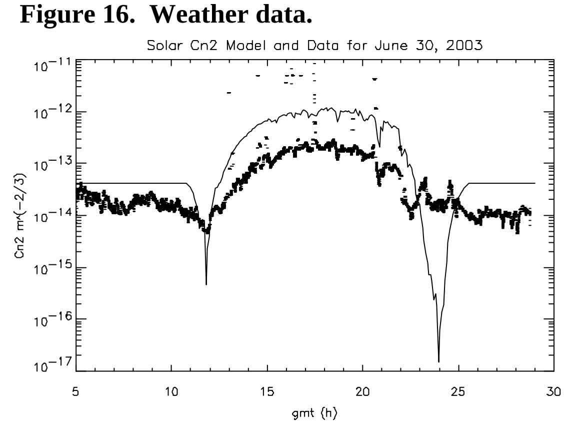

Figure 18. Solar C_n^2 model compared with data.

3.5 Data for 23 June 2003

The data taken on this day did not correspond closely with the C_n^2 model predictions. Neither the solar nor theoretical C_n^2 model accurately described what occurred during the period 7-12 GMT. The C_n^2 values stayed near 10e-13 for about 5 hours. We suspect this was due to the high winds, but cannot be certain from the data set provided here. We are working towards identifying more dependencies that can explain such phenomena.

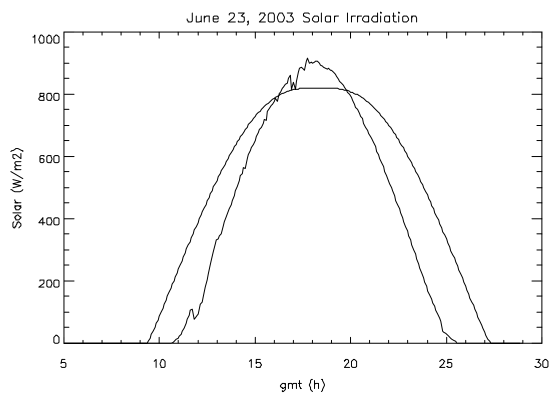

Figure 19. Modeled solar insolation vs. measured.

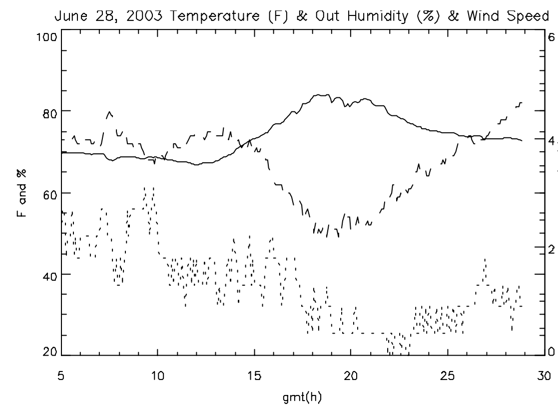

Figure 20. Weather data.

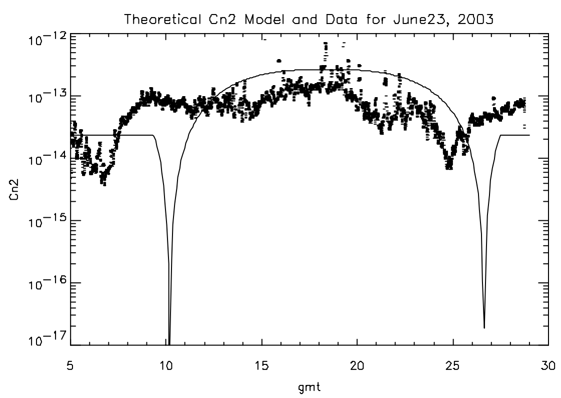

Figure 21. Theoretical C_n^2 model compared with data.

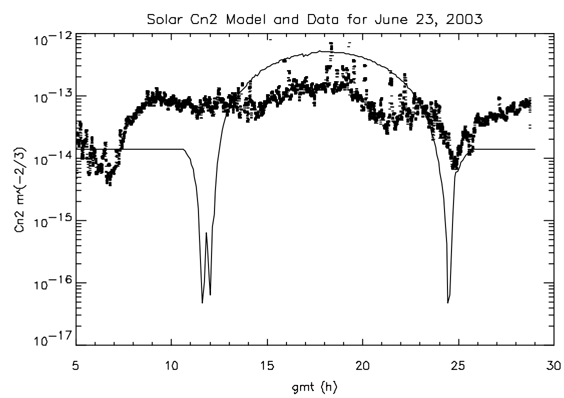

Figure 22. Solar C_n^2 model compared with data.

4. CONCLUDING REMARKS

The simplified model used here to estimate Cn2 does a reasonable job of predicting the diurnal variation in C_n^2 for most cases. It is clear that solar insolation is one of the dominant factors contributing to C_n^2. Wind speed also appears to be a dominant factor. Although the simplified C_n^2 model considered here can easily be adapted to account for diurnal changes in wind speed and atmospheric temperature, we did not consider these variations here. Only single average values of temperature and wind speed were used. Continued and expanded experiments coupled with modified code will further test the efficiency and impact of this new Optical Turbulence Model.

5. ACKNOWLEDGEMENTS

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