Remote Sensing of Atmospheric Turbulence by Means of a Fast Optical Method: A Comparison with Simultaneous *In Situ* Measurements

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ABSTRACT

In this paper we describe an experiment in which we measure the energy of the atmospheric turbulence up to an altitude of 20 000 m. The measurements have been performed simultaneously by a remote optical system attached to an astronomical telescope and by a free flying balloon-borne radiosonde carrying thermal sensors for detecting the *in situ* microturbulence.

The consistency of the results shows that the ground based optical equipment for remote testing of atmospheric turbulence is a reliable device for a fast, continuous measurement of vertical profiles of turbulence.

1. Introduction

In a paper by Azouit and Vernin (1980, hereafter called paper I) a fast technique was described for deriving in real time vertical profiles of the refractive index structure coefficient C_N^2 by means of a two dimensional statistical analysis of the scintillation of a double star.

This technique is especially valuable for measuring temporal or spatial variations of the turbulence, assuming the turbulence to remain frozen while moving across the ray path. The experimental setup has been described in detail in paper I. Briefly, it consists of an astronomical telescope whose entrance pupil is imaged onto a TV camera target. The telescope is pointed at a double star, and the TV signal is processed by a computer which performs the two-dimensional correlation of the shadow band pattern on the camera target. From this correlation it is possible to evaluate the intensity and location of the different turbulent layers.

This method is based on the same principle as that described by Vernin *et al.* (1979) already tested at Aire sur l'Adour where optically determined vertical scans of the atmospheric turbulence were compared with those obtained by balloon-borne radiosondes similar to those extensively used by the Arcetri Observatory for astronomical site testing (Barletti *et al.*, 1974a) in the frame of the JOSO project (Joint Organization for Solar Observations).

The test performed at Aire sur l'Adour was successful, showing that for periods during which the overall turbulence could be considered stable the results of both devices were nearly identical.

However, the two methods for measuring atmospheric turbulence show relevant differences which must be taken into account when evaluating the results. The vertical resolution is good for *in situ* measurements (40 m), whereas it is very poor (6 km) for the optical sensor. For the optical method the scanning line is fixed, as it is determined by the line of sight of an observed double star. On the other hand the path of the balloon is directly related to the wind profile, which may be quite different from the optical line of sight. These differences may introduce serious errors in the comparison of the data; however, if the turbulence is stable, as was discovered at Aire sur l'Adour, the errors may be kept within an acceptable range. Typically, the data obtained during the ascent and descent of the balloon may differ by a factor of three.

Starting from these premises, a joint campaign for measuring atmospheric turbulence optically and thermally was programmed at the Nice Observatory during March 1978. Optical measurements were performed by the group of the Laboratoire d'Astrophysique de l'Université de Nice at the 76 cm refractor of the Observatory of Nice, while thermal measurements were performed by the Arcetri Observatory JOSO group, who launched radiosondes from the grounds of the Nice Observatory.

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2. The radiosondes

The radiosondes were designed mainly for astronomical site testing, but they turned out to be a valuable tool for atmospheric physics. The idea of measuring the C_T^2, i.e., the energy of the fluctuating temperature field in the atmosphere with two microthermal sensors one meter apart, was put forward by Bufton *et al.* (1972). At the Arcetri Observatory this idea was developed (Barletti *et al.*, 1974b, 1976, 1977a, 1977b), resulting in a compact device which flew for more than 100 h and obtained about 80 vertical profiles of the turbulence from the ground to a height of more than 20 000 m.

The radiosonde measures the temperature difference between two points 1 m apart, in the horizontal plane, as a function of altitude. Assuming a homogeneous and isotropic turbulence with a spectrum following the Kolmogorov − 5/3 power law, the average of the squared difference signal is numerically equal to the C_T^2 along the radiosonde path.

It is well known that C_T^2 may be easily related to C_N^2, the energy parameter of the fluctuating refractive index field, by

$$C_N^2(h) = \left[\frac{80P(h)}{T^2(h)} \times 10^{-6}\right]^2 C_T^2(h),$$

where $P(h)$ is the pressure (mb), $T(h)$ the absolute temperature and h the height (km).

Each sensor is constructed with platinum wire (diameter 10 μm, length 50 cm) wound around a 6 × 6 cm glass frame. A direct current is fed through each sensor, and resistance changes corresponding to temperature fluctuations produce fluctuating voltage signals which are applied to the inputs of a differential amplifier. The bandwidth of the system (sensor and amplifier) ranges from 0.5 to 125 Hz. The amplified signal is voltage-to-frequency converted (bandwidth from 2 to 5 KHz) and then modulates the amplitude of a 137 MHz radio carrier.

The dynamic temperature range is 0.5 K peak to peak. The equivalent rms noise is about 1.5 10^{-3} K, corresponding to a sensitivity $C_T^2 \approx 2 \times 10^{-6}$ K^2 $m^{-2/3}$. Pressure is measured by coded interruptions of a standard baroswitch. At the ground station, the detected signal is recorded on analogic magnetic tape. For data reduction, the signal is converted back from frequency to voltage and an analogic to digital conversion is performed at a sampling rate of 250 s^{-1}. A value of C_N^2 is computed from the ensemble average of 2000 samples, corresponding to a layer about 40 m thick.

Experiments have shown that the separation between the radiosonde and the balloon can influence the quality of the results. For reliable results a cord of at least 100 m is needed between the balloon and the radiosonde, in order to avoid wake effects.

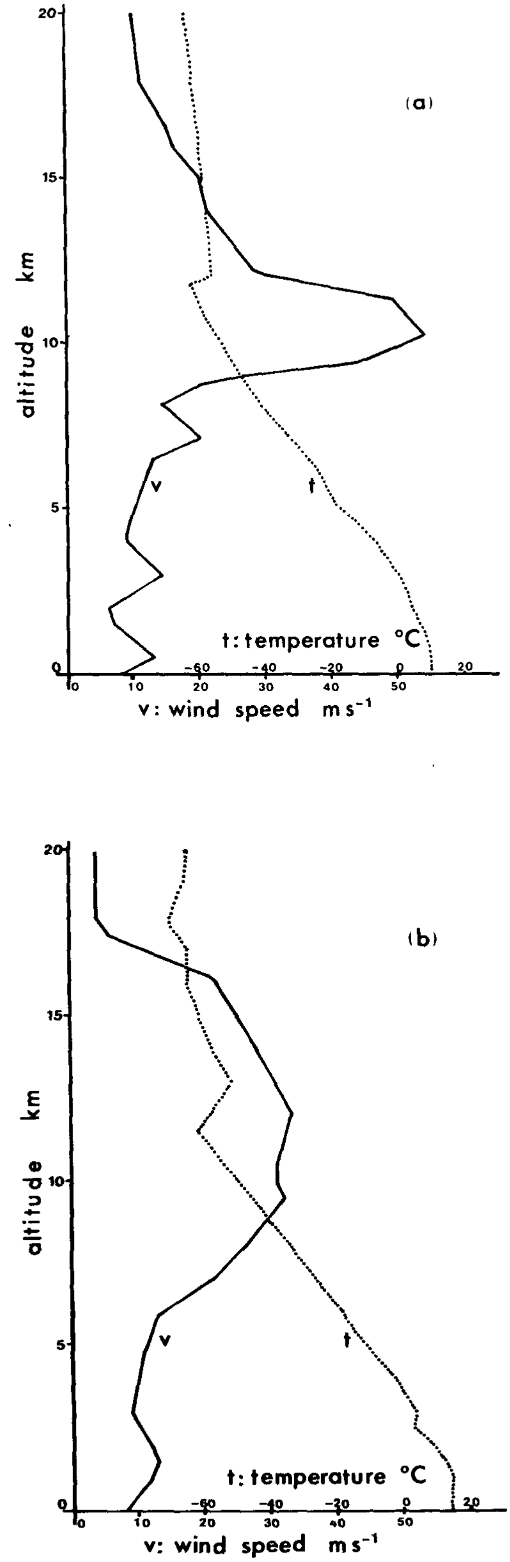

FIG. 1. Vertical profiles of temperature (dots) and wind (full line) given by the Nîmes meteorological station at 0000 GMT 8 March (a) and at 0000 GMT 11 March (b).

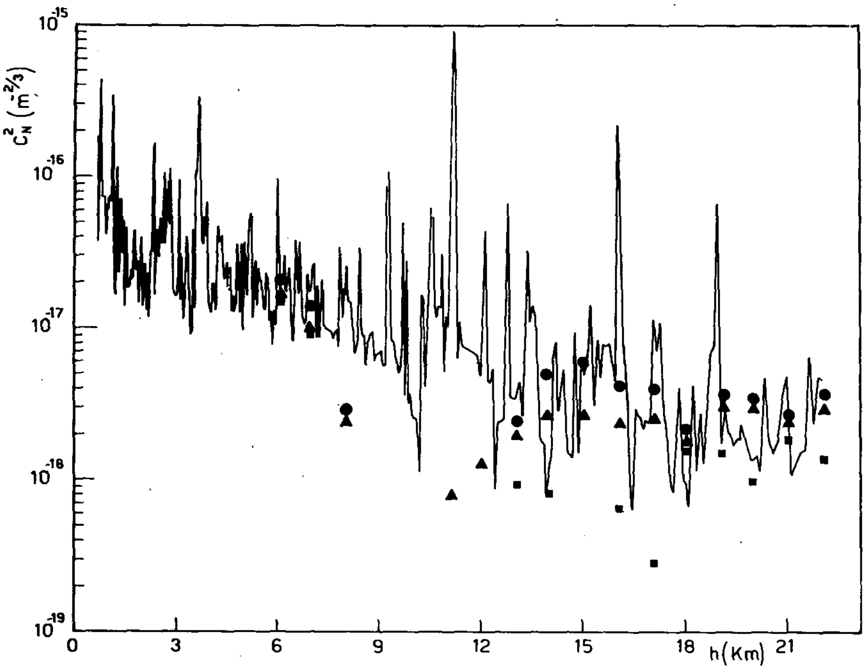

FIG. 2. Vertical profile of C_N^2 as measured on 7 March by the radiosonde *Camélia* (descent). The optically deduced C_N^2 profiles for the same night are also shown as follows: average (triangles); most turbulent (dots); least turbulent (squares).

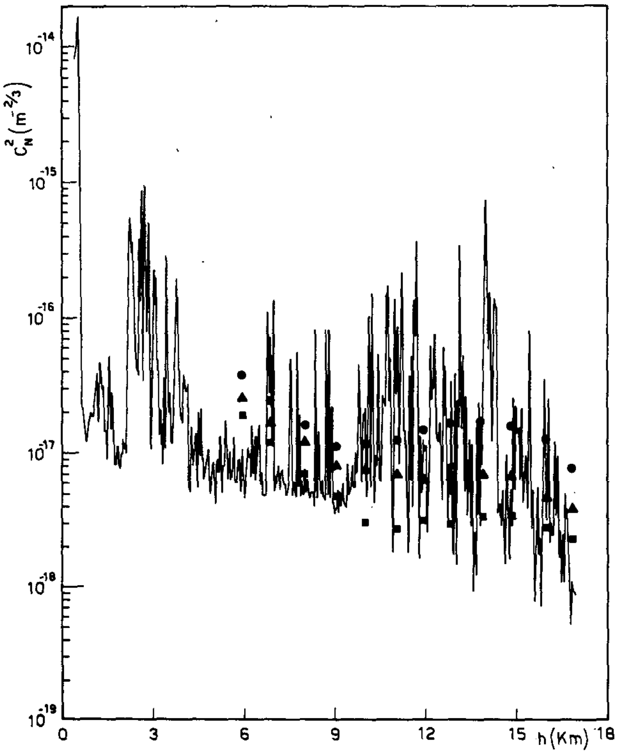

FIG. 3. As in Fig. 2 except for the 10 March ascent of the radiosonde *Désirée*.

3. Observations

Due to unfavorable weather conditions only two radiosondes were launched in the programmed testing period, which ranged from 1 February to 15 March 1978. The launching site was very near to the 76 cm telescope at the Nice Observatory (400 m MSL). Due to strong winds a cord length of only ten meters was used during the first flight, thus spoiling the thermal measurements obtained during the ascent. The telescope was set to track the double star Castor (α Gem, 2 arcsec separation between the two components).

Each optical determination of the turbulence profile was obtained with a 100 s integration time, and in order to obtain a time-averaged profile consistent with the 2 h balloon flight about 50 profiles were averaged.

Vertical profiles of temperature and wind, needed for thermal data reduction and for a better comparison of the optical and thermal results, were provided by the Nîmes meteorological station, which is about 200 km from the Nice Observatory (see Figs. 1a and 1b).

4. Results

In Figs. 2, 3 and 4 we plot the results of the thermal scans obtained on March 7 (payload *Camelia*) and on

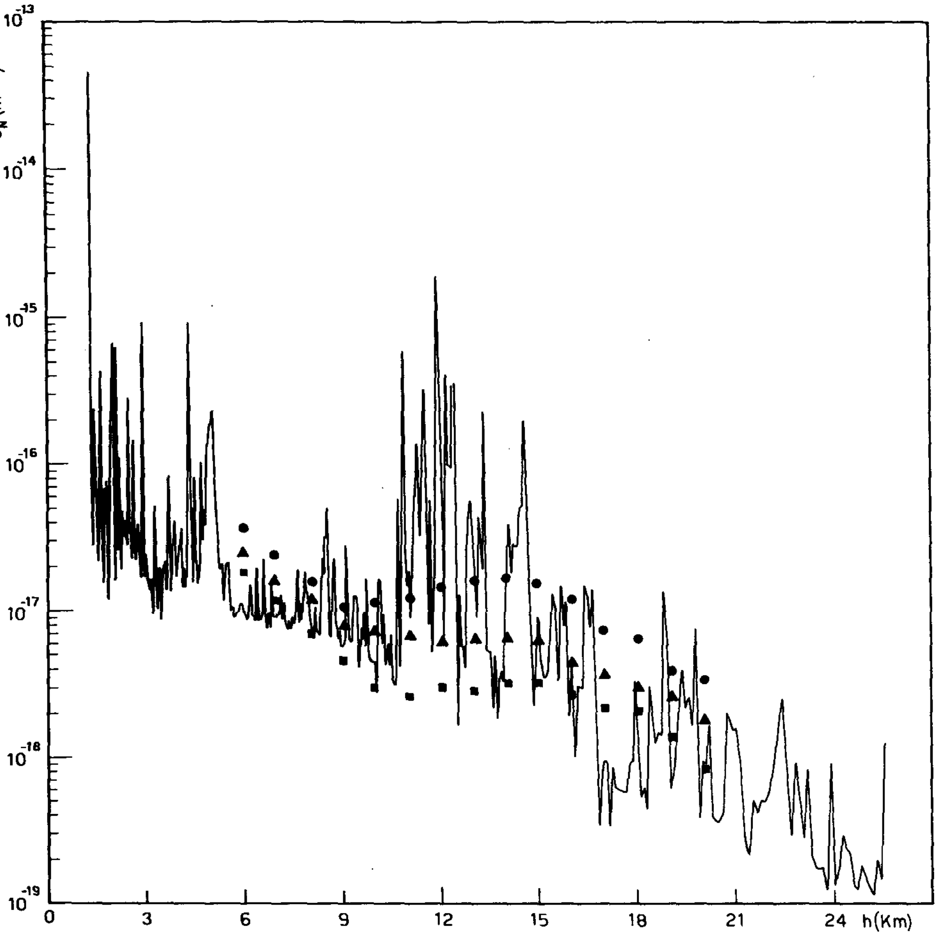

FIG. 4. As in Fig. 2 except for the 10 March descent of the radiosonde *Désirée*.

March 10 (payload *Désirée*). Altitudes are with respect to sea level. For the first flight we report the descent data, since the short distance between the balloon and the radiosonde spoiled that of the ascent. In the same Figs. (2, 3 and 4) the optical data are also plotted. It can be seen that the optical and thermal data lie in the same area of the graph, although they are more consistent for the flight *Désirée* in which a 100 m cord was used between the balloon and the payload.

In Figs. 2–4, the triangles represent the average optical values, while dots represent the "most turbulent" profile and squares the "least turbulent." Both of the extreme optical profiles lie within the thermal maxima and minima. This result is obviously due to the larger spatial and temporal integration involved in the optical measurements.

The same optical data reported in Figs. 3 and 4 are shown in Fig. 5, compared with the thermal data filtered with a function similar to the vertical optical resolution profile. We note that a lack of simultaneity in time and space in the thermal measurements intro-

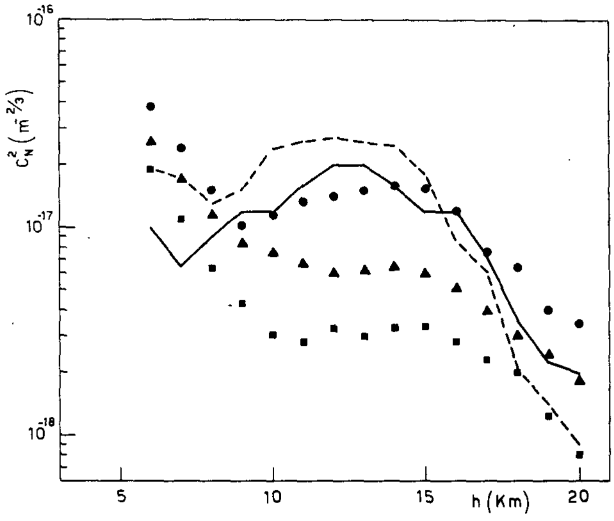

FIG. 5. Thermal data of 10 March reduced to the vertical resolution of the optical measurements (solid line for the ascent, dashed line for the descent). The optical data are the same as for Figs. 3 and 4.

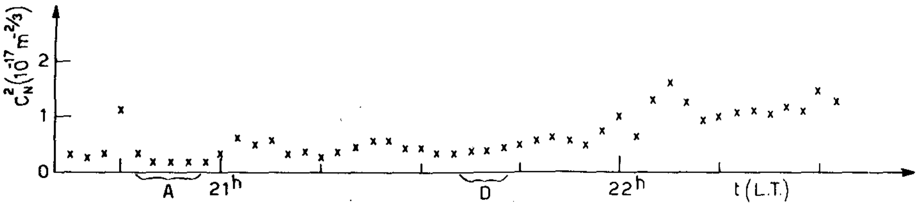

FIG. 6. Time evolution of the turbulence at 12 km, as measured on 10 March by the optical method with an integration time of 100 s. The time intervals relevant for the comparison with the radiosonde *Désirée* are A for ascent and D for descent.

duces a factor of less than 3 between the measurements obtained at the same height during the ascent and the descent.

The intermittency of the turbulence introduces a factor of about 5 between the extreme optical profiles taken at the same height. Keeping in mind this variability in thermal as well as in optical data, we may say that the overall agreement is satisfactory. The agreement is better at low and high altitudes, whereas at altitudes between 9 and 17 km, the average optical value is always lower than the thermal ones which tend to approach the optical maximum profile. Since the wind in that region during the flight was very strong, we may ascribe these effects to wind shear effects on the balloon-radiosonde ensemble. It is evident from the thermal data shown in Fig. 5 that the turbulence was rising during the night. We have tried to show this effect by optical sounding. We took 12 km as a reference height and knowing the wind intensity and direction we reconstructed the path of the balloon.

If we look at the evolution of the turbulence at 12 km, as shown in Fig. 6, we see that the turbulence measured by the telescope increases with time. From the hodogram of the balloon we find that when the balloon passed, in ascent and descent, through a 6 km layer centered at the 12 km level, it encountered the turbulence measured by the telescope in the time intervals A and D respectively. Is it evident that there is an increase in turbulence from A to D, but the optical measurements are not accurate enough to confirm the factor 1.4 shown by the radiosonde.

5. Conclusions

The fast optical technique for measuring atmospheric turbulence gives results which agree with those obtained by balloon-borne sensors. It is therefore confirmed, after the preliminary results by Vernin *et al.* (1979), that a powerful system for detecting the turbulence between 6 and 25 km is available. This system may supply a turbulence profile every ten seconds, and it may be very useful for studying the intermittency of turbulent phenomena in the atmosphere.

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