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Moiré technique improves the measurement of atmospheric turbulence parameters

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Light-beam deflections due to atmospheric turbulence are one order of magnitude more precise with the aid of moiré patterns.

Moiré is a useful means of measuring numerous physical quantities, such as refractive index gradients, optical device resolution, surface smoothness, stress, vibration parameters, and diffusion coefficients in liquids. Recently, we used a moiré technique to measure angle-of-arrival (AA) fluctuations in light propagating in the turbulent ground-level atmosphere on a telescope. This type of measurement is critical in evaluating astronomical imaging, aerial surveying, terrestrial geodesy, optical ranging, and wireless optical communication.

A moiré pattern is produced when two similar straight-line grids (or gratings) are overlaid and rotated relative to one other by a small angle (see Figure 1). In many applications, one of the superimposed gratings is the image of a physical grating. When image-forming light propagates in a perturbed medium, the image grating is distorted and the distortion is magnified by a moiré pattern. This moiré magnification can be expressed as[1]

$$\frac{d_m}{d} = \frac{1}{2sin(\theta/2)} \simeq \frac{1}{\theta},$$

where d_m, d, and θ stand for the moiré fringe spacing, the pitch, and the angle of the gratings, respectively.

Changes in ground surface temperature create turbulence in the atmosphere. Because AA fluctuations are a significant effect of atmospheric turbulence, they can be used to describe characteristic parameters of the phenomenon. AA measurements are a basic step in astronomical applications. Differential image motion monitoring systems[2] and generalized seeing monitor systems[3] are both based on these measurements, as well as the edge image waviness effect.[4] The measurements can be carried out in different ways. In some conventional approaches, AA fluctuations are derived from the displacements of one or two image points on the image of a distant object in a telescope. Other techniques exploit the displacements of the image of an edge. Overall, however, the precision of these techniques is limited to the pixel size of the recording CCD.

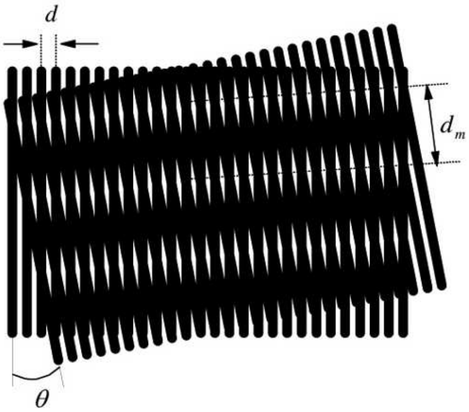

Figure 1. *A moiré pattern, formed by superimposing two sets of parallel lines, one set rotated by angle θ with respect to the other.*

We recently developed a technique, based on moiré fringe displacement, for measuring AA fluctuations that has two main advantages compared with other methods.[5] First, the displacement of the image grating lines can be magnified by a factor of ∼10, and the numerous lines of the image grating provide a large volume of data, which leads to very reliable results. Second, the acquisition of displacement data over a rather large area is very useful for evaluating the turbulence parameters that depend on displacement correlations.

Our technique is implemented as follows. A low-frequency grating is installed at a suitable distance from a telescope. An image of the grating forms at the focal plane of the telescope objective. Superimposing a physical grating of the same pitch as that of the image grating onto the latter generates the moiré pattern.

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Recording consecutive moiré patterns with a CCD camera connected to a computer and monitoring the traces of the moiré fringes in each pattern then yields AA fluctuations versus time across the grating image. A schematic diagram of the experimental setup is shown in Figure 2. Typical real-time moiré fringes obtained with this configuration are shown in Figure 3(a), with corresponding low-frequency illumination in Figure 3(b).

Evaluating some atmospheric turbulence parameters requires correlating AA fluctuations at different scales. For this purpose, we can replace the probe grating in Figure 2 by the CCD and record consecutive frames of the carrier grating images. Rotating one of the frames by the desired angle and superimposing it on the other frames again generates moiré patterns. From the traces of the moiré fringes, we can derive the displacement correlations. Evaluations at different scales are performed simply by changing the angle between the superimposed images.[6] Figure 4(a) shows a typical grating image recorded in a turbulent atmosphere. The typical moiré pattern formed by superimposing two images of the grating with a small angle difference is shown in Figure 4(b).

We have used this technique to measure the modulation transfer functions of the ground-level atmosphere.[7,8] At present, we are working on developing another moiré-based method to study turbulence parameters in the vertical direction. Our work shows that incorporating a moiré technique in the study of atmospheric turbulence parameters increases the precision of the measurements while reducing the distance required between target and observer. Our study also shows that the moiré technique can be used to investigate other turbulent media, such as gases and liquids.

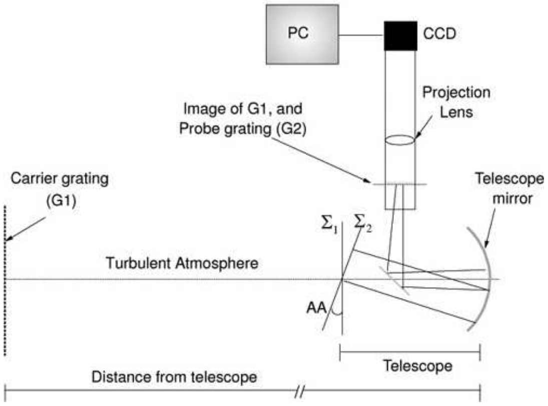

Figure 2. *Schematic diagram of the experimental setup used for moiré atmospheric turbulence studies.*

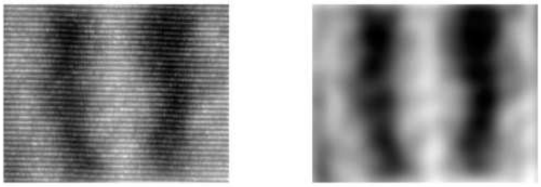
(a) (b)

Figure 3. *(a) Typical moiré pattern recorded using our experimental setup. (b) Corresponding low-frequency illumination. To see animations, click on either panel (a) or (b).*


(a) (b)

Figure 4. *Typical image of a grating recorded in a turbulent atmosphere (a), and the moiré pattern produced by superimposing two images of the grating (b). To see animations, click on either panel (a) or (b).*

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