III.

ATMOSPHERIC SEEING, INTERFEROMETRY, SPECKLE, MMTs AND ARRAYS

MEASURING ATMOSPHERIC SEEING

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INTRODUCTION

Since a lot of efforts and money are being put in building larger telescopes, astronomers are becoming more concern with the effects of "atmospheric seeing" on astronomical observations. Observers need to correct their observations for image degradation and put more and more emphasis on the importance of good seeing conditions[1]. Both observers and optical engineers try to compare the image quality between different telescopes and sites. In addition, engineers are interested in locating the origin of image degradation. What are the relative contributions of the dome and of the free atmosphere to image degradation ? As engineers become able to reduce dome seeing, the selection of a good astronomical site becomes more crucial and reliable methods for site testing become necessary.

Parameters describing seeing fall into four classes as schematically shown on table 1. Image quality and the statistics of image degradation are best measured in the telescope image plane and will be refered to as image plane parameters. Image degradation is due to wavefront perturbations which can be more directly measured in the telescope pupil plane. Wavefront statistics will thus be refered to as pupil plane parameters. They are linked to image plane parameters by the theory of image formation which is now a well established theory. Wavefront perturbations are in turn produced by the fluctuations of the air refractive index which, in the optical range, are directly related to temperature inhomogeneities in the atmosphere. These turbulence parameters can be directly measured by means of in situ or remote atmospheric soundings. Turbulence parameters are linked to pupil plane parameters by the theory of propagation through turbulence

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TABLE 1 : SEEING PARAMETERS

Image plane parameters :	Seeing disk profile Modulation transfer function Image motion and blurring Speckle statistics
↕ Image formation theory	
Pupil plane parameters :	Statistics of Wavefront perturbations
↕ Propagation theory	
Turbulence parameters :	Statistics of refractive Index fluctuations C_N^2 and C_T^2 profiles
↕ Turbulence theory	
Meteorological parameters :	Wind shears and Temperature gradients

which has undergone considerable advances during the past twenty years and is still in progress. Finally air turbulence and temperature inhomogeneities are produced by wind shears and temperature gradients and are related to meteorological conditions. The relation is described by turbulence theory which is also well established but requires the use of non-dimensional parameters which in most cases have to be empirically found.

In this paper, we shall briefly review the techniques now available to measure these four classes of parameters and we shall discuss about their relative merits.

IMAGE PLANE MEASUREMENTS

Most of the classical methods for measuring seeing are image plane measurements. They were developped in the early sixties for selecting the sites of new observatories. These methods are reviewed by Stock and Keller[3], Meinel[4] and in the proceedings[5] of the I.A.U. Symposium n° 19. The work of soviet scientists is reviewed by Kucherov[6]. Seeing was essentially estimated from measurements of the image quality through small telescopes. Due to the lack of theoretical support, little care was taken to calibrate the results on an absolute scale independent of the telescope size and of the experiment, and it was not yet clear how to extrapolate the results in order to predict image quality through larger telescopes.

The most obvious experiment consists in measuring the photometric profile of a long-exposure stellar image. Such a measurement requires careful photometric calibrations. The contribution of the telescope can be easily withdrawn by dividing the two-dimensional Fourier transform of the stellar profile by the telescope optical transfer function. The result gives the so-called atmospheric transfer function which is now known to be described by the following expression[7]

$$\mathcal{B}(f) = \exp - 3.44 \, (\lambda f / r_0)^{5/3} \qquad (1)$$

where λ is the wavelength and r_0 the seeing parameter introduced by Fried[8].

Because long exposures are sensitive to wind shakes, seeing has also been estimated from instantaneous seeing disk profiles. The average width of such profiles is known as blurring. The long-exposure seeing disk is produced by a combination of blurring and image motion. Image motion occur when the scale of the perturbation is larger than the telescope diameter, whereas blurring is produced by smaller scale perturbations. Since image motion and blurring are produced by unrelated parts of the turbulence spectrum they are statistically independent, but their average value are well related and both can be used to estimate r_0.

However analytic expressions relating these measurements to r_0 are approximate and not straightforward. Moreover, observations have to be instantaneous enough to freeze image motion and image distorsion. This condition was seldom fullfilled in the case of star trail measurements or visual measurements extensively done in the past. Such measurements are sensitive to the life time of wavefront perturbations and cannot be calibrated purely in terms of r_0.

Long exposure images as well as short exposure images are sensitive to focussing errors, telescope aberrations and misalinement. Image motion is less sensitive to focussing errors as shown by Forbes[9] but it is sensitive to wind shakes.

Short-exposure images have a speckle structure and measurements of the speckle energy spectrum can also give estimates of r_0. It is not very sensitive to telescope aberrations. However r_0 values are obtained by comparison with theoretical curves which have no accurate analytic expression and are difficult to compute numerically.

We conclude that most image plane measurements are sensitive to telescope aberrations and that most image plane parameters are related to wavefront perturbations by complex relations (integrals) which are difficult to invert accurately. Although sensitive to wind shakes, image motion seems the most reliable parameter. It is also the most directly related to wavefront perturbations : it measures the wavefront slope averaged over the telescope pupil.

PUPIL PLANE MEASUREMENTS.

Pupil plane measurements give direct access to wavefront perturbations, independently of the telescope size and of the optical aberrations.

Interferometric methods are the most accurate. Long exposure interferograms lead directly to the covariance of the field complex amplitude

$$\mathcal{B}(f) = \langle \Psi(u) . \Psi^*(u+f) \rangle \qquad (2)$$

which is nothing else than the atmospheric transfer function for long exposures described by Eq. (1). Several types of shearing interferometers have been developed for that purpose[10-13] among which the rotation shearing interferometer appear to be the most convenient because of its zoom property[14]. Interferometry makes a much better use of the dynamic range of the detector than long exposure imaging and the measurement of the fringe contrast is quite accurate. It is insensitive to telescope aberrations which only distort fringes, but it is sensitive to wind shakes. Because of their high accuracy interferometric measurements could be used as standards with which other techniques could be accurately calibrated.

Short-exposure interferograms although more difficult to obtain, can be used to study the statistics of wavefront distorsions[15] and, for instance, to determine the fourth order moments which describe speckle statistics. Although this has been done for horizontal propagation, it has never been applied to astronomical seeing.

The shape of frozen wavefronts can also be statistically studied by means of short-exposure Foucault or Hartmann tests. The measurement of differential image motion through a simplified two-aperture Hartmann test could be the easiest way to measure r_0 with a small instrument insensitive to wind shakes[3]. Incorrect results quoted in the past, were due to erroneous calibration and misunderstanding of the effect of atmospheric turbulence. The energy spectrum of short-exposure Hartmann plates could also yield fourth order moments of the wavefront perturbations. Strioscopic techniques can be used on the sun or moon limb[16-20]. However, in this case, the filtering of spatial and angular frequencies must be carefully taken into account[18]. All these methods could yield accurate information on time scales and angular properties (isoplanicity) of wavefront perturbations. Very little has been done yet in this domain.

Compared to image plane measurements, pupil plane measurements are independent of the telescope and give direct information on the wavefront perturbations. From these measurements, the statistics of image degradation can be easily and accurately computed for any telescope. However neither pupil plane nor image plane measurements tell much about the origin of wavefront perturbations. Does it occur within the dome, in the atmospheric surface layer or as far as the tropopause ? Answer can only be given by turbulence soundings.

TURBULENCE SOUNDINGS

The importance of turbulence soundings in site testing has been emphasised during the J.O.S.O. site testing campaign and is now widely recognised. Turbulence soundings can be divided into two classes : in situ $C_T^{\ 2}$ measurements and remote C_N^2 sensing . $C_T^{\ 2}$ (respectively C_N^2) is defined as the variance of the temperature (respectively refractive index) difference between two points, one meter apart. They measure the amount of thermal (respectively optical) inhomogeneities in the atmosphere and are directly related one to the other[7].

$C_T^{\ 2}$ measurements are made with small microthermal sensors mounted on towers, tethered balloons, kites, free balloons or aircrafts. These measurements are accurate but suffer from undersampling. Because turbulence occurs in thin layers and varies intermittently, a huge number of sensors would be necessary to cover appropriatly the space and time distribution of turbulence. Since we are mainly interested in a continuous monitoring of an averaged (smoothed) distribution of turbulence with height, remote sensing techniques are more appealing.

Three methods seem to compete : the SODAR or acoustic sounder, the RADAR and the newly developed SCIDAR or stellar scintillation sounder. Acoustic sounders are sensitive only to low altitude turbulence (essentially below 1 km). Absolute measurements are difficult because the propagation of sound is sensitive to wind. However, the results of tests, recently performed at Kitt Peak, comfort the idea that acoustic sounders are at least a good complement to thermal sensors on poles and tethered balloons[22].

The radar technique [23], such as developed by VANZANDT and his coworkers, consists in using a large array of dipoles(typically 60 m x 60 m) and is hardly transportable. It can detect turbulence up to 15 km but it is also sensitive to humidity fluctuations occuring in the troposphere. Simultaneous water vapor soundings are necessary to correct the observations. Moreover the RADAR now appear to be also sensitive to other scattering phenomenae (probably related to gravity waves in the atmosphere) which does not affect optical propagation[24].

The SCIDAR technique developed by VERNIN and AZOUIT[25] seems the most appealing technique. It is based on a statistical analysis of stellar scintillation. It could also be considered as a pupil plane measurement but, instead of measuring wavefront distorsions, it measures only irradiance fluctuations which little contributes to image degradation but bears a considerable amount of information on the distribution of turbulent layers. The equipment now uses a light plastic lens collector and is transportable. It gives accurate C_N^2 profiles from 1 km to at least 20 km above ground with a vertical resolution better than 1 km. Contrarily to SODAR or RADAR its sensitivity increases with height and outstep that of RADAR above 6 km. The time evolution of turbulence layers can be followed with a time resolution as short as a few tens of seconds.

The combination of a SCIDAR and a well calibrated SODAR can probably cover the whole atmosphere and give reliable estimates of the C_N^2 distribution with height. Fried's parameter r_0 , describing image quality, is simply related[7] to the integral of C_N^2 over the whole atmosphere and is easily deduced from such measurements[26]. Comparison with measurements made in a telescope pupil plane should reveal the contribution of the telescope and the dome to image degradation. This contribution can also be measured by means of autocollimated laser beams, putting reflecting corner cubes in front of the telescope[27]. It is clear that more efforts should be put in the future to reduce telescope and dome seeing to a minimum. Little can be done about external atmospheric seeing except in choosing appropriate sites or selecting observations appropriate to the current observing conditions. Unfortunately turbulence soundings give no indication on how to find better sites nor how to forecast future seeing conditions in order to plan observations accordingly. To do this, turbulence must be related to meteorological conditions.

METEOROLOGICAL SOUNDINGS.

C_T^2 can in principle be deduced from wind velocity and temperature profiles in the atmosphere. Unfortunately, turbulence occurs within thin atmospheric layers and C_T^2 can be estimated only from very high resolution profiles. However , as noted above, we are not interested in the precise location of turbulent layers but rather in a smoothed distribution of C_N^2 with height. In this case, Vanzandt and his coworkers[28, 29] have shown that the behaviour of free atmosphere can be reasonably well modeled, using only meteorological data and a statistical approach. Since meteorological soundings are made routinely on a worldwide basis, they provide an enormous data base which can be used in searching for good astronomical sites. Moreover as weather forecasts become more reliable, it should be possible to predict seeing at a given site and to adapt in advance optical configuration and instrumentation to the forecast seeing.

Bely[30] has made a systematic comparison between the image quality at the C.F.H. telescope and the prediction of the Vanzandt model. This is a very difficult test because, as we have seen, both types of measurements are subject to errors. The correlation was indeed found to be low not only because of these errors but mainly because turbulence in the surface layer, in the dome and in the telescope were not taken into account by the model. As a matter of fact, in nearly all cases the observed image quality was found lower than that computed from the model.

Turbulence in the surface layer can be theoretically modeled in the simple case of a flat extended plain as done by Wyngaard[31] . In the complex orography of a mountain site, this could be done empirically with a statistical approach similar to that of Vanzandt. Similarly the telescope and dome seeing could also be predicted using local temperature measurements and some modelisation. Then seeing forecast would become a reality.

CONCLUSION.

Many different ways of measuring seeing have been described and discussed. What is the best approach ? Clearly the answer depends upon the final use of the measurement. If observations have to be corrected for image degradation, image plane measurements made under the same conditions are certainly the most suitable. For comparing seeing conditions between existing telescopes and sites, pupil plane measurements are the most accurate. In order to improve image quality, one has to locate the origin of bad seeing and C_N^2 or $C_T{}^2$ measurements become necessary. A combination of remote sensing techniques and pupil plane measurements seems the most appropriate approach. For site testing, a good understanding of the relation between these parameters and atmospheric conditions become essential. A lot of progress have already been made and there is no doubt that appropriate modelling should be possible in the future.This would open the door to seeing forecast and more efficient use of telescopes.

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DISCUSSION

O. Von der Lühe: You mentioned image motion as a reliable seeing indicator. Wouldn't this require a high telescope stability to ensure that seeing quality estimates are not disturbed by telescope shaking?

F. Roddier: Yes, indeed. However, you need only a short term stability over a time scale of the order of a few tenths of seconds.