ASIAN JOURNAL OF PHYSICS, 13: 227-232, 2004

Micro-fluctuations of Fried's parameter (r_0)

S. K. Saha and L. Yeswanth
Indian Institute of Astrophysics, Koramangala, Bangalore 560034, India
e-mail: sks@iiap.res.in; sks@iiap.ernet.in

The atmospheric coherence is a highly variable parameter depending upon the high velocity wind. The size of the atmospheric coherence length widely known as, Fried's parameter, r_0, has been computed during night at the Cassegrain focus of the 2.34 meter Vainu Bappu Telescope (VBT), Vainu Bappu Observatory (VBO), Kavalur, India, using the speckle interferometric technique. The variation of r_0 value at a different intervals during the night is also computed. Measurements of r_0 at a step of ∼100 milliseconds (msec) have been carried out.

1. Introduction

Conventional mode of imaging/spectroscopy in optical astronomy cannot achieve the highest possible angular resolution on the ground because of atmospheric 'seeing'. The ideally flat wave fronts from distant stars get distorted by the atmospheric turbulence of the earth, containing a distribution of cells of differing size and refractive index [1]. Owing to the winds at various heights, convection in and around the building and the dome, off the surface of the telescope structure, inside the primary mirror cell etc., these cells move rapidly across the path of the light. Hence, the performance of large ground-based telescopes are severely degraded due to which the theoretical limit of angular resolution which is proportional to the aperture of the telescope is in practice never achieved [2]. Images recorded at the telescope are convolved with the combined point spread functions (PSF) of the atmosphere and the telescope. The nature of the turbulent atmosphere is carried out on the 2.34 meter Vainu Bappu Telescope (VBT), Vainu Bappu Observatory (VBO), Kavalur, India. The theoretical limit of resolution of the telescope in optical band is 0.05 arc second. But one can see from the following study that the atmosphere does not allow the telescope to resolve anything less than about 1.0 sec of arc.

The degradation of atmospheric images by the turbulent atmosphere is called seeing. Measurement of seeing is important for the purpose of site evaluation and its seasonal variation at a particular site. Seeing varies from place to place and time to time. It is of interest to study the variation of seeing at intervals of minutes and milliseconds. Such a study facilitates apart from gaining insight into the telescope mirror, mirror assembly and telescope dome seeing, a knowledge of the optimal exposure time required for a good specklegram and any other imaging technique.

Different methods of estimating the seeing value at any given place has been described in the literature [3, 4]. But the most effective method is to measure r_0 from the short exposure (<20 msec) images using speckle interferometric technique [5]. We have used such an interferometric technique to calculate the transfer functions of the point sources(unresolved stars). In what follows, we present the night time variation of r_o from the data obtained at 2.34 meter Vainu Bappu Telescope (VBT), at Vainu Bappu Observatory (VBO), Kavalur.

2. Vital parameters of atmospheric turbulence

A plane wavefront, for example light from a distant star, after passing through the earth's turbulent atmosphere gets distorted both in amplitude and in phase. The magnitude of its distortion has been very well characterized by the atmospheric coherence length, well known Fried's parameter r_0 [2].

It is the cophasal cell size in the atmosphere over which the wavefront distortion has a root-mean-square (RMS) value not exceeding 1 radian. For a plane wavefront, r_0 has been shown to be the integral of the refractive index structure constant, $\mathcal{C}_n$, taken over the path traversed by the light:

$$r_0 = \left(\frac{6.88}{a}\right)^{3/5}, \tag{1}$$

where

$$a = 2.91\kappa^2 \int_{-\infty}^{\infty} \mathcal{C}_n^2(h)dh, \tag{2}$$

in which $\kappa = 2\pi/\lambda$ is the wave number, λ the wavelength of the light, h the height of the turbulence layer, and $\mathcal{C}_n$ the refractive index structure constant.

The refractive index structure constant, $\mathcal{C}_n$, provides the strength of the turbulence. It is a function of the path length, h, through the atmosphere. It also varies with time and geographic location. The atmospheric time constant, τ, is represented by,

$$\tau = 0.31\frac{r_0}{v}, \tag{3}$$

in which v is the wind velocity averaged over the altitude (typical value is v = 20 meter/sec).

The conventional method of measuring seeing from the star image is to measure the full width half maximum (FWHM) of a long exposure stellar image at zenith:

$$FWHM = 0.98\frac{\lambda}{r_0}, \tag{4}$$

where λ is the wavelength of observation and r_o is the Fried's parameter.

The wavefront coherent area σ can be found by using the following relation:

$$\sigma = 0.342\left(\frac{r_0}{\lambda}\right)^2. \tag{5}$$

3. Measurement of Fried's parameter (r_0)

The power spectral density of refractive index fluctuations caused by the atmospheric turbulence follows a power law with large eddies having greater power. When a flat wavefront passes down through the atmosphere, it suffers phase fluctuations and reaches the entrance pupil of a telescope with patches of random excursions in phase [2]. If the exposure time is shorter (<20 msec) than the evolution time of the phase inhomogeneities, each patch of the wavefront with diameter r_0 would act independently of the rest of the wavefront resulting in many bright spots - speckles - spread over the area defined by the long exposure image. These speckles can occur randomly along any direction within an angular patch of diameter $\sim 1.22\lambda/r_0$. The resolution θ of a large telescope, limited by the atmospheric turbulence, as defined by the Strehl criterion is,

$$\theta = \frac{4}{\phi}\frac{\lambda}{r_0}. \tag{6}$$

The above equation (6) states that the atmospheric coherence time, r_0, is directly related to the seeing at any place.

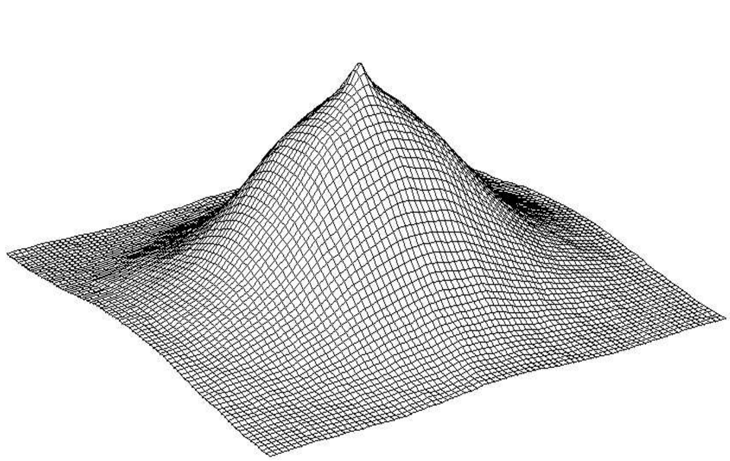

Figure 1: Autocorrelation of seeing disk, as well as of speckle component.

3. The apparatus

We have recorded several unresolved stars (point source) in and around 30° zenith using the speckle interferometer [6] on 28-29 March 1991, at the Cassegrain focus of the VBT using the uncooled Intensified CCD [7]. The image at the said focus is sampled to 0.027 arc second per pixel. Specklegrams of these stars were recorded at the VBT through a filter centered on 6761 Åwith FWHM 100 Å. These images were acquired with the ICCD camera with an exposure time of 20 msec. Out of these data, 45 sets of specklegrams have been processed and the value of r_0 have been plotted over a time interval ranging from 15 hr UT to 22 hr UT. The delay time between each set of observations was 60 sec. Figure 1 depicts the seeing disk of a star, HR2305 observed at the Cassegrain focus of 2.34 meter VBT, Kavalur, India, at 1510 hrs. UT. It comprises the width of the seeing disk, as well as the width of the speckle component [8].

Another set of data was taken on a different night, on 28 February, 1997, through a filter centered on 6563 Åwith FWHM 50 Å. with the instrument developed by Saha et al. [9, 10]. This camera system was used at the Cassegrain focus of the 2.34 meter VBT. An uncooled intensified CCD (ICCD) camera was used to capture the image at 0.015" per pixel.

5. Observations and data processing

The visual magnitude, m_v, of observed stars on 28-29 March, 1991 varied from 5 to 7. The observations were carried out between 1500 and 2330 hrs. UT. The ICCD provides video signal as output. The images were acquired at an exposure times of 20 msec using a frame grabber card DT-2861 manufactured by Data Translation^{TM} and stored on to the hard disk of a PC. Each frame consists of odd and even field, thus giving effective exposure of 10 msec per field. Data analysis was carried out by taking both the fields separately.

The averaged autocorrelation of the short exposure images of a point source contains autocorrelation of the seeing disk together with the autocorrelation of mean speckle cell. From the Figure 1, we find that the size of the r_0 is 8.5 cm at 6761 Å. The form of transfer function, $< |\widehat{S}(\mathbf{u})|^{\mathbf{2}} >$,

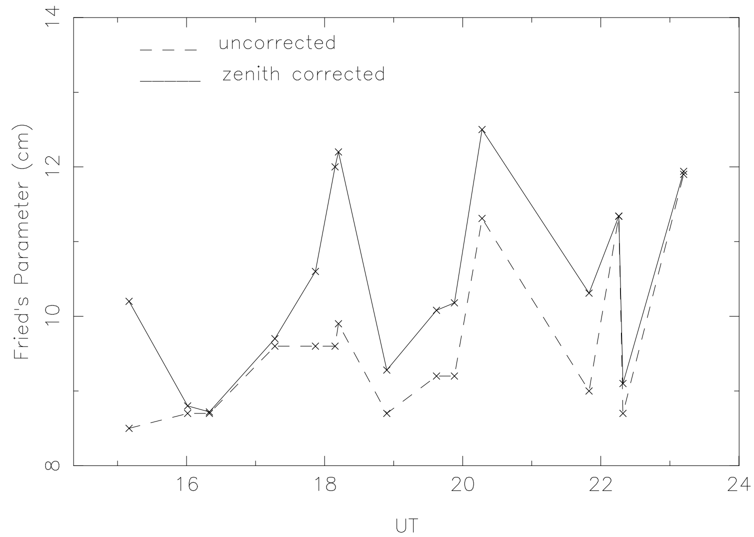

Figure 2: Night time variation of r_0 on 28-29 March, 1991, at VBT, Kavalur.

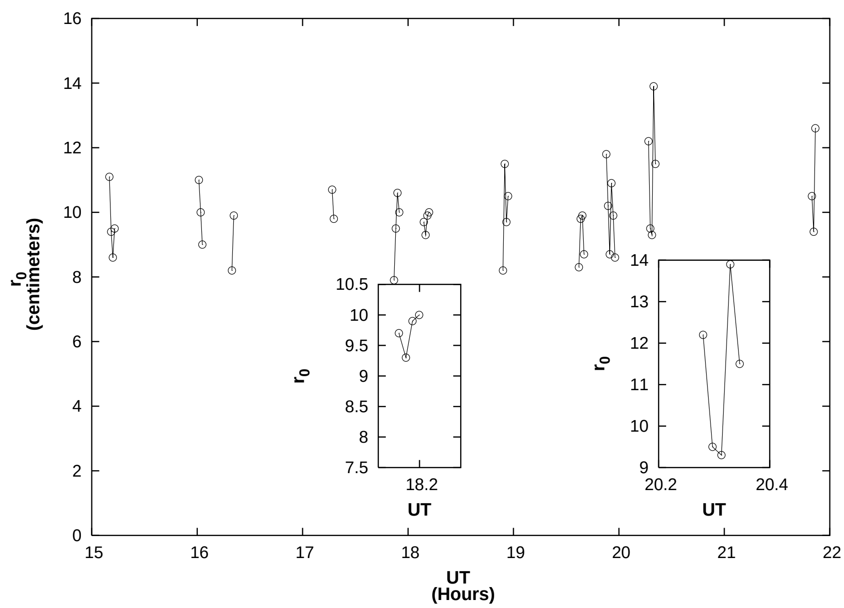

Figure 3: A set of r_0 values from 12 different stars acquired on 28-29 Mar., 1991, at VBT, Kavalur.

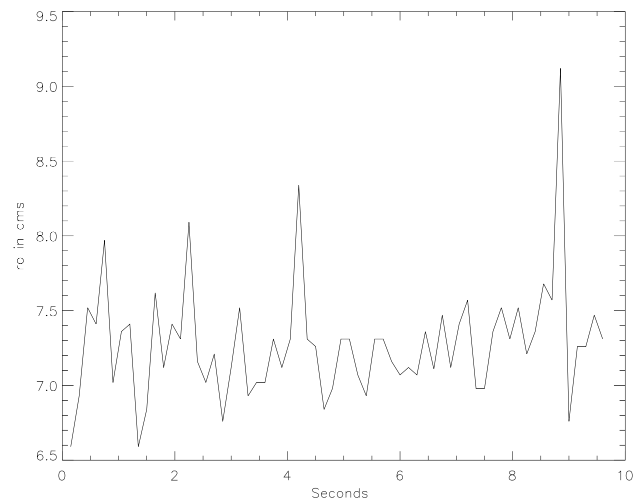

Figure 4: The value of r_0 at step of 150 msec on a different night at VBT, Kavalur.

is obtained by calculating Wiener spectrum of the instantaneous intensity distribution from each of these stars. Here, $\widehat{S}$ is the transfer function, $\mathbf{u}$ = (u, v) is a 2-dimensional space vector, $<>$ indicates the ensemble average and $||$ the modulus. Analysis of the data were carried out using the programme developed by Saha and Maitra [11]. The r_0 is measured from the two speckle-grams acquired at an exposure times of 20 msec, containing odd and even fields of a single frame. The average of these frame is the instantaneous value of r_0 at the time of observation. The estimated error in this measurement is of the order of $\pm$ 0.05 arcsec. Figure 2 depicts the night time variation of r_0 on 28-29 March 1991 comprising of zenith distance corrected value (solid line) and uncorrected value.

6. Discussion and Conclusions

The quality of the image degrades due to the following reasons: (i) variations of air mass X ($\sim 1/\cos Z$) or of its time average between the object and the reference, (ii) seeing differences between the modulation transfer function (MTF) for the object and its estimation from the reference, (iii) deformation of mirrors or to a slight misalignment while changing its pointing direction, (iv) bad focusing, (v) thermal effect from the telescope etc. [12]. The speckle life time is an important atmospheric parameter since it describes the longest possible exposure time for recording specklegrams. It is an important parameter too for testing the atmospheric condition at existing and incoming astronomical sites [13].

Systematic studies of r_0 would enable to understand the various causes of the local seeing, for example, thermal inhomogeneities associated with the building, aberrations in the design, manufacture and alignment of the optical train etc. Due to the winds at various heights, convection in and around the building and the dome, off the surface of the telescope structure, inside the primary mirror cell etc., these cells move rapidly across the path of the light. Depending upon the high velocity wind, the coherence time varies from $<$1 msec to $\sim$ 0.1 sec [12].

Figure 3 shows the plot of r_0 values calculated from several sets of specklegrams of twelve different stars acquired on 28/29th March 1991. The observations were carried out from 15 hrs to 22 hrs UT. The autocorrelation of these sets were plotted and the r_0 value calculated from it. The parameter r_0 reaches its maximum value of 13.9 cms at 20.329 UT. This corresponds to a seeing of 0.98 arcsecond by equation (1). A poor seeing of 1.7 arcsecond occurs at 17.867 UT (23 hr 22 mints LST, 28th Mar). Astronomers speak of nights of good seeing and bad seeing. A night of good seeing does not mean that the value of r_0 was at a fairly high constant value. It is noted in Figure (3), a few sets of plots of r_0 (shown insets) depict points at which the value of r_0 changes not more than 1-2 cm during an interval of 1 min., while another set shows a variation of as high as 5 cm. This is the typical value of the atmospheric time constant.

The atmospheric fluctuations change rapidly, on timescales of tens of milliseconds, causing the quality of the focused image also to vary rapidly. As can be seen from the plot in Figure (4), r_0 fluctuates drastically every 150 msec. The value of r_0 in one particular time had increased by about 3 cm. By using a high speed camera one can select the images that are least affected by the atmosphere from a large dataset of short-exposures, one can reconstruct diffraction-limited images [14]. This technique, known as selective image reconstruction method, can be used both for ground based astronomical observations, as well as for ground-ground imaging such as surveillance work with long focus lenses.

Acknowledgment: The authors are grateful to V. Chinnappan for the helpful discussions.

References

1 Tatarski V I, *Wave Propagation in a Turbulent Medium*, (1967), Dover, New York.

2 Fried D C, *J. Opt. Soc. Am.*, 56 (1966), 1972.

3 Von der Lühe O, *J. Opt. Soc. Am. A*, 1 (1984), 510.

4 Wood P R, *Proc., Astron Soc. Australia*, 6 (1985), 120.

5 Labeyrie A, *Astron. Astrophy*, 6 (1970), 85.

6 Saha S K, Venkatakrishnan P, Jayarajan A P, Jayavel N, *Curr. Sci.*, 57 (1987), 985.

7 Chinnappan V, Saha S K, Faseehana, *Kod. Obs. bull.*, 11 (1991), 87.

8 Saha S K, Chinnappan V, *Bull. Astron. Soc. Ind.*, 27 (1999), 327.

9 Saha S K, Jayarajan A P, Sudheendra G, Umesh Chandra A, *Bull, Astron. Soc. Ind.*, 25 (1997), 379.

10 Saha S K, Sudheendra G, Umesh Chandra A, Chinnappan V, *Expt. Astron.*, 9 (1999), 39.

11 Saha S K, Maitra D, *Ind. J. Phys.*, 75B(2001), 391.

12 Foy R, *Proc. "Instrumentation for Ground-Based Optical Astronomy - Present and future"*, ed. L.Robinson, Springer-Verlag, NY, (1988), 345.

13 Vernin J, Weigelt G, Caccia J L, Müller M, *Astron. Astrophys.*, 243 (1991), 553.

14 Baldwin J, Tubbs R, Cox G, Mackay C, Wilson R, Anderson M, *Astron. Astrophys.*, 368 (2001), L1.

Received : November 02, 2004 *Revised : November 25,2004* *Accepted : December 13, 2004*