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Performance of a speckle interferometer

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Abstract. An interferometer system to obtain speckle-grams of astronomical objects in the visible wavelength, has been developed for use at the 2.34 meter Vainu Bappu Telescope (VBT), situated at the Vainu Bappu Observatory (VBO), Kavalur. Laboratory tests of resultant intensity distributions due to the point source, with phase modulation screens, as well as the images obtained using this interferometer at the Cassegrain end of the said telescope are discussed.

Key words : interferometer, speckle, binary

1. Introduction

Atmospherically induced phase fluctuations distort otherwise flat wave fronts from distant stars which reach the entrance pupil of a telescope with patches of random excursions in phase. Such phase distortions restrict the effective angular resolution of most telescopes to 1 second of arc or worse. Random phase excursions are attributed to the refractive index fluctuations created by pockets of inhomogeneities in the atmosphere characterised by the value of quasi-coherent areas of diameter r_0, ($r_0 \sim 10$ cm under general conditions), known as Fried parameter (Fried, 1966). If the exposure time is shorter (< 20 millisecond) than the evolution time of the phase inhomogeneities, then each patch of the wave front would act independently of the rest of the wave front resulting in multiple images of the source, called, 'Speckle' (the term 'Speckle' refers to a grainy structure observed when an uneven surface of an object is illuminated by a coherent source).

Its structure in astronomical images is the result of constructive and destructive bi-dimensional interferences between rays coming from different zones of incident wave. These speckles can occur randomly along any direction within an angular patch of diameter λ/r_0. The sum of several statistically uncorrelated speckle patterns from a point source can result in an uniform patch of light a few seconds of arc wide (conventional image).

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* Superannuated

The technique of speckle interferometry (Labeyrie, 1970) has become an invaluable tool for astronomical research in obtaining diffraction limited spatial Fourier spectrum and image features of the object intensity distribution from a series of short exposure images through a narrow band filter. The intensity distribution in the focal plane in case of quasi-monochromatic incoherent source can be described by the following equations.

$$c\,(x, y) = o\,(x, y) * p\,(x, y)$$

where $c\,(x, y)$ is the image, $o\,(x, y)$ is object intensity distribution, $p\,(x, y)$ is the telescope-atmosphere point spread function (PSF) and $*$ denotes convolution.

The Fourier space relationships between objects and their images are

$$C\,(u, v) = O\,(u, v)\,.\,P\,(u, v).$$

Here, $O\,(u, v)$ is the object spectrum and $P\,(u, v)$ is the transfer function. In the conventional speckle interferometry, the ensemble averaged power spectrum is obtained for a large set of short exposure images.

$$<|C\,(u, v)|^2> = |O\,(u, v)|^2\,.\,<|P\,(u,v)|^2>$$

where $<>$ indicates the ensemble average and $||$ the modulus.

The form of transfer function $<|P\,(u,v)|^2>$ can be obtained by calculating Weiner spectrum of the instantaneous intensity from the unresolved star (reference).

The 2.34 meter Vainu Bappu Telescope (VBT) at Vainu Bappu Observatory (VBO), Kavalur can be used extensively to study high resolution features of many types of celestial objects. These may be in the form of separation and orientation of close binary stars (separation < 1 arc second), shapes of asteroids, sizes of certain types of circumstellar envelopes, the structure of active galactic nuclei etc. The latitude of this observatory gives us access to almost 70° south of the celestial equator. Most of the observational results beyond 30° south of zenith at high latitude stations obtained earlier require to be confirmed utilising positional advantage of VBT. This paper presents the design and performance of the new speckle camera suitable for operation at the prime focus of this telescope.

2. Speckle interferometer

A speckle interferometer is a high quality diffraction limited camera where magnified (~ f/100) short exposure images can be recorded. Additional element for atmospheric dispersion corrections is necessary to be incorporated. At increasing zenith distance speckles get elongated owing to this effect. Either a pair of Risley prism must be provided for the corrections or the observation may be carried out using a narrow bandwidth filter. In this set up, we have used a narrow band filter to minimise the effect.

To arrive at the design of this equipment, preliminary investigations were made by us with a modest equipment (Saha *et al.*, 1987) consisting of a Barlow lens, a broad band filter in the blue region and a movie camera. Speckles and interference fringes of various bright stars were recorded with the f/13 beam of the 1 meter telescope at VBO. The power of this technique was demonstrated by the detection of some telescope aberrations (Saha *et al.*, 1987). Owing to the low quantum efficiency of photographic emulsion, use of an image intensifier becomes essential (Breckinridge *et al.*, 1979) to record speckle-grams of faint astronomical objects. New developments in instrumentation technology enable us to detect the photon events per frame (Blazit *et al.*, 1977; Blazit, 1986) up to a frame rate of ~ 50 Hz. To detect individual photon event, recording time resolution ~ 1 µs has been successfully employed (Papaliolios *et al.*, 1985; Durand *et al.*, 1987). We have modified the afore-mentioned set up by replacing the movie camera with an EEV uncooled intensified CCD (ICCD) camera (385 x 288) which provides a standard CCIR video output (Chinnappan *et al.*, 1991) and were able to obtain speckle-grams of several close binaries through a 5 nm filter centered on Hα with the Cassegrain end (f/13) beam of the 2.34 meter VBT at VBO. Two of these binaries were processed using Blind Iterative De-convolution (BID) technique and reconstructed the Fourier phases (Saha and Venkatakrishnan, 1997).

Figure 1 depicts the optical design of the speckle camera system. Provisions have been made to observe at both the foci (Prime f/3.25 as well as Cassegrain f/13) of the afore-mentioned telescope. Before arriving at the final concept of the design of this interferometer, the optical alignment was optimized at the laboratory. An artificial star image and the telescope with f/3.25 beam were generated. Atmospheric seeing was simulated by introducing various static dielectric cells (SDC) of different sizes etched in a glass plate with hydrofluoric acid. Several glass plates with both regular and random distribution of SDCs of known sizes have been made and were used to produce speckle at the laboratory. The image was magnified to discern the individual speckles with a microscope objective. A 10 nm filter centered on OI [5577] was used to reduce the chromatic blurring. For an accurate evaluation of the performance of the design of this interferometer, we have also obtained fringes by placing a mask with multiple apertures in front of the telescope in the laboratory and compared those with the computer simulation of the intensity distribution (Saha *et al.*, 1988). The similarity of the observed image shape obtained at the laboratory, as well as the computer simulated image pattern proved the perfection of the design of this interferometer.

One of the most difficult problems was solved by us by making a focal plane optical flat of a low expansion glass with high precision hole of aperture ~ 350 µ, at an angle of 15 degree on its surface. A novel technique was developed to make this aperture in the laboratory. This aperture is equivalent to a field of ~9 arc sec at the prime focus and to a field of ~2.25 arc sec at Cassegrain focus of the VBT. The rear side of the flat was shaped suitably to enable the microscope objective, to be brought very close to the focal plane (~1mm). The field covered by this aperture of the flat at Prime focus of the VBT allows us to observe both the object and the reference star simultaneously, if the latter is located within the iso-planatic domain around the object. The image of the object is passed on to the microscope objective through this aperture. The surrounding star field of ~4.5 arcmin at the Prime focus and ~1.25 arc min at the Cassegrain focus is re-imaged on an intensified CCD for guiding.

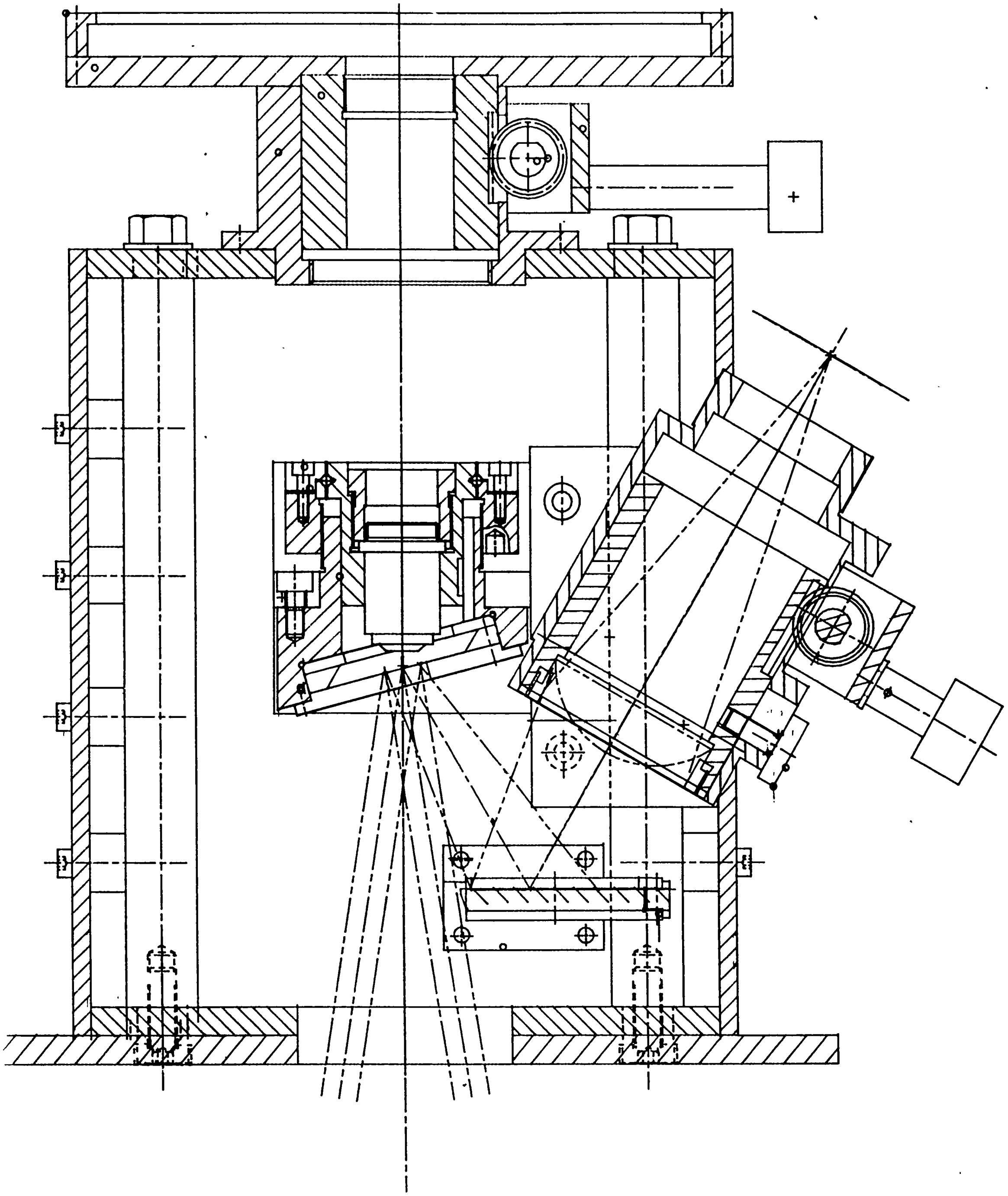

Figure 1. Optical design of the speckle interferometer.

Before finalizing the mechanical design for the mounts and the housing of this interferometer, Finite Element Method (FEM) analysis was performed to have prior information about the deflections, deformation, stress, flexure etc. of the material. The computer simulation test had shown that the instrument can hold any detector of 10 kgs weight kept at a distance of 200 mm away from the rear end of the interferometer with a flexure of ~1.3μ. The model was analysed for strength and deflection for a load of 20 kgs over the span of the instrument. The analysis shows a deflection of ~0.7μ. Figure 2 shows the FEM model of the structure of the speckle interferometer.

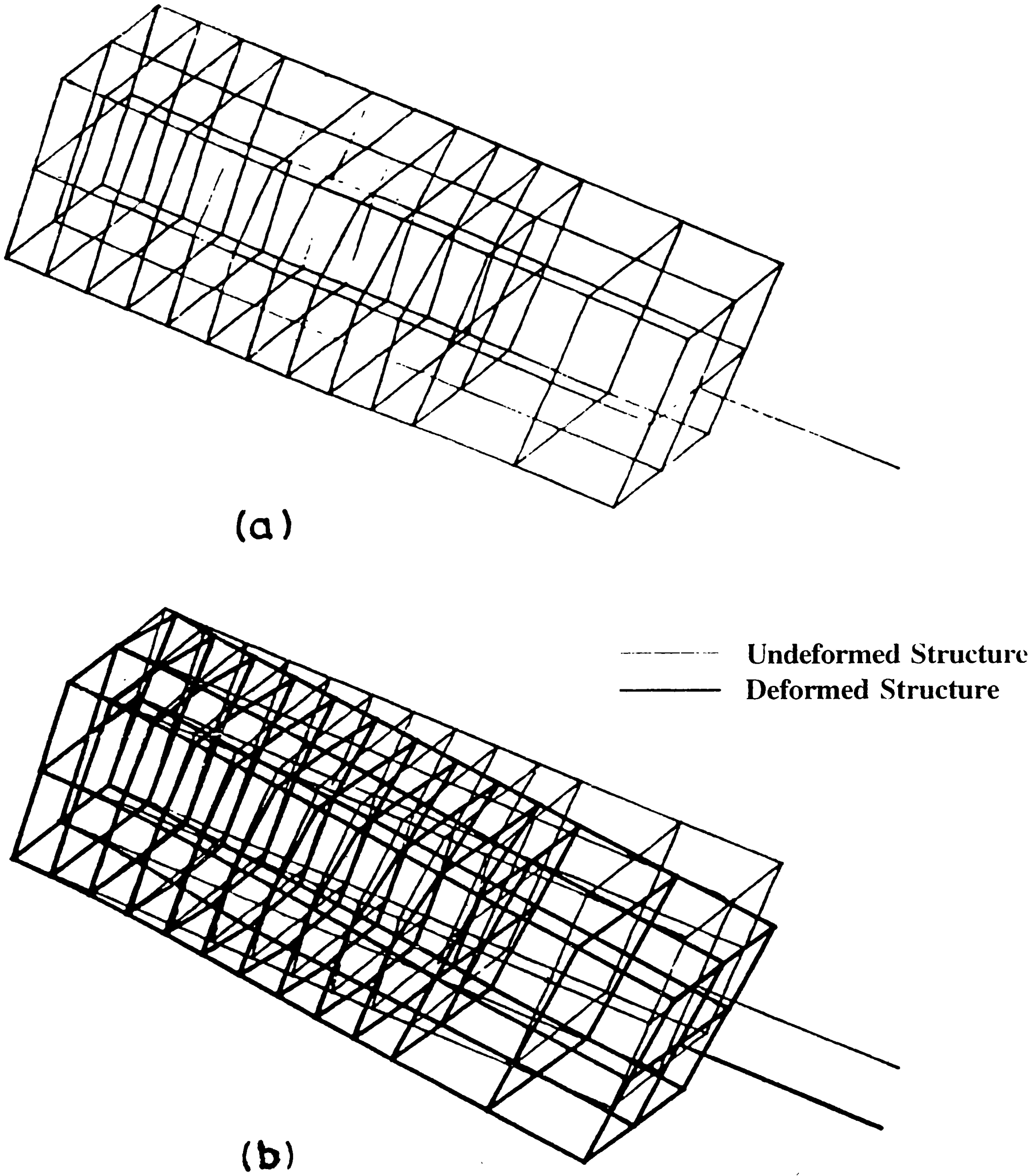

Figure 2 a, b. Finite element model of the structure of the speckle interferometer and the same with the load of 20 kgs over the span of the instrument respectively.

The mechanical design requirements which have to be met while designing the interferometer are : (i) high accuracy, (ii) light weight, (iii) minimum deflection at various orientations of the telescope, (iv) provision for fine adjustment of the microscope without allowing rotation of the image, (v) provision for fine focusing of the camera without disturbing / rotating the image, (vi) provision for adjusting the inclined beam, (vii) rigid locking of the lens positions during use of the instrument.

To assure high accuracy even at varying ambient temperatures, a Martensitic variety of stainless steel material (SS 410) with low coefficient of linear expansion has been used. The instrument has been conceived as a box made of two end plates of thickness 8 mm and joined by means of struts of section 22 mm square. The struts have been machined from a cylinder of 25 mm diameter of required length ground at the ends. The struts are provided with spigots of 18 mm diameter at ends for locating the end plates with corresponding holes. The concentricity between spigots can be ensured by grinding. The end plates are machined together and the four holes which receive the spigots as well as the central hole are machined in one setting on wire cut Electro-discharge Machining (EDM) to assure required center distance accuracies. The end plates when locked with the struts, form a box structure of light weight with required strength to house the desired mounts with minimum deflection. A bottom plate is clamped on to two of the struts and this forms a platform on which the various mounts for the microscope, flat and the lens can be mounted. The mounts themselves are designed and machined in such a way that lens mounting holes are at an accurate distance from their bases. In case of any error, the base can be ground to get the required center height accuracy. Thus, the plane in which the light travels through the microscope and mirrors is maintained accurately. The individual mechanisms in each of the mounts provide for fine adjustment which help in fine focusing of the image. Plate I shows the photograph of the interferometer. In order to avoid reflection from other surfaces, black chrome plating was done to achieve blackening of the stainless steel.

3. Observations

We have successfully made an attempt to observe a few close binary systems using this newly built interferometer at the Cassegrain focus of the VBT. The image scale at the Cassegrain focus (6.7 arc second per mm) of this telescope was magnified to 0.67 arc second per mm, using a microscope objective. This enlarged image was recorded through a 5 nm filter centered on Hα using the ICCD camera (Chinnappan *et al.*, 1991). The images were acquired with exposure times of 20 ms using a Data Translation™ frame-grabber card DT-2861 and subsequently stored on to the hard disk of a PC 486 computer. This computer allowed us to record 64 images continuously in a few seconds time. Figure 3 shows the speckle-gram of α-Andromeda. The observing conditions were fair with an average seeing of ~2 arcseconds during the nights of 29/30 November 1996.

Plate 1. Shows the photograph of the speckle interferometer.

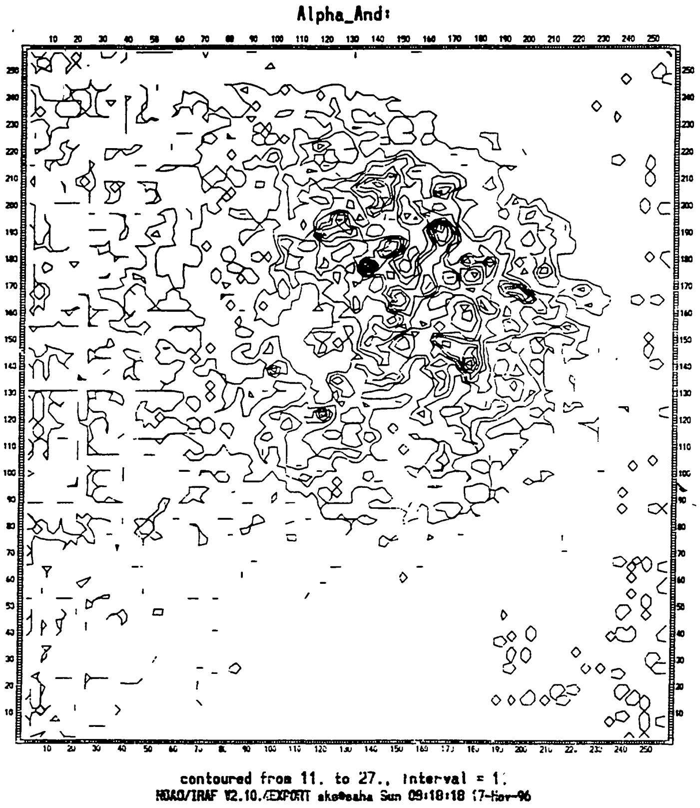

Figure 3. Contours of the speckle image of α-Andromeda.

4. Discussions and conclusions

Studies involving the optimization of speckle imaging, are part of the important groundwork for addressing the basic astrophysical problems. The quality of the image degrades due to the following reasons : (i) variations of air mass X (~1/cosZ) 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 focussing, (v) thermal effect from the telescope etc. These may lead to a dangerous artifact, yielding a wrong identification of the companion star. A group of observers found a spurious secondary peak in the mean auto-correlation at a distance equal to the first Airy ring (Foy, 1988). Labeyrie (Foy, 1988) opined that spider-induced temperature gradient might be the cause of this phenomenon since the upper faces of spider cool fast. Here, we have fabricated a mechanical spacer of 450 mm to keep the instrument away from the rear end of the Cassegrain end of the VBT. Care has been taken while designing the spacer (see Plate I) that no hot air would be trapped in and around the interferometer, which may help to get rid of such phenomena.

To estimate the MTF, it is necessary to calibrate it on unresolved star, for which all observing conditions are required to be identical to those for the object. In this respect, we have taken a precautionary measure by optimizing the size of the aperture in the focal point flat of this interferometer. In the prime focus of the VBT, this aperture will allow us to observe both the object, as well as reference star simultaneously, if the latter is located in the isoplanatic domain.

Depending on the variability in temperature, air currents etc., the atmospheric time constant is generally assumed to range between 1 to 100 msec. If the integration time is too long, there is a degradation of signal to noise ratio. The need for fast exposure time implies the use of detectors facilitating desired integration time. The recently acquired Peltier-cooled Intensified CCD (386 x 578) camera, which has the option of various exposures, viz., 5 msec, 10 msec, 20 msec etc. will be used to record the speckle-grams of faint objects. But photon-counting detectors with frame integration are subject to limitations in detecting fast photon-event pairs. A pair of photons closer than a minimum separation cannot be detected as a pair by the aforementioned sensor. This yields a loss in HF information which, in turn, produces a hole in the centre of the auto-correlation, known as Centreur hole (Foy, 1988). Therefore, it is desirable to have a detector which facilitates the oversample image of the order of ~ f/500 in place of the former typical ~ f/100, with a high degree of accuracy to determine the time coordinate of each event. The present interferometer has the capability of oversampling the image of the order of f/520 at the Cassegrain focus of the VBT. If the modern detector, viz., PAPA (Precision Analogue Photon Address), or IPD (Image Photon Detector) is made available, this camera will be able to record speckle-grams of the objects of the faintest limiting magnitudes.

To reiterate, optimised instruments and meticulous observing procedures are essential for obtaining error-free information. It is required to have a simulation bench consisting of an artificial star, a telescope with various focal ratios, a reducing optical system for calibration of the focal point instruments. Calibration is needed both before and after the on-site observations. Systematic use of simulated image to validate the image processing algorithms could be beneficial in retrieving the diffraction limited information.

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