Interferometric imaging with an aperture masked telescope

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Atmospheric turbulence seriously affects the process of telescope image formation through the corrugation of the phase of the electromagnetic wavefront (light) coming from an extraterrestrial source as seen from the ground. The effect is such that, the larger the telescope, the worse the image. One of the methods for overcoming the effects of atmospheric turbulence is that of aperture masking, an interferometric technique that dates back to the time of Albert Michelson. This paper will detail work being done at UPRM’s Physics Department to produce an aperture mask for the Department’s 16 inch diameter optical telescope.

Key Words: Aperture masking; Interferometry; High resolution imaging.

1. Introduction

Since the invention of the telescope in the 1600’s, astronomers have been striving for a clearer definition of the objects they observe. This has led to the development of larger and larger telescopes. As the telescope size increase, fainter objects became easier to see. The detail seen in the images improved as well, although not as much as it should have theoretically. The problem was that the turbulent layers of the atmosphere, caused by temperature distortions which led to random refractive index variations, altered the passage of light waves through the atmosphere. This problem was seen in the visible, at the closest viewing sites, for telescopes of more than about 10cm in diameter. Up to 10cm diameter, telescopes were not too affected by the atmospheric distortions [Readhead1988]. This motivated the invention of the technique of aperture masking. We cover a large telescope’s entrance pupil (or its conjugate) to form a series of separate, usually circular, areas. This creates a series of separate telescopes from the original. Each mini–telescope is designed to be unaffected by atmospheric turbulence due to its size. The array produces a single image which is covered with interference fringes which may be recorded and processed into a single, detailed picture with the same angular resolution as the theoretical limit of the main telescope mirror, thereby overcoming the limiting factor of the atmosphere.

The insuperable problems of earlier workers were to do with this recording and processing of data, since technology at those times was not up to the task. It took until 1987 for the first results of optical aperture synthesis to be reported [Haniff1987].

1.1. Principles

Optical aperture synthesis is a technique based on the concept of measuring interference of the electromagnetic field. Lets start from the simplest two aperture interference experiment, Young’s double slits, Figure 1. The light passed by the
apertures at $P_1$ and $P_2$ from point source $S$ form interference fringes centered at $O$ on the screen. The fringes are modulated by a diffraction envelope whose width is set by the size of the apertures. The angular separation of adjacent interference fringes, as seen from the plane of apertures is $\approx \lambda/d$ where $d$ is the separation of the two apertures. The fringes for a monochromatic point source have maximum contrast with zero intensity between the maxima in intensity. Consider the situation when the source has a finite angular extent in the direction parallel to the line joining the apertures, as shown in Figure 2. Each point on the source produces its own set of fringes and these will be displaced relative to one another. Fringes for representative points on the source will add and produce a fringe pattern of lower contrast.

1.2. The complex degree of coherence

The interaction of the waves from $P_1$ and $P_2$ in the previous figures is treated more formally in the theory of partially coherent light. In Figure 3 the complex degree of coherence between the wave disturbances at the points labelled $P_1$ and $P_2$ due to the extended source $S$ is represented by $\gamma_{12}(\tau)$. $\tau$ is the time difference corresponding to the path difference $\Delta OPL = s_1 - s_2$ between the two disturbances at $Q$, the point of superposition [Born1964]. The intensity at $Q$ is given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \Re \{\gamma_{12}(\tau)\} \quad [2]$$

where $I_1$ and $I_2$ are the intensities at $Q$ from $P_1$ and $P_2$ respectively, when each is present alone. The complex degree of coherence can be expressed as a modulus $|\gamma_{12}(\tau)|$ and a phase $\phi_{12}(\tau)$:

$$\gamma_{12}(\tau) = |\gamma_{12}(\tau)| \exp i\phi_{12}(\tau) \quad [3]$$
Thus the real part of the complex degree of coherence in Equation 2 can be expressed as

$$Re[\gamma_{12}(\tau)] = |\gamma_{12}(\tau)| \cos \phi_{12}(\tau)$$ \[4\]

The modulus of $\gamma_{12}(\tau)$ is known as the degree of coherence and when $I_1 = I_2$, it is equal to the fringe visibility given by Equation 1. That is to say, given $I_1 = I_2$,

$$V_{12}(0) = |\gamma_{12}(0)|$$ \[5\]

When $\tau = 0$, we talk about the complex degree of spatial coherence $\gamma_{12}(0)$. The angular distribution of intensity across the source $I_\alpha$ is a Fourier transform of $\gamma_{12}(0)$, by the van Cittert–Zernike theorem,

$$\gamma_{12}(0) = \int_{-\infty}^{\infty} I_\alpha \exp \left( \frac{-2\pi i \alpha}{\lambda} \right) d\alpha$$ \[6\]

Thus if $|\gamma_{12}(0)|$ and $\phi_{12}(0)$ are measured over an appropriate range of baselines\(^1\) then the angular intensity distribution $I_\alpha$ of the source can be found. The fringe phase for an aperture separation $d$ is the displacement of the fringes relative to the fringes for $d \approx 0$, expressed as a fraction of the fringe spacing $s$. If the fringes are displaced by a distance $\Delta s$, the phase $\phi_{12}(0) = 2\pi \Delta s / s$. This fringe phase provides information on asymmetries in the angular intensity distribution as a function of aperture separation. For a symmetrical source, the fringe phase will be zero for all aperture separations.

Generally, the Earth’s turbulent atmosphere will disrupt the phase and for observations made with a single baseline at a time, so only the degree of coherence $|\gamma_{12}(0)|$ is measurable. In the absence of phase, departures from symmetry in the intensity distribution cannot be detected. Thus measurements with a single baseline yield only the visibility which are interpreted as the angular size of an equivalent strip source or the angular diameter of a radially symmetric disk source. From this it is clear, to obtain images, both the modulus and the phase must be measured for at least three baselines simultaneously.

2. Laboratory experiment

The aperture masking experiment on stellar objects will be carried out using the Department of Physics’ 16-inch telescope, which is based in the Departmental Observatory Dome (Figure 4). We place an aluminium foil mask in the collimated beam. The mask of three apertures (pinholes) will be at the conjugate plane of the telescope entrance pupil. A mount with the appropriate optical system and data capture equipment has to be designed. This has led to a laboratory prototype, Figure 5. The beam from the test telescope focus is collimated by a lens. It then passes through the three aperture aluminium mask, and is finally focused through an objective lens onto a digital camera (not shown). The digital camera used in the laboratory is an SBIG ST–7. Eventually this will be replaced by a fast framing CCD camera (Dalsa) once one is available.

3. Results

A HeNe laser source ($\lambda = 633\text{nm}$) is used for the initial alignment of the system and to test the data taking mechanism. Example interference fringe data that

\(^1\)This is the vector distance between any two apertures in an interferometer.
Aperture Masking System set-up

1. HeNe laser
2. Spatial filter and Collimator
3. Mirrors
4. Microscope objective
5. Lens
6. Mask (pinholes in aluminum foil)
7. CCD camera
8. Telescope

FIG. 5: Laboratory prototype geometry.

has been recorded using the HeNe laser as a point source is shown in Figure 5, with its two dimensional Fourier transform. The Fourier Transform image shows the spatial frequencies contained within the raw image more clearly; the axes have not been rescaled. The zeroth (d.c.) frequency lies in the centre of the plot, at (382.5, 255). It may be seen that the main set of higher frequencies occur around 100 cycles, so that the median horizontal fringe width is about 0.69mm.

A calibration check was done to verify that the image capture method is linear. The horizontal baseline in the mask was calculated to be 1.5mm and the mean diameter of each pinhole in the mask was found to be 0.12mm, although the diffraction pattern shows the pinholes to be rather more elliptical than circular. These calculated values were found to match direct measurements to within experimental accuracy.

4. Conclusion

A prototype aperture masking system has been shown and the preliminary results demonstrate that it is functional. More work is required to calibrate the system, especially using a low coherence white light source (which is being constructed). We will soon start to play with the geometry of the mask, following [Haniff1992].

References


