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Seeing the Sky More Clearly –
The Search for Higher Resolving Power

R. Hanbury Brown

Professor Emeritus, University of Sydney, Australia;
White Cottage, Penton Mewsey, Near Andover, Hants SP11 0RQ, England.

This evening I am going to talk about the many attempts which have been made, and are still being made to see what there is in the sky more clearly, in other words about the efforts to see fainter objects and to see them in greater detail.

One of the first people to make a serious attempt to see a more detailed picture of the sky was Galileo. He needed it in his battle with the opponents of the Copernican theory. Among the many serious objections to that theory was the observation that the stars do not appear to move in the sky as they should if the Earth really does travel around the Sun. Galileo argued that this awkward fact might be explained if the stars are at distances which are large compared with the orbit of the Earth, and in an effort to support his argument he tried to measure the angular size of the bright star Vega. To do this he suspended a fine silk cord vertically and measured how far away from the cord he had to stand so that it just occulted the star.

Galileo reached the conclusion that the angular diameter of Vega is 5 arcseconds. As we now know his result is far too large; nevertheless at that time it was a significant advance compared with the currently accepted value of about 2 arcminutes, and Galileo was able to use it to considerable effect in his arguments with the critics of Copernicus.

Galileo's next contribution to our topic was more fruitful. Learning of the invention of the telescope in Holland in 1608 he built one himself and applied it assiduously to looking at the sky. As we all know he saw mountains on the Moon, satellites circling around Jupiter and many more stars than could be seen with the naked eye.

Elementary textbooks tell us that the ability of any instrument to show us fainter things and also greater detail is limited by its physical size. Thus if θ is the smallest angular detail which can be measured, then

$$\theta \approx \lambda / D, \tag{i}$$

where D is the physical aperture of the instrument and λ is the wavelength of the radiation. If, for example, we use the naked eye (D = 3mm) then the smallest angle which we can discern is about 40 arcseconds, and a small telescope, say with an aperture of only 12cm, will reduce this angle to 1 arcsecond. Clearly the invention of the telescope represented a major step forward in our search for higher resolving power.

The obvious way of getting an even better view of the sky was to build a larger telescope, but it was soon found that although larger telescopes collect more light and so reveal fainter objects, they do not give the increase in detail that theory predicts. The reason is that, in practice, their resolving power is not limited by simple diffraction but mainly by turbulence in the Earth's atmosphere so that the image of a star seen through a large telescope, no matter how large, looks like a roughly circular blur with a typical angular size of between 1 and 2 arcseconds. This means that once we have built a telescope of about 12cm aperture, any further increase in size is not rewarded by much improvement in the detail which can be seen. The most common objects in the sky are stars and the angular size of even the brightest star (Sirius) is only 0·0068 arcseconds! Clearly, if we are going to see any significant detail in the stars we must look for a very great improvement over what can be done with a simple telescope.

THE IDEA OF USING INTERFERENCE FRINGES TO INCREASE RESOLVING POWER

Suppose that the light from a distant point source falls on the opaque screen shown in figure 1 and that in this screen we make two slits which allow the light to fall on a second screen. Then, as

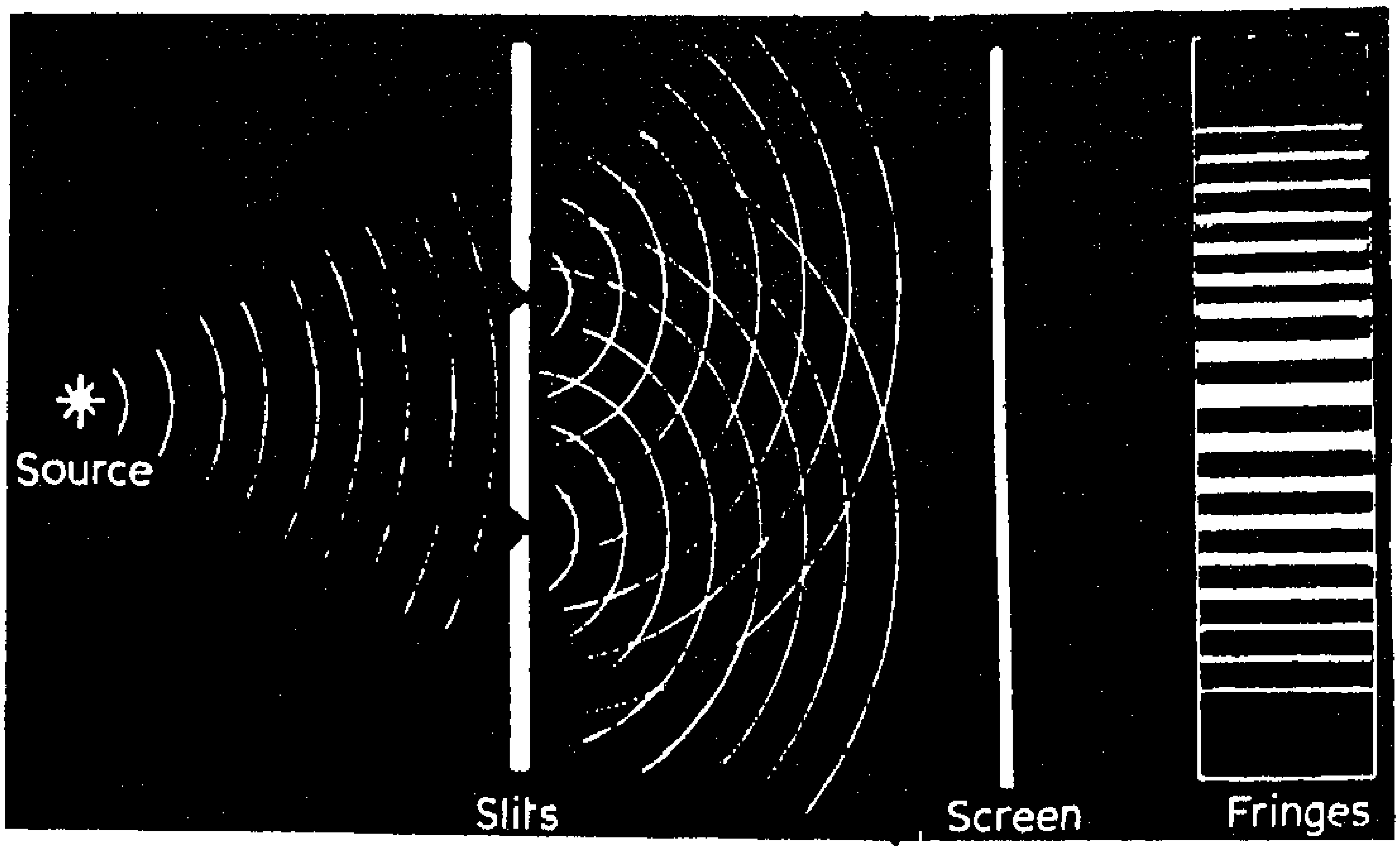

Figure 1. Young's fringes.

Thomas Young showed in 1803, on the second screen we shall see a system of bright and dark bands – "Young's fringes" – due to the alternate reinforcement and cancellation of the light arriving from the two slits. As far as we are concerned the most interesting thing about these fringes is that they can be used to measure the *spatial coherence* of the light at the two slits, and it is this spatial coherence which carries the information which we seek about the angular distribution of brightness over the source.

Fringes as a Measure of Spatial Coherence

It can be shown that the intensity of the light falling on any point Q in the fringe pattern shown in figure 1 is given by,

$$I_Q = I_{1Q} + I_{2Q} + 2\,\{I_{1Q} I_{2Q}\}^{1/2}\, R_e[\gamma_D\,(\tau)]\,, \tag{2}$$

where I_{1Q}, I_{2Q} are the intensities of the light arriving at Q from the two slits respectively and $\gamma_D\,(\tau)$ is the *complex degree of spatial coherence* of the light at the two slits defined by,

$$\gamma_D(\tau) = \langle V_1^*(t)\, V_2(t+\tau)\rangle \,/\, \langle V_1^*(t)\, V_1(t)\rangle \langle V_2^*\,(t)\, V_2(t)\rangle \tag{3}$$

and $V_1(t)$, $V_2(t)$ are complex analytic signals representing the radiation incident on the two slits, and τ is the difference between the times taken by the radiation from the two slits to reach the point Q.

If now we define the *visibility* of the fringes as V where in figure 2b,

$$V = (I_{max} - I_{min}) \,/\, (I_{max} + I_{min}) \tag{4}$$

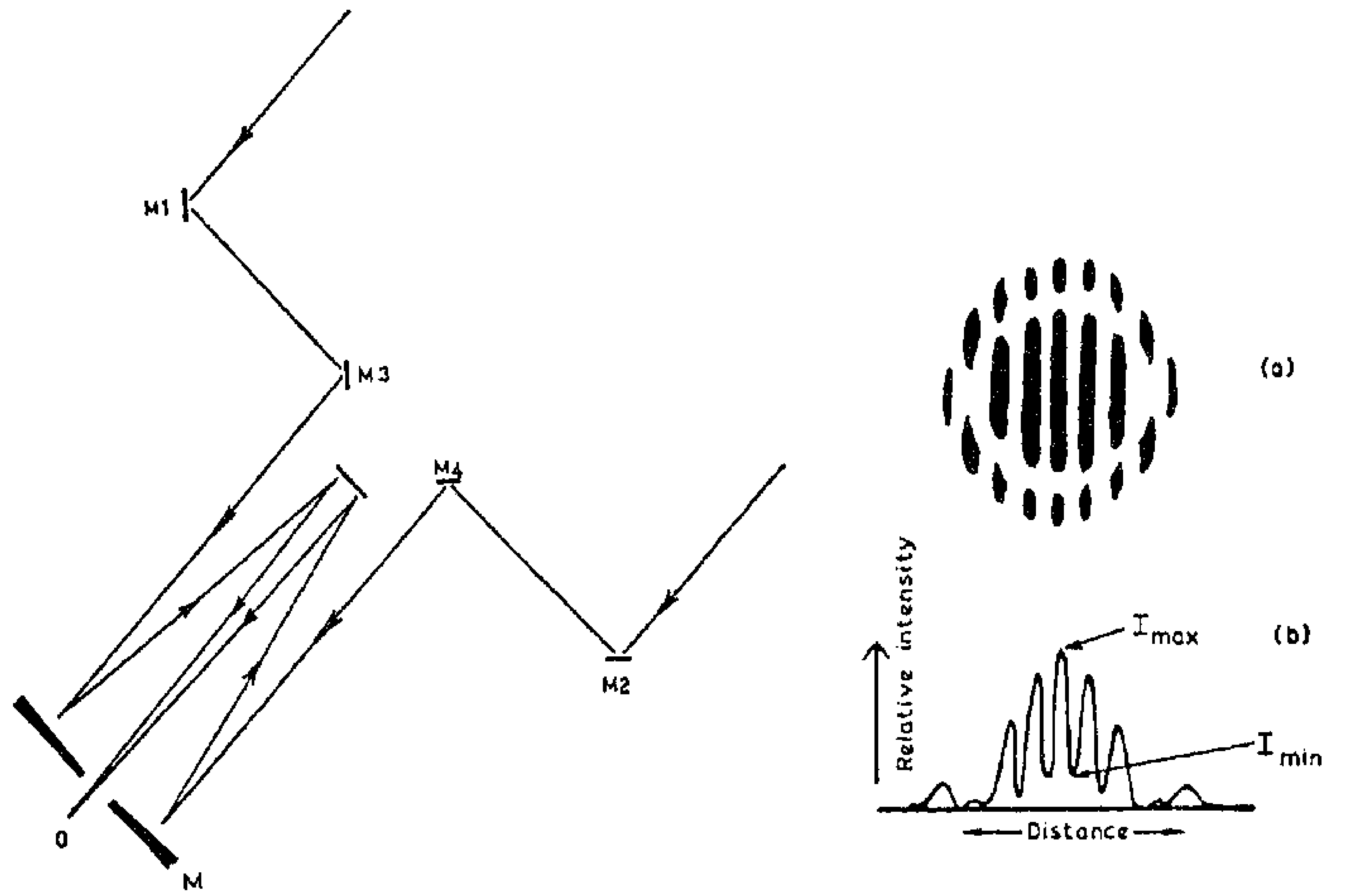

Figure 2. Michelson's Stellar Interferometer, (a) Fringes crossing image of a star. (b) Variation of intensity across the fringe pattern.

then from equation (2),

$$V = |\gamma_D| \qquad (5)$$

and so *the visibility of the fringes is directly proportional to the modulus of the spatial coherence of the light at the two slits.*

The *position* of the fringes – their displacement relative to the centre of the system – is a measure of the phase angle of the complex degree of spatial coherence.

It is therefore possible, at least in principle, to measure the complex degree of spatial coherence of the light arriving at two points by measuring the visibility and position of the fringes formed by the light from these two points.

Spatial Coherence as a Measure of the Angular Distribution of Brightness over a Source

If now we vary the spacing between the two slits and measure how the spatial coherence of the light varies as a function of the distance between them, then we can use the Van Cittert-Zernike theorem to find the angular distribution of brightness over the source. This powerful theorem tells us that the variation of spatial coherence with distance gives us what we seek – the Fourier transform of the distribution of brightness over the source. As an example, in the simple case where the source has a circular disc of uniform brightness, the modulus of the complex spatial coherence, and hence the visibility of the fringes, is given (figure 3) by

$$V = |\gamma| = 2\, J_1(\pi d\theta/\lambda)/(\pi d\theta/\lambda)\ , \qquad (6)$$

where d is the separation of the two slits and θ is the angular diameter of the source.

Thus the Van Cittert – Zernike theorem tells us that if we map the complex degree of coherence between points in a plane normal to a source we can use that information to make a "picture" of the source.

An attempt to put this idea of using fringes into practice was made by Stephan in 1873. He mounted two small apertures in front of the 80cm refractor at Marseilles and observed interference fringes in the images of stars. The fringes were sharp and Stephan concluded that much larger apertures would be needed to resolve stars.

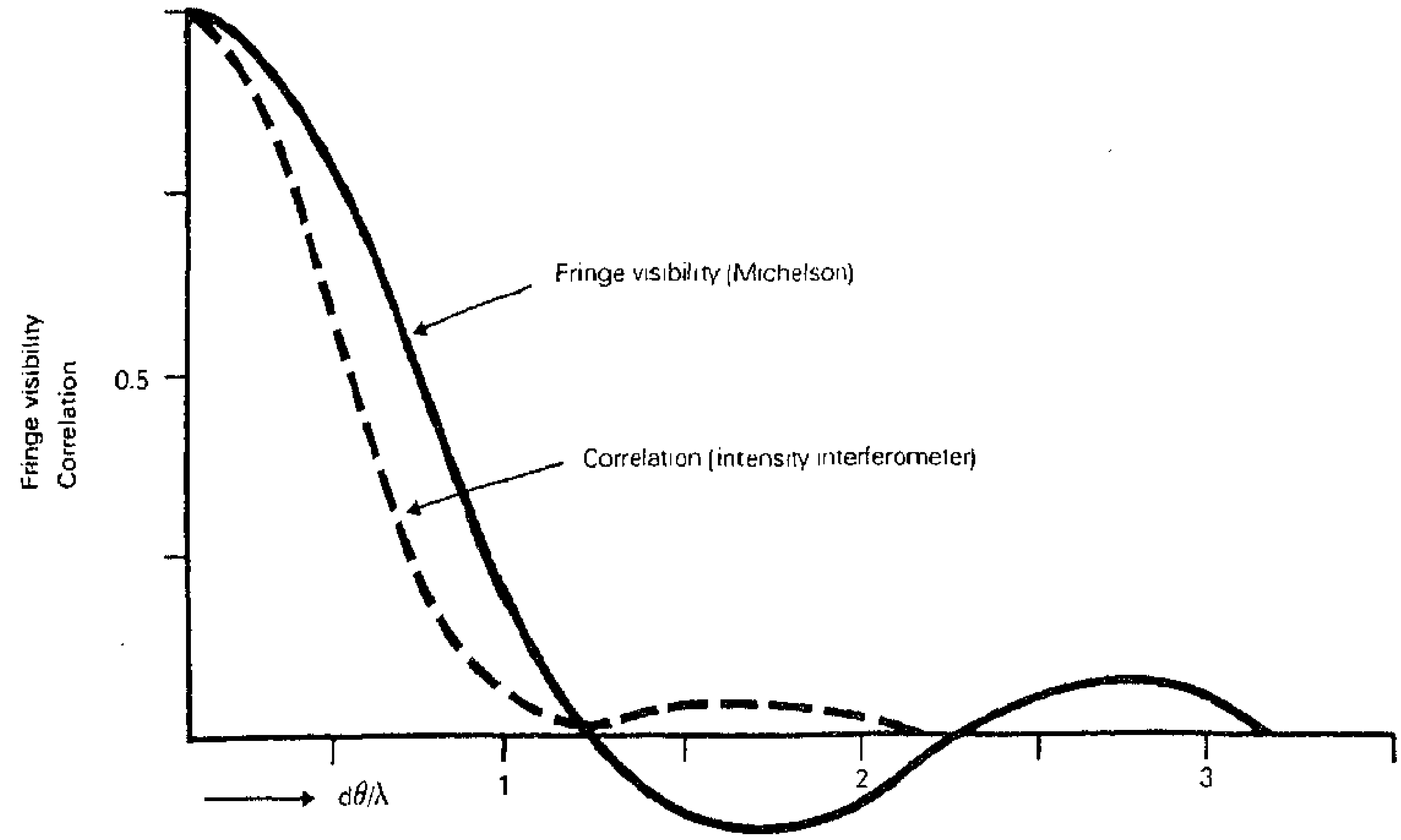

Figure 3. The variation of fringe visibility in a Michelson interferometer (solid line), and of the correlation in an intensity interferometer (broken line) as a function of the baseline, where d = length of baseline, θ = angular diameter of star, λ = wavelength of light.

The first successful application of the idea was made by Michelson in 1891 when he used a small interferometer to measure the angular diameters of the satellites of Jupiter. To make these measurements Michelson observed the satellites through two narrow slits mounted in front of the objective lens of an 11 inch refractor at Lick Observatory. He found that as the separation between the slits was increased the visibility of the fringes decreased until it became zero at a distance of about 4 inches. By measuring this distance for each of the four satellites, Michelson found their angular diameters to lie in the range 0·94 to 1·37 arcseconds.

THE IDEA OF USING TWO SMALL MIRRORS TO MIMIC A LARGE APERTURE

But Michelson was not satisfied with measuring the satellites of a planet, his ambition was to measure a star. Realising that the angular size of a star might be of the order of one hundredth of an arcsecond and that to resolve such a small angle he would need to build an unreasonably large telescope, perhaps 40ft in diameter, *Michelson made a most fruitful suggestion*. He put forward the idea that, instead of mounting slits in front of a large telescope, the necessary resolving power might be achieved by collecting the light from the star on two small mirrors whose separation could be made great enough to resolve the star and which could be arranged so as to reflect the light into a relatively small telescope.

Michelson's Stellar Interferometer

Following this suggestion Michelson together with his colleagues Anderson and Pease, built the instrument whose simplified outline is shown in figure 2. The two small mirrors M_1, M_2 were mounted on a beam in front of the 100 inch telescope at Mt Wilson and reflected the light from a star to the focus where the two images were superimposed. The fringes crossing the composite image were observed through an eyepiece and their visibility was estimated as the separation of the two mirrors was varied. The separation at which the fringe visibility fell to zero was used as a measure of the apparent angular diameter of the star.

The first star to be measured (December 1920) was Betelgeuse. The fringes disappeared when the two mirrors were separated by 121 inches, corresponding to an angular diameter of 0·047 arcseconds.

Only 6 stars were measured by Michelson's stellar interferometer because its resolving power was limited to about 0·02 arcseconds by the maximum possible spacing between the two mirrors of 20ft. All these 6 stars were giants or supergiants; the instrument could never have been used to measure a main sequence star because, as we now know, the largest angular size subtended by a main sequence star (Sirius) is 0·0068 arcseconds.

In an effort to extend the work to more stars, especially to main sequence stars, Hale and Pease built a 50ft interferometer at Mt Wilson in 1930. But it proved to be a very difficult instrument to operate and it required considerable skill to observe any sign of fringes, let alone to estimate their visibility. Despite several years' work no reliable measurements were made and the use of the instrument was discontinued after Pease died.

One of the main difficulties in extending the resolving power of Michelson's stellar interferometer is that unless the light paths from the two small mirrors to the focus are very nearly equal the fringe visibility is reduced. This reduction can be calculated simply from the Wiener-Kintchine theorem which tells us that *the auto-correlation function of a stationary variable is the Fourier transform of its power spectrum*. Thus if $V(\tau)$ is the fringe visibility for an unresolved source when the relative time delay between the two paths through the instrument is τ, then

$$V(\tau) = \int_0^\infty G(\nu) \exp(-2\pi i\nu\tau)d\nu \Big/ \int_0^\infty G(\nu)d\nu \, , \tag{7}$$

where $G(\nu)$ is the power spectrum of the light. In the simple case where the optical passband is uniform over a width $\Delta\nu$ equation (7) tells us that,

$$|V(\tau)| = \sin \pi\Delta\nu\tau \,/\, \pi\Delta\nu\tau \tag{8}$$

and it follows that for an optical bandwidth of 100nm at a wavelength of 500nm a path difference of 1 wavelength will reduce the visibility by 10 per cent. As Hale and Pease found, this places an extremely stringent requirement on the mechanical stability and pointing accuracy of a large instrument.

A second major difficulty is the presence of atmospheric scintillations. Turbulence in the atmosphere creates inhomogeneities in the temperature and humidity of the air which introduce random changes into the amplitude and phase of the light reaching the two small mirrors, and these changes are usually uncorrelated over distances greater than about 10cm. The major effect of these scintillations is to move the fringes about rapidly in the focal plane and to change their shape and visibility at a speed which depends on the scale of the atmospheric irregularities and on the speed of the wind. For this reason it was only possible to estimate the visibility of the fringes in Michelson's interferometer when the atmospheric seeing was good.

Early Forms of Michelson's Interferometer in Radio Astronomy

One of the great difficulties in the early days of Radio Astronomy was to interpret the observations in terms of what was already known about the sky from Optical Astronomy. This was, in part, due to the fact that the resolving power which could be achieved at radio wavelengths was so low that the optical and radio pictures of the sky could not be compared in adequate detail. As a consequence radio astronomers developed a great interest in achieving higher resolving power; in fact their search for higher resolving power has proved to be one of the most vigorous and fruitful developments in modern astronomy.

An early step in this research was to build an analogue of Michelson's stellar interferometer for use in Radio Astronomy. The principal difficulties in making such an instrument are very different to those encountered at optical wavelengths. Thus, although it is relatively easy to achieve adequate mechanical stability in an instrument for use at radio wavelengths and the effects of atmospheric scintillation are not significant over most of the radio spectrum, there are technical problems in making a radio interferometer with the very long baselines which are needed to achieve a high resolving power. For example, to resolve an angle of 1 arcsecond at a wavelength of 1m requires a baseline of about 200km and in the early days of Radio Astronomy it was a major technical problem to compare the signals at two places so far apart. Indeed the story of the search for high resolving power in Radio Astronomy is largely the story of the efforts to solve that problem.

The first radio analogue of Michelson's stellar interferometer was built by Ryle and Vonberg at Cambridge (UK) in 1946 to study the radio emissions from the Sun at a wavelength of 1·71m (175 MHz). To collect the radiation they used two arrays of dipoles which were connected to a central receiver by cables. At the receiver the signals were first combined so that they interfered; they were then amplified, detected and applied to a pen recorder. A radio source in transit through the field of view produced a fringe pattern on the pen recorder analogous to the fringes crossing the image in an optical interferometer. The spacing or baseline between the two antenna arrays could be varied, and by comparing the amplitude of the fringes at different baselines it was possible to establish the angular size of the source. The maximum baseline was 240m giving an effective resolving power of roughly 10 arcminutes.

The next step in the pursuit of higher resolving power was to lengthen the baseline beyond the distance which could conveniently be spanned by a cable. To do this the cable had to be replaced by a radio link designed to preserve the mutual coherence of the two signals, and provision had to be made to equalise the paths in the two arms of the interferometer. The first instrument to incorporate both these features was built in Australia by Mills in 1952. He used a radio link to bring the two signals together and a mercury delay cell to equalise their paths. The maximum baseline of his instrument was 10km, which at a wavelength of 3m gave a resolving power of about 1 arcminute.

Ten years later an interferometer with a baseline of 110km was in use at Jodrell Bank (UK) giving a resolving power of 1 arcsecond at 1·89m. Such a long baseline presents its own peculiar problems; for example the path differences which have to be equalised become very large and the fringes have an inconveniently high frequency. To make the system work it was necessary to develop a path-equalising system using supersonic sound in a block of quartz and a method of reducing the fringe frequency.

Aperture Synthesis

As we have already seen it was Michelson who put forward the idea that the resolving power of a large telescope can be "synthesised" by two small movable mirrors. If, as in Michelson's Stellar Interferometer, these two mirrors are moved apart in a straight line, then the variation of fringe visibility as a function of their separation gives us the Fourier transform of the brightness distribution across the source, but only in one dimension. More precisely we shall get a "picture" of the source reduced to a rectangular strip, the brightness of any point on this strip being the integrated brightness along a line normal to the strip.

With the mirrors at one particular spacing and orientation all we get is one Fourier component of the distribution of brightness over the source. But by moving the mirrors to different baselines with different spacings and orientations, we can build up a two-dimensional Fourier transform of the source and by Fourier inversion find its two-dimensional brightness distribution. The simplest and most economical method of changing the orientation of the baseline is to make continuous observations of a source throughout 12 or 24 hours and take advantage of the fact that the Earth's rotation changes the orientation of the baseline relative to the source.

To make such observations we must, of course, be able to measure the complex degree of coherence at each baseline by measuring both the visibility and position of the fringes which at radio wavelengths, unlike at optical wavelengths, is comparatively easy to do. In this way we can get a picture of the source with a resolving power determined by the dimensions of the "aperture" or area over which we move our mirrors.

THE INTENSITY INTERFEROMETER

The next step forward in the search for higher resolving power was the development of the intensity interferometer which was originally introduced for use in Radio Astronomy. In figure 4 light from a star is focussed by two separated mirrors on to the photoelectric detectors D_1, D_2. The output

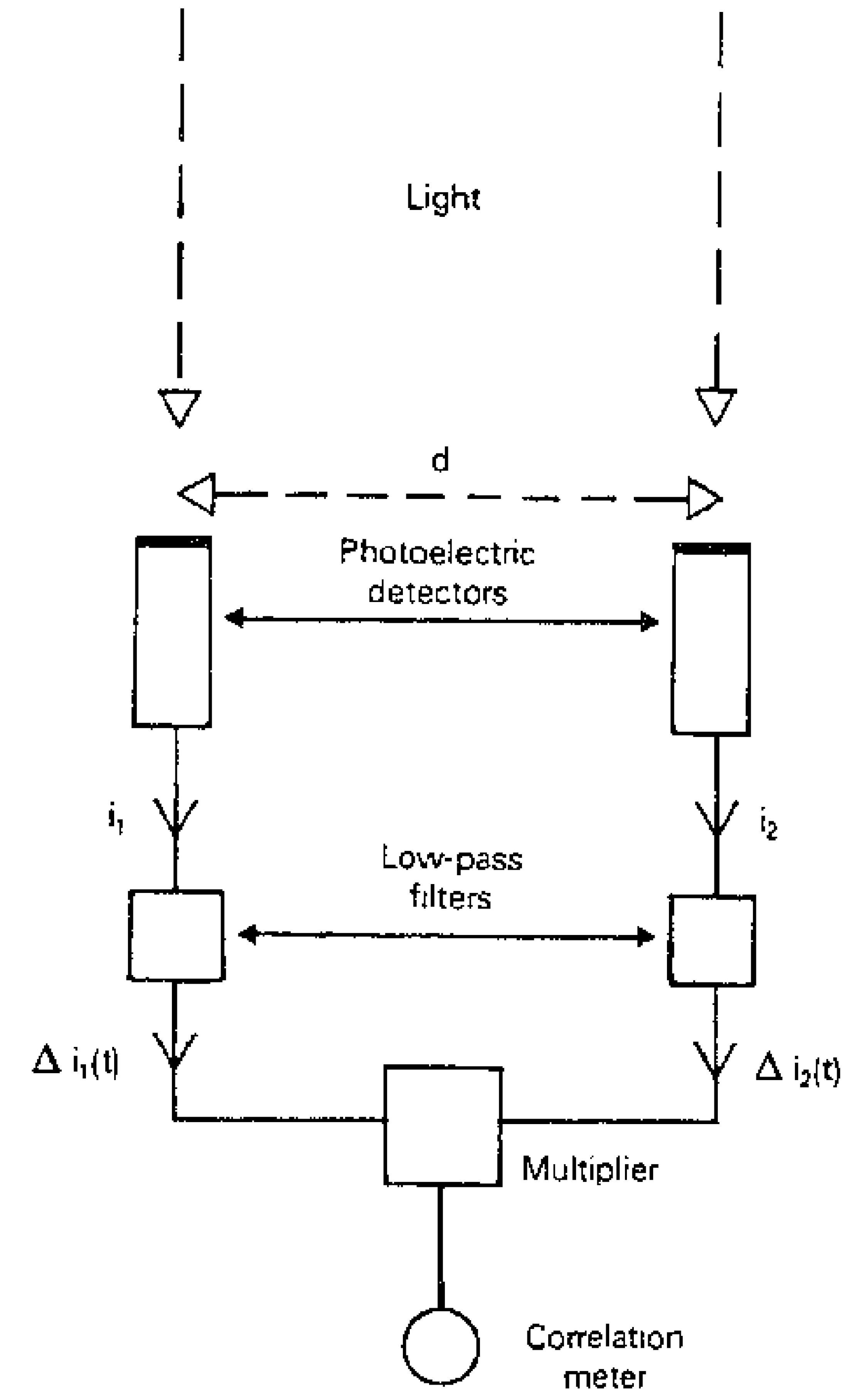

Figure 4. A simplified outline of an intensity interferometer for light waves.

currents i_1, i_2 from these detectors contain two fluctuating components, classical "shot noise" due to the finite charge on the electron, and a smaller component of "wave noise" due to the fluctuations in the incident light. The fluctuations in the two currents are first limited in frequency band by low-pass filters, they are then amplified and correlated in a linear multiplier.

The basic idea of the technique is that if the light incident on the two detectors is mutually coherent then the fluctuations in the intensity and hence in the "wave noise" components will be correlated; the "shot noise" components will, of course, be uncorrelated. Thus if $\Delta i_1(t)$ and $\Delta i_2(t)$ are the fluctuations in output currents from the two detectors then it can be shown that,

$$\langle \Delta i_1(t)\, \Delta i_2(t) \rangle / \langle i_1 \rangle \langle i_2 \rangle = |\gamma_{12}|^2 = V^2 \tag{9}$$

and comparing (5) and (9) we can see that *the normalised correlation between the wave noise components is equal to the square of the modulus of the degree of coherence and therefore to the square of the fringe visibility in a Michelson interferometer with the same baseline.* Thus for a star with a uniform circular disc the correlation at different baselines would follow the broken line in figure 3 and so by measuring the correlation from a star as a function of baseline length we can find its angular size.

The essential point of the intensity interferometer was that it has two remarkable properties which made it possible to overcome the two main difficulties which had, up to that time, retarded the development of Michelson's stellar interferometer. Firstly it can be built to give very high resolving power without the need for extremely high mechanical precision, and secondly it is not significantly affected by atmospheric scintillation.

The explanation underlying both these properties is that the loss of correlation due to unwanted path differences in the two arms of the instrument is a function of the bandwidth (Δf) of the electrical fluctuations which are correlated and not, as in Michelson's interferometer, of the bandwidth ($\Delta\nu$) of the light which is interfered. Taking reasonable values for these quantities [$\Delta f = 10^8$Hz, $\Delta\nu = 10^{14}$Hz] the Wiener-Kintchine theorem tells us that the permissible path difference (or time delay) for the same loss of correlation is about one million times greater than it is in a Michelson interferometer. For example, for a loss of correlation of 2 per cent the path difference in an intensity interferometer must be kept to less than 30cm or 1ns, which is easy to achieve even in a large instrument; furthermore the atmosphere cannot affect the correlation because any path difference which it can introduce will be very small compared with 30cm.

The first optical intensity interferometer was built at Jodrell Bank (UK) in 1956. It had two 156 cm searchlight mirrors and was used to measure the angular diameter of Sirius with a maximum baseline of 10m. This was the first measurement of a main sequence star ever to be made. Following the success of this pilot model a full-scale stellar interferometer was built and installed at Narrabri Observatory in Australia in 1962.

The Stellar Intensity Interferometer at Narrabri consisted of two very large optical reflectors (6.5m) running on a circular track with a diameter of 188m. At the focus of each reflector there was a phototube and the output currents from these phototubes were taken to a laboratory in the centre of the track where they were correlated.

In an observing programme lasting 7 years the Intensity Interferometer extended the resolving power of optical observations by a factor of about 50. The smallest angular diameters measured with Michelson's interferometer were those of α Taur and α Boo (0·02 arcseconds), while the smallest diameter measured by the Intensity Interferometer was that of ζ Pup (0·0004 arcseconds). Its principal contribution to Optical Astronomy was to measure the angular diameters of 32 single stars in the spectral range *O* to *F* including several main sequence stars. Apart from the experimental test of the pilot model on Sirius these measurements were the first ever to be made on main sequence stars. The data were combined with absolute photometric measurements to establish the first essentially empirical temperature scale for hot stars – that is to say the first scale to be based entirely on measurements (apart from a minor correction for limb-darkening) and not on theory. The data were also used to find the physical diameters of those stars in the list for which the parallax was reasonably well known.

The performance of the instrument at Narrabri was limited by sensitivity and not by resolving power. Despite using very large reflectors it was limited to measuring stars brighter than about magnitude + 2.5 and hotter than the Sun. By 1974 it had measured almost all the stars within its reach and as we were anxious to develop its successor with a much higher sensitivity and resolving power we dismantled it and shut the Observatory.

SPECKLE

As Hariharan has pointed out the phenomenon which we now call "speckle" has been known for over one hundred years. A particularly interesting discussion of it is to be found in a lecture by Raman on "Coronae, Haloes and Galaxies". Raman discusses the appearance of a point source of light as seen through a cloud of small particles, and draws attention to the fact that the image consists of a multitude of small spots which are irregularly distributed in position and brightness. To illustrate this phenomenon he shows photographs of a circular pinhole and a triangular aperture seen through a glass plate coated with lycopodium. Raman makes the interesting point that,

> *"Each of the bright spots in the field is a focussed image of the original source of light formed by the joint action of the diffracting particles and the lens of the photographic camera".*

He goes on to tell us that if the film of lycopodium is replaced by a film of milk in which the diffracting particles are moving, then the bright spots in the image also move about.

In 1970 Labeyrie drew attention to this same phenomenon in a different context. The image of a star as seen through a large telescope, either by eye or on a long photographic exposure, is a roughly circular blur with a typical angular size of 1 or 2 arcseconds. If, however, we look at the image recorded in an exposure of only a few milliseconds this blur is seen to consist of many small bright spots or speckles. These speckles are comparable in size with the Airy disc of the telescope and correspond roughly to the image of the star which the telescope would form in the absence of the atmosphere. What Labeyrie demonstrated was that it is possible, by analysing a series of these images taken with a very short exposure, to recover angular information about the source with a resolving power which is limited by the telescope and not by the atmosphere.

To visualise how "speckle" works it is helpful to think of the aperture of a large telescope as being made up of a large number of sub-apertures whose size is comparable with the characteristic size (r_0 = 10cm) of the atmospheric irregularities. In this picture each speckle is the image formed by several sub-apertures located at points across the aperture of the telescope where the phase is momentarily equal. For a telescope with an aperture D, the typical angular size of a speckle will be λ/D, and the speckles will be distributed over a circular image of size λ/r_0. Thus for a 1m telescope and r_0 = 10cm the speckles will be roughly 0·1 arcsec in size distributed over an image with an angular size of 1 arcsecond.

One way of recovering a "true" image of the source from these speckles — the way first used by Labeyrie — is to take a series of short exposures of the speckle pattern using an exposure time which is so short that the movement of the speckles due to atmospheric seeing is frozen. The next step is to average these exposures, not directly, but as Fourier transforms; more precisely it is to find the average of the square of the moduli of their Fourier transforms. The final step is to take the Fourier transform of this average which yields the *spatial auto-correlation function* of the diffraction-limited image of the source.

This technique does *not* reconstruct a unique image because half of the information – the phase of the Fourier components – is lost. Nevertheless when there is a model of the source, such as a disc or a binary star, the spatial auto-correlation function can be interpreted in terms of a true image. In fact the technique of speckle has been applied successfully to many large telescopes to recover the "diffraction-limited" images of planetary satellites and multiple stars. But it is, of course, limited in resolving power by the size of the telescope; even the largest telescope at present under construction, the Keck Telescope in California, will have a resolving power of 0·01 arcseconds which is not sufficient to resolve the largest angular diameter presented by a main sequence star (0·0068 arcseconds). Clearly we shall need a much higher resolving power if we are to see the details of objects such as stars.

Modern Long Baseline Interferometers

Modern Long Baseline Optical Interferometers

The successful observing programme of the Stellar Intensity Interferometer at Narrabri was a clear demonstration of what could be done by applying an instrument with high angular resolving power to Optical Astronomy, and it pointed the way to what might be done with an instrument with even higher resolving power and the necessary sensitivity.

One obvious way of building such an instrument was to make a larger version of the existing installation at Narrabri. In fact when the programme at Narrabri was completed in 1974 the Astronomy Department of the University of Sydney designed an intensity interferometer with some 70 times the sensitivity and 10 times the resolving power of the original instrument. This new design employed four optical reflectors, each 40ft in diameter, mounted on a baseline of 2km. In 1982 it would have cost about $4m and although it would certainly have worked and would not have been unduly large compared with the arrays of telescopes used nowadays by radio astronomers, nevertheless its size and cost prompted us to take a good look around to see if there was a more economical alternative. After doing so we decided to examine the possibility of modernising Michelson's Stellar Interferometer.

The attraction of Michelson's interferometer was that it offered us, at least in theory, a much higher sensitivity at a much lower cost than an intensity interferometer. But what we really needed to know was whether its resolving power could be increased by a worthwhile amount, and if it could be made to work reliably in the presence of atmospheric scintillation by means of the many new techniques, such as phototubes, narrow-band filters, lasers and "active optics" which have been developed in the last 50 years. The only way to answer these questions was to build an experimental model and find out.

A Modernised Version of Michelson's Stellar Interferometer [SUSI]

As we have already seen the two major difficulties which limited the development of Michelson's interferometer were the need for extreme mechanical precision and the effects of atmospheric seeing. The Sydney University Stellar Interferometer [SUSI] has been designed to overcome both these difficulties.

As far as the mechanical difficulties are concerned it is very stable; it uses stationary and massive siderostats which are themselves on concrete blocks mounted on very firm foundations. The two light paths through the instrument are equalised by an elaborate variable delay system in which the light paths are monitored by lasers.

The effects of atmospheric seeing are reduced in several ways; firstly by the use of small mirrors (diameter 140mm) which are comparable in size with the typical atmospheric irregularities, so that at any given moment the phase and amplitude of the light are roughly constant over the surface of each mirror; secondly the angular scintillation of the incoming starlight is removed by "active optics"; thirdly the measurements of fringe visibility are made by photon-counting detectors in exposure times which are so short (a few milliseconds) that they freeze the atmospheric seeing.

All these ideas have been tested experimentally in a pilot model with a baseline of 11·4m and have been found to work. In 1986 this pilot model was used to measure the angular diameter of Sirius which it did successfully with an uncertainty of 1·5 per cent. The result, which differs from the earlier measurements at Narrabri by only 0·5 per cent, was achieved in only one fiftieth of the time which it took to reach the same accuracy with the intensity interferometer.

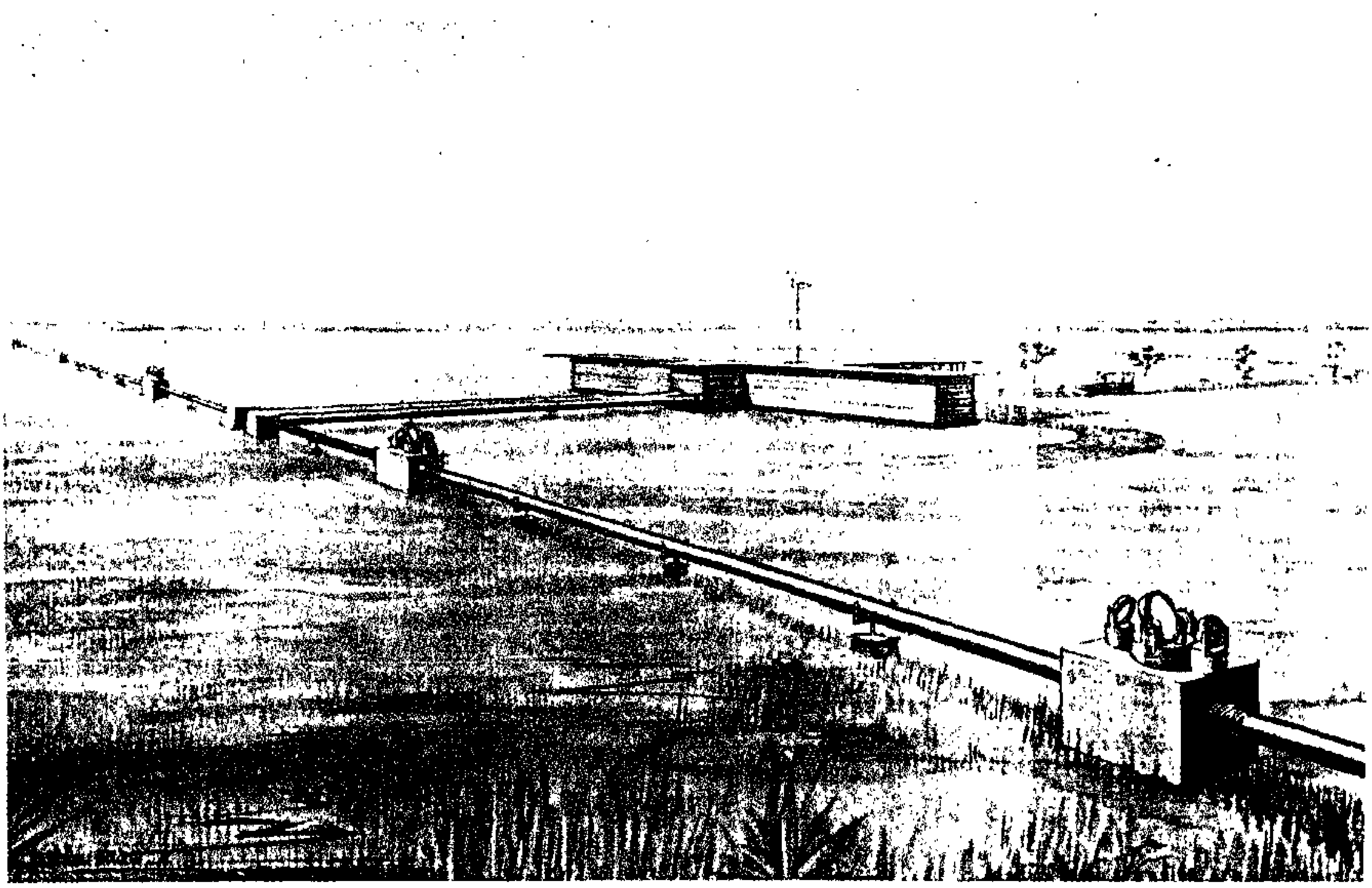

Figure 5. Artist's impression of SUSI, the new stellar interferometer under construction by the Astronomy Department of the University of Sydney.

When the full-scale version of SUSI (figure 5) is built it will have an array of 12 siderostat mirrors mounted in a north-south line and connected to a central station by an evacuated tube. This array will yield 14 different baselines varying in length from 5m to 640m. The resolving power with the longest baseline will be 5×10^{-5} arcseconds and the magnitude of the faintest star which can be measured is expected to be about +8·5. The accuracy of the measurements, at least on the brighter stars, should be about 2 per cent.

This instrument, which is already partly built at Culgoora near Narrabri, is expected to be complete in about 2 years' time. When it is working it will, I am confident, open a new and profitable field of observational astronomy.

There is, I should add, another version of Michelson's interferometer under development at

Mt Wilson. It is intended for use in astrometry and is designed to measure very precisely the angles between stars.

Arrays of Interconnected Optical Telescopes

Broadly speaking there are two principal ways in which an optical interferometer can be designed for use in astronomy. It can use light collectors which are either *large* or *small* compared with the characteristic size of atmospheric irregularities (10cm). In the design of the Sydney University Stellar Interferometer we chose to use small light collectors because we are mainly interested in stellar astronomy where it is essential to make very precise measurements, and we guessed that it would prove easier to achieve that high precision with small mirrors.

As one would expect, the alternative approach, the use of large mirrors, promises greater sensitivity and has been pursued since about 1974 by Labeyrie and his colleagues in France. At the present time they are developing an interferometer which combines the light from two 1·5m telescopes.

The technique of linking large telescopes together as optical interferometers in order to gain higher resolving power is still in an experimental stage and is being pursued by several groups. Perhaps the most ambitious project is the Very Large Telescope (VLT) proposed by the European Southern Observatory. It will have four separate 8m telescopes mounted in a line so that they can be used either separately or in combination to form a single image. It is envisaged that these telescopes will also be linked as an interferometer giving a maximum baseline of about 100m with a resolving power of about 0·001 arcseconds at visible wavelengths.

Arrays of Interconnected Radio Telescopes

Mapping the distribution of brightness over a source with an interferometer consisting of only two antennas is a slow business and it can be speeded up by building an array of antennas which can observe the sky simultaneously from several baselines. Furthermore the use of only two antennas is not a practicable way of mapping phenomena which vary rapidly with time as, for example, on the Sun. Indeed the first array of radio telescopes was constructed in Australia by Christiansen in 1951 to study the radio emission from the Sun. It consisted of 32 parabolic reflectors of 2m diameter mounted in a line 217m long giving a beam width of 3 arcminutes at a wavelength of 20cm.

Since those days many arrays of interconnected antennas have been built and operated successfully to make high resolution maps of the sky using aperture synthesis by Earth rotation. As one example the Very Large Antenna (VLA) is operated by the National Radio Astronomy Observatory at Socorro in New Mexico (USA). This remarkable instrument consists of 27 identical 25m antennas arranged along three equally spaced radial arms forming a Y-shaped array. Two of these arms are 21km long and the third is 19km. The signals from these 27 antennas can be combined to give 351 different baselines simultaneously. When operating at its highest frequency this array can "synthesize" an aperture with a diameter of 35km which has a resolving power of about 0·1 arcseconds at a wavelength of 1·3cm.

As another example the Merlin array at Jodrell Bank in UK has 7 very large antennas with a maximum baseline of 230km, and is capable of a resolving power of 0·01 arcseconds at a wavelength of 1·3cm.

These arrays of antennas are giving us maps of the sky which in many cases reveal more detail than astronomical photographs and the results have proved so valuable that even larger arrays, such as the Very Long Baseline Array (VLBA) in the USA and the Australia Telescope (AT), are under construction.

The VLBA, for example, consists of ten 25m dishes distributed over a baseline which extends from St Croix in the Virgin Islands to Mauna Kea in Hawaii. It will "synthesize" an aperture of 8000km, nearly the diameter of the Earth, giving a maximum resolving power of about 2×10^{-4} arcseconds at a wavelength of about 7mm. It is interesting to note that its resolving power will be roughly equal to the highest resolving power so far achieved in Optical Astronomy by the Intensity Interferometer at Narrabri Observatory.

VERY LONG BASELINE INTERFEROMETERS (VLBI)

The maximum length of baseline, and hence the resolving power, of early radio interferometers was limited by the technical problems of bringing the signals from two widely separated antennas together to measure their mutual coherence and of maintaining coherence between the local oscillators. In due course this limitation was removed by the development of interferometers which did not require a link between their two ends and which made it possible to use extremely long baselines, thousands of kilometres in length, and so to achieve an enormous increase in resolving power at radio wavelengths. This development, called Very Long Baseline Interferometry (VLBI), has given radio astronomers a resolving power which exceeds that of conventional astronomical photography.

The first example of an interferometer which did not necessarily require a direct link between the two stations was the intensity interferometer which, together with Jennison and Das Gupta, I developed in 1949 at Jodrell Bank (UK) especially to measure the angular diameters of the two intense radio sources Cygnus A and Cassiopeia A. At that time nothing was known about the nature of the radio sources and if, as some people thought, they were comparable in size with the visible stars then to measure their angular sizes at radio wavelengths we knew that we should need an interferometer with a baseline of thousands of kilometres.

We developed the intensity interferometer specially for use at very long baselines. It does not require any link between the two local oscillators and I envisaged that if very long baselines proved to be necessary then the signals received at the two stations would be recorded on tape recorders and subsequently correlated. Sad to say the angular diameters of the two sources proved to be of the order of minutes of arc and they were resolved with baselines of a few kilometers. It would have been much easier to have used a simple radio version of Michelson's interferometer with a radio link! Nevertheless the development of the intensity interferometer was not wasted; as we have already seen the same principle was later applied successfully to Optical Astronomy.

The subsequent development of VLBI was prompted very largely by the discovery of quasars and the intense interest in their nature, and it was made technically possible by the development of ultra-stable oscillators (masers etc.), wide-band tape recorders and digital electronics. A VLBI system can be made by using as a local oscillator an ultra-stable oscillator, such as a hydrogen maser, whose frequency is so stable that it does not alter by even a small fraction of a cycle during the observation of a source which may take a few minutes. The signals can be recorded, together with synchronizing information, on a wide-band tape recorder and then sent to some central laboratory to be correlated in a computer.

Starting in 1967 several groups in the USA and a group in Canada built VLBI systems and made them work with a wide variety of baselines. An attractive feature of the work on VLBI is that it encourages international co-operation. For example, the European Consortium for VLBI has member institutes in Italy, Germany (FDR), Netherlands, UK and Sweden and associate members in France, USSR and Poland.

The success of this work is illustrated by a measurement made by Burke and a large team of colleagues who in 1972 achieved a resolving power of 2×10^{-4} arcseconds at a wavelength of 1·3cm using antennas in Westford, Massachusetts and Simeiz in the Crimea.

Early work on VLBI was limited to observations with only two stations and the observations were interpreted in terms of simple models of the source. But in recent years simultaneous observations from several stations at different baselines and orientations have been successfully combined to make some remarkable maps.

As I have said the distinguishing feature of VLBI was that it did not require a direct link between the stations. However the more recent development of satellite communication has made it increasingly attractive to link the stations of a far flung network directly together much in the same way as the stations of a long baseline interferometer are connected by radio links. To what extent this will be adopted is, I suppose, a matter of the cost of satellite links.

THE SEARCH FOR BETTER IMAGES

A major goal of the lively modern work on higher resolving power is to produce better images of the sky, images which are limited only by diffraction.

The Reconstruction of Radio Images

A great deal of interesting work has been done in recent years by radio astronomers on improving maps of the sky produced by interferometer arrays using aperture synthesis. One principal source of defects in these maps are gaps in the "synthesised aperture", inevitably the aperture is not entirely filled and so some components of the Fourier transform of the image are missing. Other sources of error are random electrical noise and the effects of the atmosphere or ionosphere.

A number of methods of improving radio images have been developed and I will mention only two. One is called the method of "Maximum Entropy" which aims to produce an interpretation of the data with the minimum assumptions about the missing Fourier components. Another very widely used method is called "CLEAN" in which the uncorrected map is analysed into a number of point sources; these are then individually corrected for defects in the synthesised "beam" of the instrument and then added together to form a corrected map. Both these methods can produce quite remarkable improvements in the maps of the sky and both of them require a very great deal of computing. There are, I should add, some doubts about the extent to which these methods can produce false features in the maps, especially at low intensities; nevertheless they do represent a very real advance in our efforts to get clearer pictures of the sky.

Another very interesting technique evolved by radio astronomers to correct their maps is called *"phase closure"* and is based on a method originally used at Jodrell Bank in 1958 by Jennison to show that the source Cygnus A is a double source. Briefly, the method aims to extract from the phases of the fringes observed from a source some information about the "true" phases. The observed phases are affected by random phase shifts due to the atmosphere and the instruments themselves, and these unwanted components may be removed by the following method.

If the outputs from any three antennas of an array are correlated to give fringe patterns with phases ϕ_{12}, ϕ_{23}, and ϕ_{31} then it can be shown that the *"closure phase"*.

$$(\phi_{123} = \phi_{12} + \phi_{23} + \phi_{31})$$

is independent of the unwanted instrumental and atmospheric phase shifts and is a property of the source alone. This closure phase can then be used to derive a "true" map of the source.

Image-forming Optical Interferometers

Following the remarkable success of radio astronomers in using aperture synthesis to produce high resolution maps of the sky there is currently a great interest in repeating this success at optical wavelengths. Optical astronomers are actively trying to develop "image-forming" interferometers. One of the principal difficulties which they face is to measure the phase of fringes which are subject to large and rapid fluctuations due to atmospheric seeing.

One possible solution may be to use the method of "phase closure" developed by radio astronomers. Indeed Baldwin and his colleagues have already demonstrated how phase closure may be used to make a high resolution image at optical wavelengths. Using the fringes formed by 4 small apertures in the pupil plane of the 2·5m Isaac Newton telescope on Las Palmas they obtained diffraction-limited images of two stars with a resolving power of about 0·05 arcseconds.

The Reconstruction of Optical Images

The optical interferometers which I have described all fall short of the objective of producing a true image of the sky because they yield only the modulus of the Fourier transform and not its phase. The vexed question of how far it is possible to reconstruct an image uniquely from the modulus alone is a classical problem in physics and is commonly known as the "phase problem".

A good deal of work has been done on this phase problem in the last few years but it is, I would say, still sub-judice. Broadly speaking it is agreed that in the general case it is impossible to reconstruct an image from its modulus alone, but in certain *special* cases it is thought to be possible. But the difficulty lies in proving these special cases; for example, it is claimed that it is "almost always" possible to reconstruct a two-dimensional image from the modulus alone. However there are, I suspect, serious doubts about the validity of this conclusion in the presence of noise.

In the special cases where there is some model of the source, such as a simple disc or a multiple star, then it is possible to reconstruct an image. In fact a number of interesting techniques have been developed, such as speckle holography, speckle masking and so on, and some remarkable pictures of the satellites of planets and of multiple stars have been produced. Nevertheless image reconstruction in Optical Astronomy remains a difficult problem which is at an early stage and it looks as though there is a promising future in adapting to optical wavelengths some of the very successful methods developed by radio astronomers.

SPACE ASTRONOMY

High Resolution Optical Astronomy in Space

A major step in the search for higher resolving power would be to transfer our observations from the surface of the Earth out into Space. As we have seen the Earth's atmosphere is a serious impediment to Optical Astronomy. One major way in which it limits our observations is by restricting the spectrum of the radiation which reaches the ground. For example the majority of the radiation from very hot stars of spectral types *O* and *B* is at wavelengths shorter than 300nm for which the atmosphere is almost opaque. Another major effect of the atmosphere is to distort the wavefront of the light which reaches us from objects in the sky. As we have seen, turbulence in the atmosphere introduces random variations in the amplitude, phase and angle of arrival of the radiation reaching the ground which, in turn, complicates and ultimately limits our ability to see the detail of these objects.

As I have already pointed out, the resolving power of optical telescopes on the surface of the Earth is severely limited by the atmosphere; in fact in most places, and for most of the time, it rarely exceeds 1 arcsecond and we have to use complex procedures, such as speckle interferometry, to recover some of the information which is lost. If, however, a telescope is put above the Earth's atmosphere it should yield diffraction-limited images. For example the Hubble Space Telescope which has a 2·6m mirror is expected to form images with a resolving power of about 0·05 arcseconds at a wavelength of 630nm.

As we have also seen, the atmosphere has a serious effect on the performance of optical interferometers, and although it may not impose a significant limit on their resolving power it does limit their sensitivity. For example the sensitivity of the long baseline interferometer (SUSI) which we are building at the University of Sydney will be limited to stars of roughly magnitude +8 by two requirements; the first is that the amplitude and phase of the starlight must be substantially constant across the aperture of each siderostat, which limits their aperture to the size of the atmospheric irregularities; the second is that the active optics must reduce the angular scintillation to less than 0·1 arcseconds which sets a limit to the sensitivity. If the instrument could be put into Space it would be possible to greatly increase the size of the siderostats and also to dispense with the active optics, thereby greatly increasing the sensitivity.

Many proposals have been made to put optical interferometers into Space, but as far as I know nothing has yet been actually built. One proposal (TRIO) is to make an interferometer by putting three satellites in orbit; two of these satellites would carry light collectors 1m in diameter and the third would act as a central station for combining the two beams. The three orbits would be slightly inclined to each other in such a way that the separation between the two light collectors – the baseline – would vary continuously from almost zero to a maximum of 10km. The resolving power of such an instrument would be better than 10 arcseconds and the magnitude of the faintest object which it could measure is expected to be between +15 and +20. How difficult all this would be to do and how long it would take, I can't judge!

It seems to me that the Moon might eventually be a better place for an optical interferometer than a spacecraft. It has no atmosphere and is geologically stable, and once a base has been established on the Moon may be the servicing of the equipment would be easier. Whether it is on the Moon or in a spacecraft it won't be many years, I feel sure, before we see an optical interferometer in Space.

High Resolution Radio Astronomy in Space

Radio Astronomy would also benefit from getting into Space. For one thing the atmosphere and ionosphere both limit the range of wavelengths which can reach the Earth's surface from outside. At the short wave end of the radio spectrum the atmosphere absorbs significantly at wavelengths shorter than a few centimetres, and at the long wave end the ionosphere absorbs significantly at wavelengths longer than 10 or 20m. But the most obvious benefit to radio astronomy of going into Space would be the possibility of increasing the resolving power of radio interferometers by the use of very much longer baselines than are possible on the surface of the Earth.

For example an interferometer with a baseline equal to the diameter of the Earth would have a resolving power at a wavelength of 1m equal to that of an optical telescope with a diameter of 5m; only at the very short wavelength of 1cm would its resolving power match that (2×10^{-4} arcseconds) already achieved by an optical interferometer.

Although some preliminary experiments have already been carried out using the TDRSS satellite as an improvised interferometer in conjunction with stations on the ground, it looks as though the first "full time" radio interferometer in Space will be the RADIOASTRON project of the Space Research Institute of the Soviet Academy of Sciences. For this project it is proposed to launch a spacecraft carrying an antenna with a diameter of 10m which will operate as one arm of an interferometer with several different ground stations using wavelengths in the range 1·5cm to 1m. The orbit of this spacecraft will give a maximum baseline of 75,000 km — roughly ten times the diameter of the Earth — giving a resolving power at the shortest wavelength of roughly 4×10^{-5} arcseconds.

Another project which we can expect to see in the not too distant future is QUASAT, proposed by the European Space Agency and the National Aeronautics and Space Administration in the USA. QUASAT comprises a free-flying satellite in orbit around the Earth carrying a radio antenna with a diameter of 15m which would work in conjunction with the major ground stations of the existing VLBI network. The maximum resolving power of QUASAT at a wavelength of 1.35cm would be about $7{\cdot}5\times10^{-5}$ arcseconds.

Conclusion

It is now nearly 400 years since Galileo looked at the sky through his telescope and tried to measure the angular size of Vega with a silk cord. Since those days great advances have been made in observational Astronomy, mostly in the measurement of the position, brightness, spectrum and relative velocity of objects in the sky and in seeing fainter and fainter objects. It is, however, only in recent years that significant progress has been made in achieving higher angular resolving power. As we have seen the main difficulty has been to overcome the limitations set at optical wavelengths by the Earth's atmosphere. Not surprisingly, most of the recent progress has been made at radio wavelengths where the atmosphere is not such a serious limitation. Indeed the development of instruments with very high resolving power has paid off handsomely in Radio Astronomy (figure 6) and our modern understanding of the nature of extra-terrestrial radio sources depends very largely on the high-resolution maps which have been made, and are still being made, with such instruments.

As we have seen, the use of high angular resolving power in Optical Astronomy is in a comparatively early stage of development but in recent years there have also been some real advances. Successful measurements have been made of the angular diameter of several of the visible stars, and as one example, we now know from the work of Narrabri Observatory in Australia that the angular diameter of Vega is some 1500 times smaller than the result obtained by Galileo!

The search for higher resolving power is currently being pursued vigorously by both optical and radio astronomers and we shall, I think, soon see some very interesting results. In the immediate future we can expect to see the construction and operation of optical interferometers with very high angular resolution, such as SUSI, which will open up a whole new field of observational astronomy and contribute greatly to our understanding of stars. Later we can expect to see the development of optical image-forming interferometers along the general lines followed so successfully by radio astronomers, giving us very high angular resolution "pictures" of the sky at visible and infra-red wavelengths. Indeed we may soon see maps of the distribution of brightness over the surface of the nearby stars. The development of instruments giving high angular resolving power will, I feel sure, prove to be as valuable to the progress of Optical Astronomy as it has already been to the progress of Radio Astronomy.

In the longer term we can look forward to the development of interferometers with very high resolving power in Space, firstly at radio wavelengths and then in the infra-red and visible spectrum.

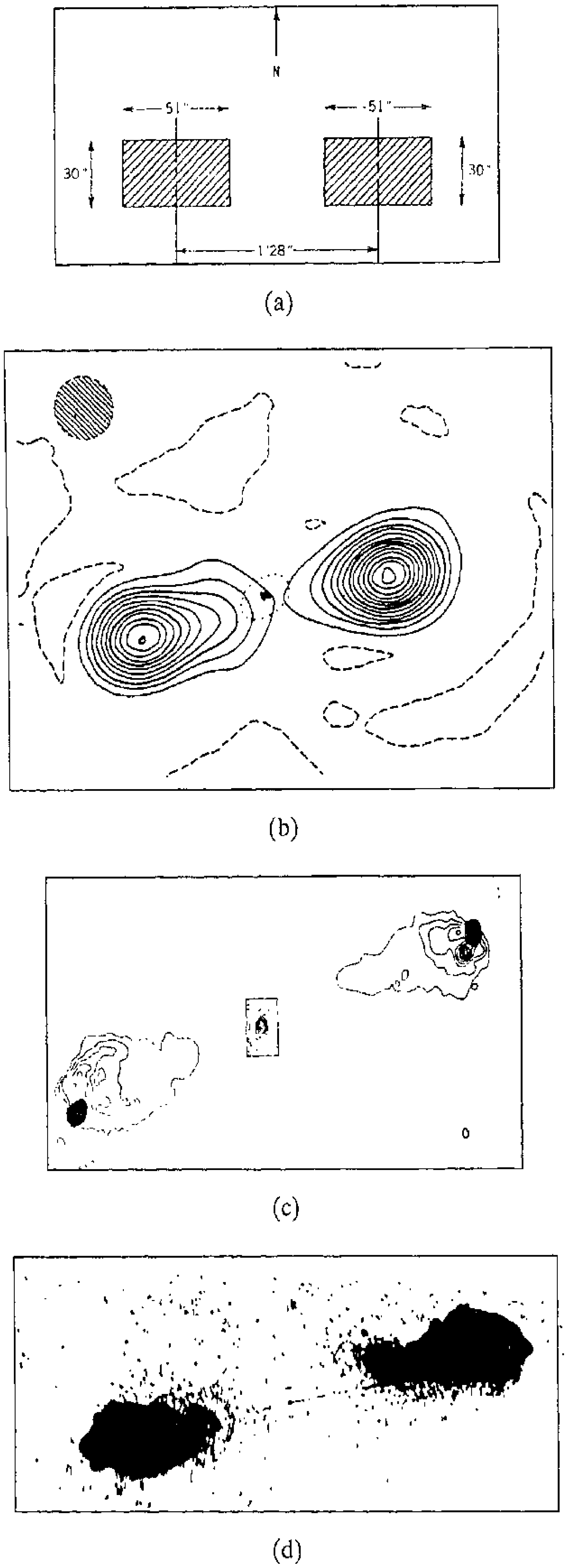

Figure 6. Progress in map-making. Cygrus A (radio source) as mapped by **(a)** An intensity interferometer at 125 MHz in 1952. **(b)** An aperture-synthesis interferometer at 1.4 GHz in 1965. **(c)** An aperture synthesis interferometer at 5 GHz in 1974. **(d)** The V.L.A. (New Mexico, U.S.A.) at 4.9 GHz in 1984.

As far as Optical Astronomy is concerned, the use of interferometers in Space will extend at both ends of the spectrum the range of wavelengths over which it is possible to achieve high angular resolving power and will also make it possible to work on much fainter objects.

As far as Radio Astronomy is concerned the use of Space will allow the use of much longer baselines than are possible on Earth; not only will this increase the angular resolving power over the whole radio spectrum but it will also make it possible to achieve high angular resolution at long radio wavelengths.

To sum up, the search for higher resolving power is an active and interesting branch of observational Astronomy which by comparison with other fields of Astronomy is still in its infancy. It has already yielded many valuable and fascinating results in Radio Astronomy and we can, I confidently expect, look forward to the same thing happening in Optical Astronomy.

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