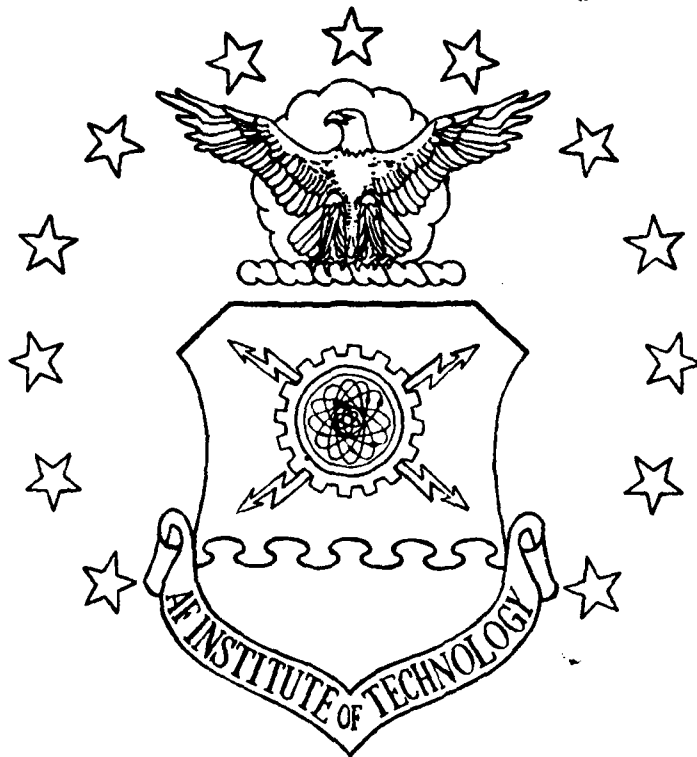


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PARTIALLY-COHERENT IMAGING
WITH A
MULTIAPERTURE OPTICAL SYSTEM

SEPTEMBER 1985

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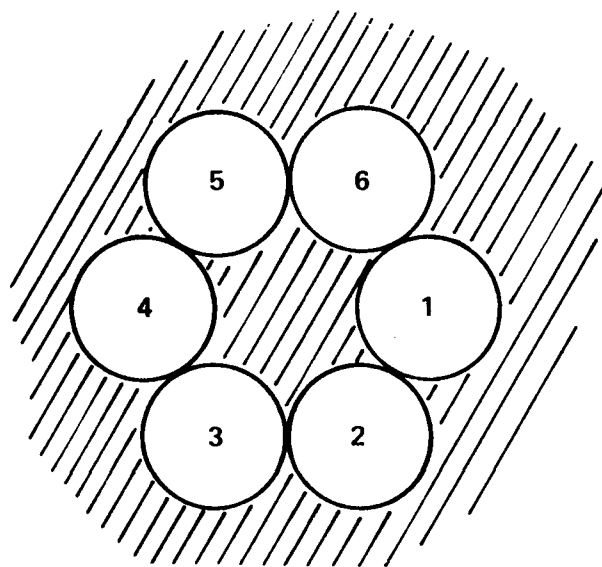
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I. INTRODUCTION

The purpose of this paper is to lay the theoretical groundwork for a multi-aperture imaging system which operates on the principles of partially-coherent imaging (1:499-510). The system described here is the optical analog of a radio-frequency interferometric antenna array. The premier example of this technology in the radio regime is the very large Array (2) near Socorro NM.

The exit pupil of the multi-aperture optical system considered here consists of six apertures arranged in an hexagonal array. As an example, one might think of the Multiple Mirror Telescope (3). An aperture arrangement similiar to the Multiple Mirror Telescope is shown in Fig. 1. Here, the six apertures (numbered 1 to 6) are arranged hexagonally.



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Fig 1. The pupil function of a six element multi-aperture system



This multi-aperture system is oriented to view a distant incoherent source. The basic principle of operation is to use opposing pairs of mirrors in the array to measure the complex degree of partial coherence of the light field.

reaching the array from the source. A two-dimensional measurement of this quantity in the plane of the aperture can be translated into a two-dimensional image of the object.

The goal of this paper is to demonstrate theoretically how imaging can be done in this manner. A two lens version of such a system is presently being built by the Environmental Research Institute of Michigan (ERIM) under contract to the Avionics Laboratory (4).

II. THEORY

The theory will first be developed for a one-dimensional system and then extended to a two-dimensional system along the lines of the Multiple Mirror Telescope. The basic principles, which are most easily explained in a one-dimensional case are completely valid in two dimensions. The treatment that follows comes primarily from Sections 10.3 and 10.4 in Born and Wolf (1:499-510).

The General Interference Law

To illustrate the principle, let's consider the optical system of Fig 2. An

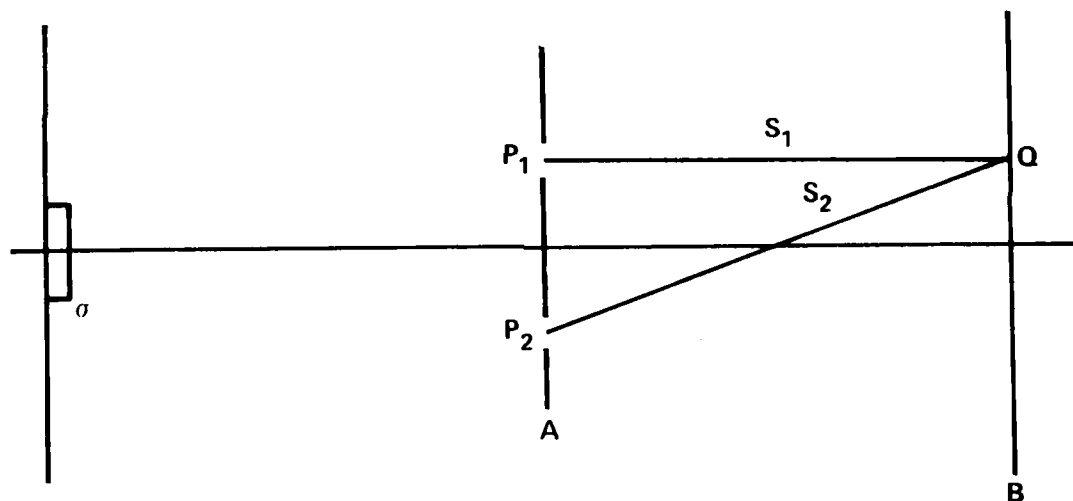


Fig 2. Geometry of a two element multi-aperture system

extended polychromatic (incoherent) source σ produces a wave field travelling toward screen A. Neglecting polarization effects, the light disturbance can be regarded as a real scalar function $v(\mathbf{r})(P,t)$ of position and time, with an associated analytic signal $V(P,t)$. The observable quantity, irradiance, is pro-

portional to the mean value of $v(r)^2(P,t)$, so that, aside from a constant multiplier,

$$I(P) = 2 \langle v(r)^2(P,t) \rangle = \langle v(P,t) v^*(P,t) \rangle . \quad (1)$$

The sharp brackets in Eq. (1) indicates that the quantity enclosed within the sharp bracket is to be averaged over a long time period, i.e.

$$\langle f(t) \rangle = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f(t) dt. \quad (2)$$

Consider now any two points P_1 and P_2 in the wave field. The irradiance at these two points $I(P_1)$ and $I(P_2)$ can be measured as can the interference effects arising from superposition of the vibrations from these two points. To measure the interference effects, an opaque screen with two pinholes could be placed in plane A of Fig. 2; and a second screen, to view that interference, could be placed in plane B. Let S_1 and S_2 be the distances of a typical point Q on the screen B from P_1 and P_2 respectively. Points P_1 and P_2 may be regarded as centers of secondary disturbances so that the complex light field at Q is given by

$$V(Q,t) = k_1 V(P_1, t-t_1) + k_2 V(P_2, t-t_2), \quad (3)$$

where t_1 and t_2 are the times needed for light to travel from P_1 and P_2 , respectively, to the observation point Q. Specifically

$$t_1 = \frac{S_1}{c} \quad \text{and} \quad t_2 = \frac{S_2}{c} , \quad (4)$$

where c is the velocity of light. The propagation factors k_1 and k_2 depend on the size of the openings and are inversely proportional to the distances S_1 and S_2 .

The irradiance at the point Q is found by substituting Eq (3) into Eq (1), with the result

$$I(Q) = K_1 K_1^* \langle V_1(t-t_1) V_1^*(t-t_1) \rangle + K_2 K_2^* \langle V_2(t-t_2) V_2^*(t-t_2) \rangle \\ + K_1 K_2^* \langle V_1(t-t_1) V_2^*(t-t_2) \rangle + K_2 K_1^* \langle V_2(t-t_2) V_1^*(t-t_1) \rangle, \quad (5)$$

where $V_1(t)$ is written in place of $V(P_1, t)$. Since the optical field is stationary in time, the origin in time can be shifted, giving for example,

$$\langle V_1(t-t_1) V_1^*(t-t_1) \rangle = \langle V_1(t) V_1^*(t) \rangle = I_1. \quad (6)$$

Using Eq (4) and the fact that k_1 and k_2 are purely imaginary, Eq (5) is simplified to

$$I(Q) = |k_1|^2 I_1 + |k_2|^2 I_2 + 2|k_1 k_2| \Gamma_{12}^{(r)} \left[\frac{S_2 - S_1}{c} \right], \quad (7)$$

where $\Gamma_{12}^{(r)} \left[\frac{S_2 - S_1}{c} \right] = \Gamma_{12}^{(r)}(\tau)$ is the real part of the function

$$\Gamma_{12}(\tau) = \langle V_1(t+\tau) V_2^*(t) \rangle. \quad (8)$$

The quantity $\Gamma_{12}(\tau)$ is termed the mutual coherence function of the wave field. In the general theory of stationary random processes, $\Gamma_{12}(\tau)$ is called the cross-correlation function of $V_1(t)$ and $V_2(t)$. When the two points coincide ($P_1 = P_2$), the result is

$$\Gamma_{11}(\tau) = \langle V_1(t+\tau) V_1^*(t) \rangle, \quad (9)$$

which is a measure of the self-coherence of the light field; it reduces to the irradiance at that point when $\tau = 0$, i.e.

$$\Gamma_{11}(0) = I_1 \quad \text{and} \quad \Gamma_{22}(0) = I_2. \quad (10)$$

The first term on the right hand side of Eq (7) is the irradiance which would be observed at Q if the pinhole at P_1 alone was open and the second term has a similar interpretation. These terms can be redefined as

$$I^{(1)}(Q) = |k_1|^2 I_1 = |k_1|^2 \Gamma_{11}(0) \quad (11a)$$

and

$$I^{(2)}(Q) = |k_2|^2 I_2 = |k_2|^2 \Gamma_{22}(0). \quad (11b)$$

Conventionally, $\Gamma_{12}(\tau)$ is normalized such that

$$\gamma_{12}(\tau) = \frac{\Gamma_{12}(\tau)}{\sqrt{\Gamma_{11}(0)} \sqrt{\Gamma_{22}(0)}} = \frac{\Gamma_{12}(\tau)}{\sqrt{I_1} \sqrt{I_2}}, \quad (12)$$

where $\gamma_{12}(\tau)$ is termed the complex degree of coherence. Using Eqs (11) and (12), Eq (7) may now be written as

$$I(Q) = I^{(1)}(Q) + I^{(2)}(Q) + 2\sqrt{I^{(1)}(Q)} \sqrt{I^{(2)}(Q)} \gamma_{12}^{(r)} \left[\frac{S_2 - S_1}{c} \right] \quad (13)$$

where $\gamma_{12}^{(r)}$ denotes the real part of γ_{12} .

Formula (13) is the general interference law for stationary optical fields. It relates the irradiance at a point Q to the single opening irradiances and the real part of the complex degree of coherence, γ_{12} . It will be shown in the next section how γ_{12} can be calculated from data which specify the source and the transmission properties of the medium.

The quantities $\gamma_{12}^{(r)}$ and $\Gamma_{12}^{(r)}$ can be determined experimentally. This can be seen by solving for $\gamma_{12}^{(r)}$ in Eq (13) and then solving for $\Gamma_{12}^{(r)}$ in Eq (12). The results of such efforts leads to

$$\gamma_{12}^{(r)} = \frac{I(Q) - I^{(1)}(Q) - I^{(2)}(Q)}{2\sqrt{I^{(1)}(Q)} \sqrt{I^{(2)}(Q)}} \quad (14)$$

and

$$\Gamma_{12}^{(r)} = \sqrt{I(P_1)} \sqrt{I(P_2)} \gamma_{12}^{(r)} = \frac{1}{2} \frac{\sqrt{I(P_1)I(P_2)}}{\sqrt{I^{(1)}(Q)I^{(2)}(Q)}} [I(Q) - I^{(1)}(Q) - I^{(2)}(Q)]. \quad (15)$$

The significance of γ_{12} is seen by expressing Eq (12) in polar terms:

$$\gamma_{12}(\tau) = |\gamma_{12}(\tau)| e^{i[\alpha_{12}(\tau) - 2\pi\bar{\nu}\tau]}, \quad (16)$$

where

$$\alpha_{12}(\tau) = 2\pi\bar{\nu}\tau + \arg \gamma_{12}(\tau), \quad (17)$$

and $\bar{\nu}$ is the mean frequency of the light. Then Eq (13) becomes

$$I(Q) = I^{(1)}(Q) + I^{(2)}(Q) + 2\sqrt{I^{(1)}(Q)}\sqrt{I^{(2)}(Q)} |\gamma_{12}(\tau)| \cos[\alpha_{12}(\tau) - \delta], \quad (18)$$

where

$$\delta = 2\pi\bar{\nu}\tau = \frac{2\pi}{\lambda} (S_2 - S_1), \quad (19)$$

and $\bar{\lambda}$ is the mean wavelength. Now, $\gamma_{12}(\tau)$ is a normalized quantity, so that $|\gamma_{12}(\tau)|$ varies between unity and zero; it specifies the degree of coherence. When $|\gamma_{12}(\tau)|=1$, the intensity at Q, as described by Eq (18), is the same as if the light from the source were strictly monochromatic of wavelength $\bar{\lambda}$, and with the phase difference between the vibration at P₁ and P₂ equal to $\alpha_{12}(\tau)$. In this case, the vibrations at P₁ and P₂ are coherent. When $|\gamma_{12}(\tau)|=0$, there is no interference between the beams. In this case, the vibrations at P₁ and P₂ are incoherent. If, as in most cases, $0 \leq |\gamma_{12}(\tau)| \leq 1$, the vibrations are said to be partially coherent with $|\gamma_{12}(\tau)|$ representing the degree of coherence.

The main points to be made from this section are, first of all, that an incoherent source of light gives rise to wave fields which are partially coherent. Secondly, the quantity which specifies the coherence of this wave-field, $\gamma_{12}(\tau)$, is measurable. The next section will show the relationship between the physical parameters (size, distance, and intensity distribution) of the source and the measurable quantity γ_{12} in some distant plane.

The van Cittert - Zernike Theorem

The analysis will now be restricted to the quasi-monochromatic case; that

is, when the spectral bandwidth of the illumination Δ is much less than the mean frequency of the light, or

$$\Delta \ll \bar{\nu} . \quad (20)$$

The analysis is further restricted to the case where the time delay introduced between the interfering beams is small; ie,

$$|\tau| \ll \frac{1}{\Delta\nu} . \quad (21)$$

When these two conditions are met, a new set of variables which describe the correlation in the optical field are usually defined. These are

$$J_{12} = \Gamma_{12}(0) = \langle v_1(t)v_2^*(t) \rangle \quad (22)$$

$$\mu_{12} = \gamma_{12}(0) = \frac{\Gamma_{12}(0)}{\sqrt{\Gamma_{11}(0)}\sqrt{\Gamma_{22}(0)}} = \frac{J_{12}}{\sqrt{J_{11}}\sqrt{J_{22}}} = \frac{J_{12}}{\sqrt{I_1}\sqrt{I_2}} \quad (23)$$

$$\beta_{12} = \alpha_{12}(0) = \arg \gamma_{12}(0) = \arg \mu_{12} \quad (24)$$

The quantity J_{12} is called the mutual intensity and μ_{12} is called the complex degree of coherence.

It will now be shown how the mutual intensity J_{12} can be determined for points P_1 and P_2 on a screen A illuminated by an extended quasi-monochromatic primary source (see Fig. 3).

To simplify the analysis, the source is assumed to be parallel to the observation plane A. It is also assumed that the maximum linear dimension in σ is much smaller than the separation OO' between the source and the plane A, and that the angles between OO' and the lines joining a typical source point S to P_1 and P_2 are small.

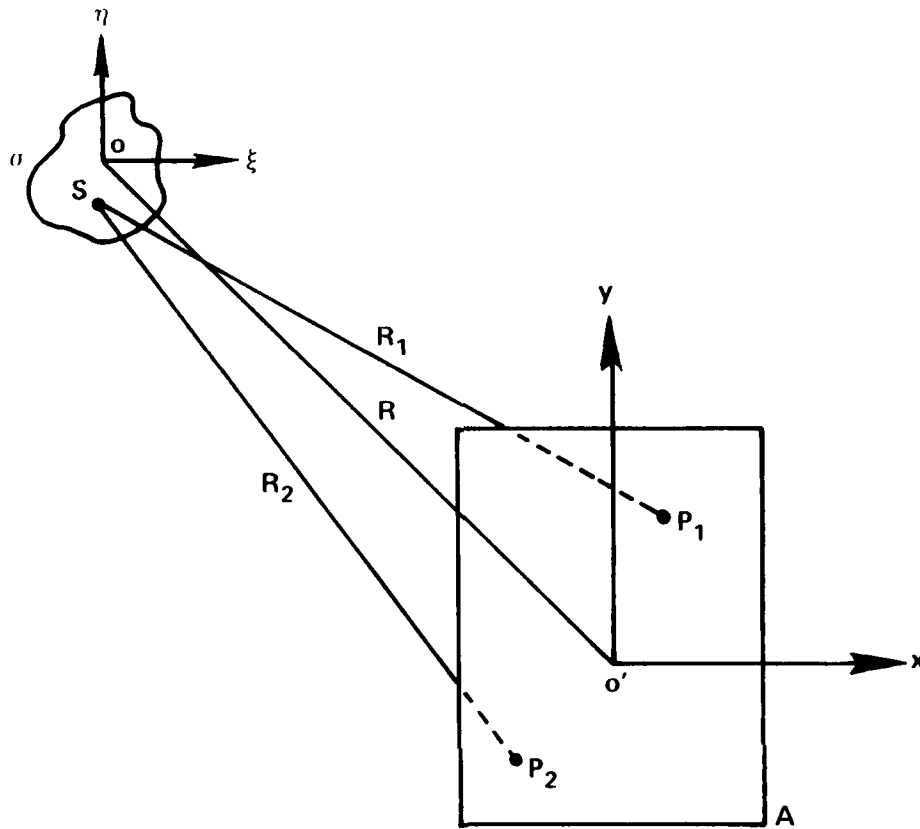


Fig 3. An incoherent quasi-monochromatic extended source σ in the ξ, η plane illuminates points P_1 and P_2 in the x, y plane.

The source is divided into elements $d\sigma_1, d\sigma_2, \dots$ centered on points S_1, S_2, \dots , each having linear dimensions small compared to the mean wavelength $\bar{\lambda}$. If $V_{m1}(t)$ and $V_{m2}(t)$ are the complex disturbances at P_1 and P_2 from the element $d\sigma_m$, then the total disturbance at these points from all elements of the source are

$$V_1(t) = \sum_m V_{m1}(t) \quad \text{and} \quad V_2(t) = \sum_m V_{m2}(t) . \quad (25)$$

Thus, the mutual intensity function associated with these two points is

$$J_{12} = \langle V_1(t) V_2^*(t) \rangle = \sum_m \langle V_{m1}(t) V_{m2}^*(t) \rangle + \sum_{m \neq n} \langle V_{m1}(t) V_{n2}^*(t) \rangle. \quad (26)$$

The light source was assumed incoherent which implies that the individual source elements are statistically independent and of zero mean value, so that

$$\langle V_{m1}(t) V_{n2}^*(t) \rangle = \langle V_{m1}(t) \rangle \langle V_{n2}^*(t) \rangle = 0 \quad (27)$$

when $m \neq n$. If R_{m1} and R_{m2} are the distances of P_1 and P_2 from the source element $d\sigma_m$, then

$$V_{m1} = A_m(t - R_{m1}/v) \frac{\exp[-i2\pi\bar{v}(t - R_{m1}/v)]}{R_{m1}} \quad (28a)$$

and

$$V_{m2} = A_m(t - R_{m2}/v) \frac{\exp[-i2\pi\bar{v}(t - R_{m2}/v)]}{R_{m2}}, \quad (28b)$$

where $|A_m|$ is the strength and $\arg A_m$ is the phase of the radiation from the m^{th} source element, and v is the velocity of light in the medium between the source and the screen. Then, the correlation at the two observation points from the m^{th} source element is

$$\begin{aligned} \langle V_{m1}(t) V_{m2}^*(t) \rangle &= \langle A_m(t - R_{m1}/v) A_m^*(t - R_{m2}/v) \rangle \frac{\exp[i2\pi\bar{v}(R_{m1} - R_{m2})/v]}{R_{m1} R_{m2}} \\ &= \langle A_m(t) A_m^*(t - \frac{R_{m2} - R_{m1}}{v}) \rangle \frac{\exp[i2\pi\bar{v}(R_{m1} - R_{m2})/v]}{R_{m1} R_{m2}} \end{aligned} \quad (29)$$

Assuming that the path difference $R_{m2} - R_{m1}$ is small compared to the coherence length of light, the mutual coherence (correlation) of the radiation in the

observation plane is, from Eqs (26), (27), and (29)

$$J_{12} = \sum_m \langle A_m(t) A_m^*(t) \rangle \frac{\exp[i2\pi\bar{v}(R_{m1}-R_{m2})/v]}{R_{m1} R_{m2}} \quad (30)$$

The quantity in sharp brackets is the radiance in the source plane of the m^{th} source element. For any real source, the total number of source elements may be assumed to be large, so that the source may be regarded as being effectively continuous. Denoting by $I(S)$ the radiance distribution of the source $I(S_m) d\sigma_m = \langle A_m(t) A_m^*(t) \rangle$, Eq (30) becomes

$$J_{12} = \int_{\sigma} I(S) \frac{\exp[i\bar{k}(R_1-R_2)]}{R_1 R_2} ds, \quad (31)$$

where $\bar{k} = 2\pi\bar{v}/v = 2\pi/\lambda$ is the wave number of the medium. The complex degree of coherence, Eq (23) can now be written as

$$\mu_{12} = \frac{1}{\sqrt{I(P_1)} \sqrt{I(P_2)}} \int_{\sigma} I(S) \frac{\exp[i\bar{k}(R_1-R_2)]}{R_1 R_2} ds, \quad (32)$$

where

$$I(P_1) = J_{11} = \int_{\sigma} \frac{I(S)}{R_1^2} ds \quad \text{and} \quad I(P_2) = J_{22} = \int_{\sigma} \frac{I(S)}{R_2^2} ds \quad (33)$$

are the irradiances at the observation points P_1 and P_2

The integral, Eq (32), is the same which occurs in a different connection. It arises in the calculation of the complex disturbance in the diffraction pattern arising from diffraction of a spherical wave from an aperture in an opaque screen.

More precisely, Eq (32) "implies that the complex degree of coherence,

which describes the correlation of vibrations at a fixed point P_2 and a variable point P_1 in a plane illuminated by an extended quasi-monochromatic primary source, is equal to the normalized complex amplitude at the corresponding point P_1 in a certain diffraction pattern, centered on P_2 . This same pattern would be obtained on replacing the source by a diffracting aperture of the same size and shape as the source, and on filling it with a spherical wave converging to P_2 , the amplitude distribution over the wavefront in the aperture being proportional to the intensity distribution across the source." (1)

This result was first established by van Cittert (5) and later in a simpler way by Zernike(6). It is referred to as the van Cittert-Zernike Theorem.

Referring again to Fig. 3, (ϵ, η) are the coordinates of a typical source point S , relative to the axes at O , and (X_1, Y_1) and (X_2, Y_2) are the coordinates of P_1 and P_2 , respectively, relative to parallel axes at O' . Then, if R denotes the distance OO' ,

$$R_1 = (X_1 - \epsilon)^2 + (Y_1 - \eta)^2 + R^2, \quad (34)$$

so that

$$R_1 \cong R + \frac{(X_1 - \epsilon)^2 + (Y_1 - \eta)^2}{2R}, \quad (35)$$

where the binomial expansion of a square root has been used, keeping only the leading terms in X_1/R , Y_1/R , ϵ/R , and η/R . Thus

$$R_1 - R_2 \cong \frac{(X_1^2 + Y_1^2) - (X_2^2 + Y_2^2)}{2R} - \frac{(X_1 - X_2)\epsilon + (Y_1 - Y_2)\eta}{R} \quad (36)$$

In the denominator of (32), R_1 and R_2 may, to a good approximation be replaced by R . Making the substitutions

$$p = \frac{X_1 - X_2}{R}, \quad q = \frac{Y_1 - Y_2}{R}, \quad \text{and} \quad (37a)$$

$$\psi = \frac{\bar{k}[(X_1^2 + Y_1^2) - (X_2^2 + Y_2^2)]}{2R}, \quad (37b)$$

Eq. (32) may be written as

$$\mu_{12} = \frac{[e^{i\psi}] \iint_{\sigma} I(\xi, \eta) \exp[-i\bar{k}(p\xi + q\eta)] d\xi d\eta}{\iint_{\sigma} I(\xi, \eta) d\xi d\eta}. \quad (38)$$

Thus if the linear dimensions of the source and the distance between P_1 and P_2 are small compared to the distance of these points from the source, the complex degree of coherence μ_{12} is equal to the normalized Fourier transform of the intensity distribution of the source.

III. Sampling the Mutual Intensity Function

The development so far has shown that an incoherent source produces an optical field which is partially coherent, that the complex degree of coherence μ_{12} of this field is an observable parameter, and that the relationship between the source irradiance distribution and μ_{12} is described by a Fourier transform if certain conditions are met.

If the complex degree of coherence is measured in the two-dimensional plane, then the object irradiance distribution can be calculated by performing an inverse Fourier transform on the measured data. This is a form of imaging.

To see how this might be done, consider the one-dimensional system of Fig. 4. There is an incoherent source S in the ξ plane having a rectangular shape and a width w . The measurement device consists of two small equal-sized

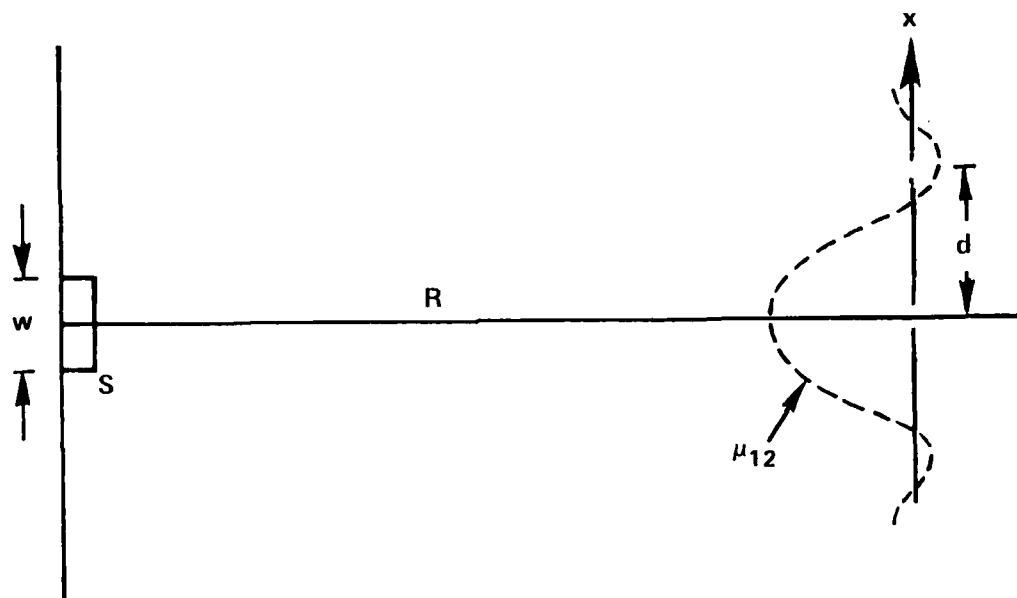


Fig 4. The relationship of source and system geometries to the complex degree of coherence function.

apertures separated by a distance d in the x plane, which is a distance R away from the source. Assuming that both w and d are much smaller than R , the functional shape of μ_{12} is a sinc function, perhaps like the one shown superimposed on Fig. 4 near the x axis.

The purpose of the measurement system is to make enough measurements in the x plane to adequately sample μ_{12} . The actual measurement apparatus which must exist somewhere to the right of the x plane in Fig. 4 will not be covered in this paper.

The function to be measured is represented as the dashed curve in Fig. 5. The apertures as shown in Fig. 4 allow the measurement of a sample of μ_{12} (sample #1 in Fig. 5) directly. Sample #1' can be inferred from the first measurement because of the Hermitian nature of μ_{12} . That is, since the source S is a real function, its Fourier transform (μ_{12}) is Hermitian; see Table 7.1 in

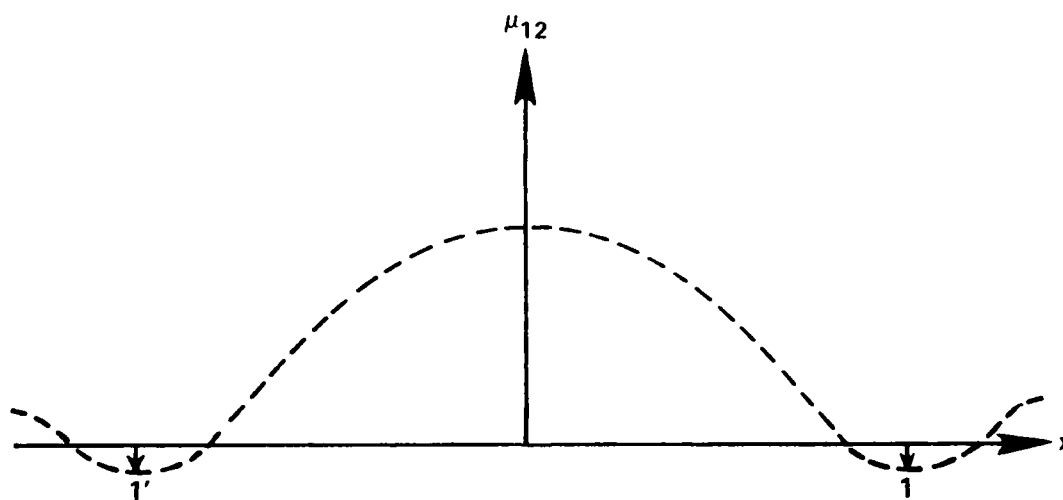


Fig 5. The complex degree of coherence μ_{12} (dashed curve) and measured samples of this function at 1 and 1'.

Gaskill (7:193). This means that samples μ_1 and μ_1^* are a complex conjugate pair.

Other samples of μ_{12} can be made with the same two apertures by varying the center wavelength of the quasi-monochromatic light measured. This can be seen by examining Eq. (38) which is rewritten here:

$$\mu_{12} = \frac{[e^{i\psi}] \iint_{\sigma} I(\xi, \eta) \exp[-i\bar{k}(\rho\xi + q\eta)] d\xi d\eta}{\iint_{\sigma} I(\xi, \eta) d\xi d\eta} \quad (38)$$

The pertinent part of this equation is the product $\bar{k}\rho$ (or $\bar{k}q$ but consider only $\bar{k}\rho$):

$$\bar{k}\rho = \frac{2\pi}{\bar{\lambda}} \frac{x_1 - x_2}{R} \quad (39)$$

where $\bar{\lambda}$ is the center wavelength of the quasi-monochromatic (narrow) band of light accepted in making the first measurement above and $x_1 - x_2$ is the physical separation of the apertures. If $\bar{\lambda}$ is varied, the effect on the Fourier integral in (38) is the same as if $\bar{\lambda}$ were fixed and $\rho = x_1 - x_2$ were varied. This means that more samples of the function μ_{12} can be obtained, perhaps as shown in Fig. 6, where samples 2 and 2' occur at center wavelength λ_2 , and so on. If enough samples of μ_{12} are made in this manner, then the original function S can be reproduced with sufficient accuracy. The Whittaker-Shannon sampling Theorem (8:21) will be of use in making this determination.

Now consider the two dimensional measurement system of Fig 7a. The apertures 1 and 4 yield samples of μ_{12} along the x axis as shown in figure 6. If now two other aperture pairs 3-6 and 2-5 are added to the system and used at the same time, then the sampled pattern of μ_{12} appear as in Fig 7b.

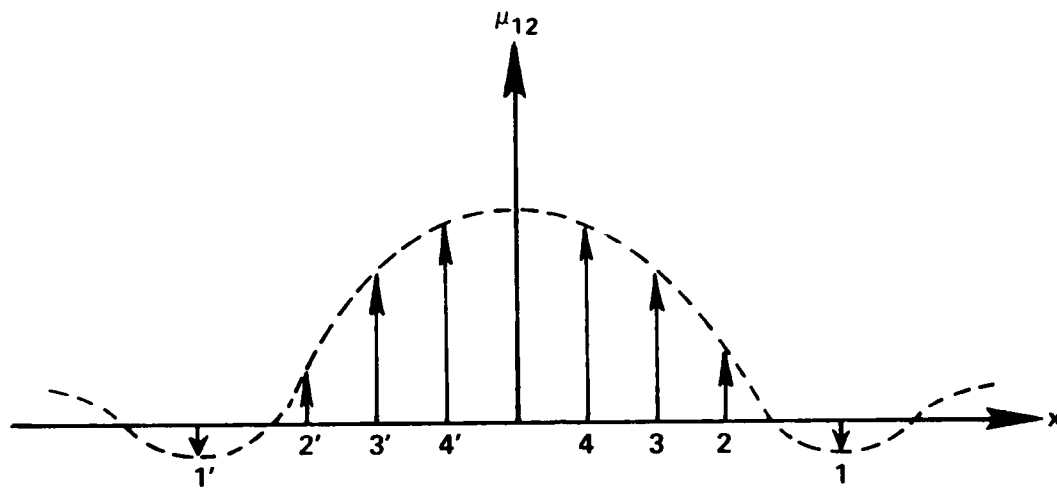


Fig 6. The complex degree of coherence μ_{12} (dashed curve) and the measured samples of this function.

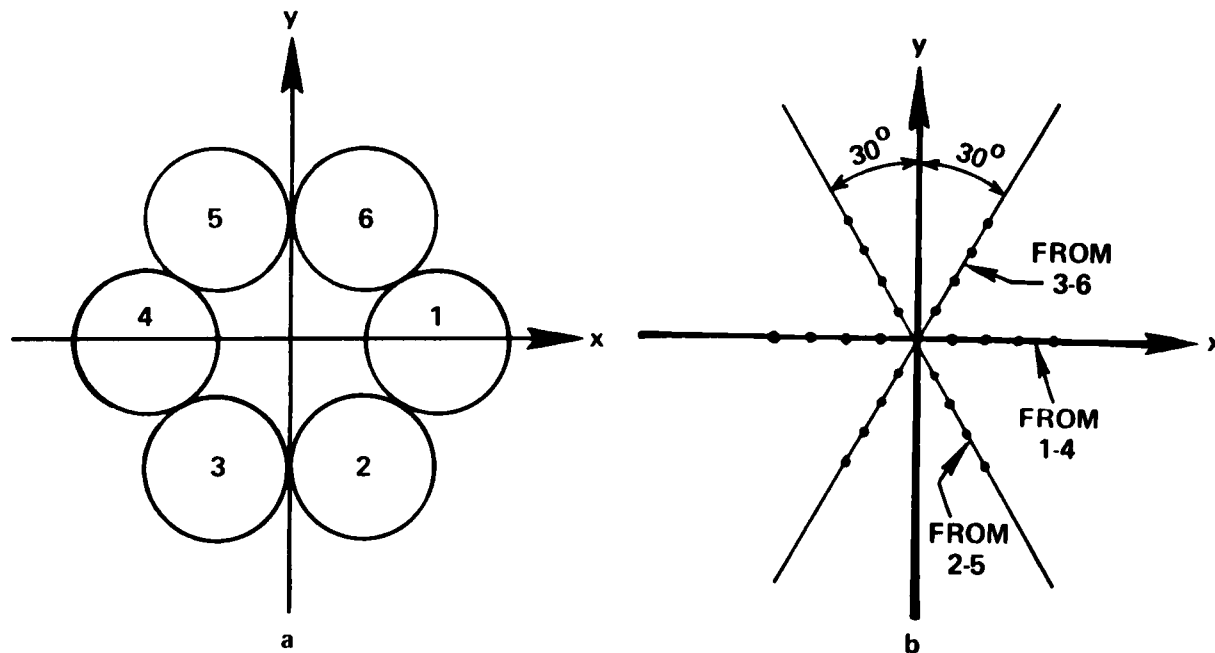


Fig 7. A two-dimensional multi-aperture system (a) and the location of some of the possible samples of the complex degree of coherence μ_{12} in the aperture plane (b).

Other pairs of apertures besides these can also be used. The pairs 2-6, 1-5, and 1-3 can yield information in new directions. This new information is along different radial lines and at lower spatial frequencies. Using all the pairs of apertures could yield a sample pattern like that shown in Fig 8.

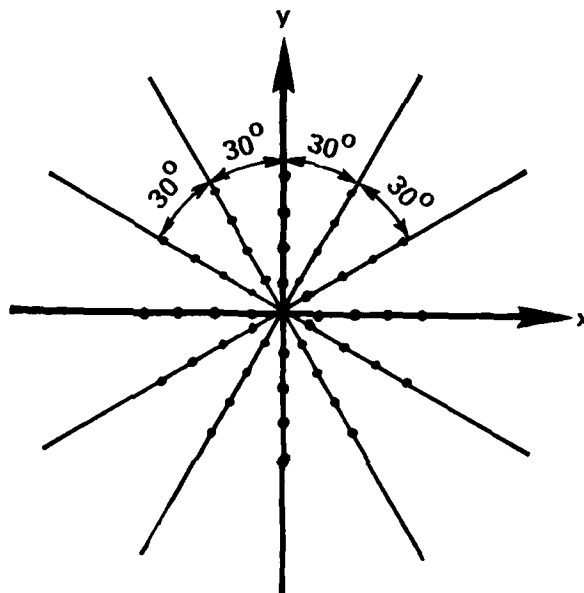


Fig 8. Possible samples of the complex degree of coherence μ_{12} when all possible pairs of apertures in Fig 7a are used.

The image is recovered by performing an inverse Fourier transform on this sampled data. If the sampling is sufficiently dense then a good image will be formed.

The resolution of this image is determined by the largest spatial frequency sampled by the array. This is, in turn, determined by the maximum separation of the apertures and the lowest wavelength passed by the system.

If the two dimensional array of measured values of μ_{12} does not sample in the function densely enough, there are two remedies. First, the number of samples along a particular radial line can be increased. This can be done by increasing the number of wavelength bands measured.

The second method involves a rotation of the telescope array or the object. This would result in a doubling of total samples if measurements from all the apertures are taken at two rationally different orientations.

IV. Conclusion

The purpose of this report was to point out that a multi-aperture telescope like the Multiple Mirror Telescope could be used for partially coherent imaging and to show that this is possible in a mathematically rigorous manner.

The derivation which was presented followed closely that of sections 10.3 and 10.4 in Born and Wolf (1:499-510). The main results of this development were that an incoherently illuminated source produces a partially coherent field, that the degree of coherence of this field can be measured, and that it is related by a Fourier transform to the two-dimensional intensity distribution of the source.

It was then suggested that a six-element multi-aperture optical system could make this measurement in an efficient manner.

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