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monitor binary stars could be built for about 1.4 million dollars.

USING SMALL APERTURE INTERFEROMETRY TO DETECT PLANETS IN NEARBY BINARY STAR SYSTEMS

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ABSTRACT

If suitably accurate binary star orbits can be observed, the effects of planets in the binary star system may be detectable in the reflex motion of the component binary stars. We show that interferometric measurements of binary star systems will provide this information. We discuss the effects of the atmosphere on degrading images and how interferometry will remove these effects to provide very accurate binary star positions relative to the other components in the binary system. Two systems, amplitude interferometry and speckle interferometry, can accomplish this using existing telescopes and techniques. With these methods, yearly accuracies of 2×10^{-5} arc second are possible for binaries of 1 arc second separation and 10^{-4} arc second for a 5 arc second binary. These accuracies are more than enough to detect planets in orbits like Jupiter's out to over 20 pc. There are 188 observable systems within 20 pc, in most of which it is possible to have stable planetary orbits similar to solar system orbits. With advanced data recording systems it is possible to observe binary systems where the components are as faint as +16 stellar magnitudes. A dedicated 2-meter interferometric telescope to monitor binary stars could be built for about 1.4 million dollars.

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I. INTRODUCTION

Low mass and non-luminous companions of nearby stars may be detected in several ways. Among the most promising methods are indirect methods; that is detecting the effects of an invisible object on its visible companion. Spectroscopic methods may be used to observe radial velocity fluctuations in the visible star caused by the orbital reflex motion relative to the invisible companion. Astrometric detection involves observing the positional perturbation caused by the orbit of the unseen object. Astrometry therefore requires establishing the position of the center of light in a stellar image and referencing this center to a fixed frame.

Astrometry is limited by the ability to establish the center of a star image and uncertainties in the reference frame. Star images, perturbed by seeing, are roughly gaussian. The accuracy for finding the center of the gaussian is obviously dependent on the stability of the gaussian profile. Long exposures are therefore used to: 1) collect enough photons to accurately define the center of each star image and 2) to average out seeing for image motion. The reference frame of these measurements may in principle be established by the centers of three or more other star images. Since the proper motions of these stars may influence the coordinate frame, the reference stars are chosen to be distant background stars. The Earth's atmosphere can also distort the reference frame as a function of atmospheric conditions and colors of the reference stars. These uncertainties may be reduced by using a relatively large number of reference stars in conjunction with sophisticated mathematical error

analysis schemes. In spite of such difficulties conventional astrometry may now reach   positional accuracies of ± ".05 for a single exposure, this may be improved to better than ± ".001 (Gatewood, 1976) for the results of one year's observation.

Astrometric accuracy could be improved by getting smaller star images. The problem of finding a star image center is clearly easier the smaller the image is. If images were improved to the diffraction limit the increase is substantial. The task of finding the center of a 2 meter telescope diffraction limited spot of ".05 may be done with much higher precision than finding the center of a 1 arc-second seeing disk with the same number of photons. We can also increase accuracy by removing the atmospheric effects on the reference frame. Both things are possible   using some form of interferometry.

Stellar interferometry, first demonstrated by Michelson (1920), makes it possible to approach the full theoretical (diffraction limited) resolving power of large optical systems. Large baseline (hundreds of meters) instruments like the intensity interferometer (Hanbury-Brown 1968) have been demonstrated. Smaller scale instruments have recently been perfected to adapt existing telescopes into diffraction limited systems using techniques known as Amplitude Interferometry (Currie, 1967; Currier et al., 1974) and Speckle Interferometry (Gezari et al., 1972). These techniques were extensively reviewed by Dainty (1974), Worden (1977) and Labeyrie (1978). Long baseline interferometers have been proposed which would convert the image scale to the full diffraction limit and remove atmospheric effects on the reference frame. Such systems are ideal for detecting small scale astrometric perturbations due to planetary

mass objects. However these instruments are costly and have yet to be completely demonstrated in the field. On the other hand, Amplitude and Speckle Interferometry have already demonstrated the ability to make conventional telescopes diffraction limited.

Both Amplitude and Speckle Interferometry are limited by the so-called isoplanatic problem. This is shown schematically in Figure 1. To remove atmospheric effects using these interferometry methods it is necessary that light from all objects to be studied pass through the same column of turbulent atmosphere. Thus a program star and its reference star must lie within an angle known as the isoplanatic angle so that the light from both passes through essentially the same atmosphere. The precise value of the isoplanatic angle depends upon conditions in the atmosphere, the definition, and the observing instrument, but is probably less than 10 arc-seconds (Hubbard et al., 1979).

Binary stars are suitable candidates for planetary searches. McAlister (1978) has used speckle interferometry in a systematic program to determine binary star separations to accuracies of a few thousands of an arc-second, using relatively simple detectors and calibration methods. If a planet orbits one component of a binary star system, then the orbit of that component about the other star will "wobble". For the nearby stars this may be a modulation of up to ".01 for Jovian type planets. Harrington (1977) has shown that most binary star systems have stable planetary orbits. Interferometric searches for planetary perturbations of binary star orbits are therefore important. Indeed, interferometric searches of small separation binaries is almost the only way to search these systems.

Binary star interferometry is therefore important to assure a complete search for low mass stellar companions through all nearby stars and all types of stellar systems.

In this document we discuss interferometric methods to search binary star systems for planets. This suggestion was presented in some detail by McAlister (1977). We briefly discuss the physics behind atmospheric degradation of images and the interferometric instruments and techniques to remove this degradation. We address the accuracies and limitations of these techniques. A discussion of the sample of nearby binary star systems follows. Finally we provide information on the costs and features of possible dedicated telescopes for an interferometric binary star search.

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II. ATMOSPHERIC IMAGE DEGRADATION

Small scale temperature inhomogeneities in the Earth's atmosphere produce index of refraction changes. These refractive index changes cause phase delays along an incoming plane wave, which may be light from a stellar point source. This is represented schematically in Figure 2. Without the phase errors optical systems produce the image in Figure 2a which is said to be "diffraction limited", where a point source image is the classical Airy disc for a circular telescope aperture. The size of this image is inversely proportional to the telescope diameter. With any phase errors, telescope resolution is degraded to that appropriate for an optical system only as large as the scale over which some phase coherence (i.e the phase is the same) exists. Since the atmosphere breaks an incoming plane wave into about 10 cm fragments, all telescopes produce images with resolution no better than a 10 cm telescope, namely one arc-second. This process is shown in Figure 2b.

In 1970, Labeyrie (1970) proposed a method to recover some information down to large telescope diffraction limits. He pointed out that short exposure ($\Delta \tau \approx .01$ sec) photographs "freeze" the turbulence in the atmosphere. Although the phase coherence size in this "frozen" system is still only 10 cm there will be some 10 cm patches scattered over the entire aperture which are at the same phase. These portions act in concert as a form of "multiple aperture interferometer which provides some information down to the

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diffraction limit of the entire telescope aperture. As shown in Figure 2c, the image of a point source seen through a multiple aperture inter-ferometer is a series of nearly diffraction limited images modulated by a one arc-second seeing disk. This process is known as speckle inter-ferometry since the short exposure photos, shown in Figure 3, look like laser speckle photos.

As alternate approach to steller interferometry, suggested by Currie (1967) Currie et al. (1974), is similar to Michelson's interferometry. Known as Amplitude Interferometry, this technique uses a device like that shown in Figure 4. The individual collection apertures are smaller than the 10 cm coherence length along a stellar wavefront in order to reduce the correction due to atmospheric degradation to a negligible level. As the atmosphere modulates the relative phase shifts between these two apertures, the coherence properties (and thus angular size) of the object as it appears outside the atmosphere can be learned. To obtain complete two-dimensional size and shape information the observer varies the separ-ation and position angle for the two apertures. Currie has proposed and built a multiple aperture amplitude interferometer system, so that the full telescope aperture may be covered simultaneously and all Fourier components sampled simultaneously. The efficiency of such a system should be comparable to a speckle interferometry system.

III. INTERFEROMETRIC INSTRUMENTS AND DATA REDUCTION

In this section we describe interferometric data recording systems
and data reduction techniques.

A diagram of the Kitt Peak photographic speckle interferometer is
shown in Figure 5. There are about six similar systems in use at the
present time. The Kitt Peak camera was designed by Lynds (Lynds et al.,
1975; Breckinridge et al., 1978). As shown in the figure light from the
telescope passes through a shutter and focuses at the telescope image
plane. The shutter is necessary to insure exposures shorter than the
atmospheric change time, typically 20 milli-seconds. The telescope image is
relayed and magnified by a microscope objective. The magnification is set
to provide a pixel resolution oversampling the telescope diffraction spot
size by at least a factor of 4. For the Kitt Peak 4-meter telescope this
provides a final image scale of .2 arc-sec/mm Atmospheric dispersion
blurs speckle image pattern in the sense that the "red" portion of an image
focuses at a slightly different portion than the "blue" portion. Since
this may be significant for even 200 $\overset{\circ}{A}$ bandpass photos a set of rotating
atmospheric compensating prisms are included to counteract the dispersion.
Since there are about 20 orders of optical interference across a narrow
band ($\Delta \lambda \sim 200 \overset{\circ}{A}$), an interference filter is used to preserve coherence across
the entire speckle photo. If this were not included the "speckles" near
the edge of the photos would be elongated. A three stage image tube

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intensifies the image enough to allow photographic data recording. A
transfer lens relays the intensified image to a data recording system,
in this case a 35 mm film camera.

The speckle photos in Figure 3 were taken with the Kitt Peak System.
The different character of these photos is readily apparent. This is
understandable from the analogy to a multiple aperture interferometer.
Each speckle should be a diffraction limited image of the object. Indeed,
the binary star (α Aur) speckles are double, the point source speckles
roughly diffraction spots, and the resolved star (α Ori) speckles somewhat
larger. This aspect led Lynds et al (1975) to a direct speckle image
reconstruction scheme whereby individual speckles were identified and
co-added to produce a nearly diffraction limited image for the special case
of stars like α Ori.

A number of methods exist to reduce speckle interferometry data.
Labeyrie's original method is widely used; in particular for binary star
measurements. Individual speckle photos are Fourier transformed either
optically or digitally and the Fourier modulus computed. If the speckle
image is represented in one dimension as $i(x)$, and its transform as $I(s)$,
this process is mathematically represented by:

$$I(s) = \int_{-\infty}^{\infty} i(x)e^{-2\pi i x s}dx \qquad (1)$$

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The modulus or power spectrum, $|I(s)|^2$, of this transform contains the diffraction limited information in an easily extractable form. Examples of the mean power spectra for several binary star systems are shown in Figure 6. In the case of the binaries, power spectra show banding which represents the binary separation, the wider the bands are apart, the closer the binary separation. The orientation of these bands represents the position angle of the binary system. Superimposed in this signal is a background attributable to the residual effects of seeing. For stars brighter than about +7 visual magnitudes about fifty individual speckle snapshots are transformed to produce a mean power spectrum. A least square fit to the spacing and orientation angle of the bands in this power spectrum yield the binary separation and position angle; All accomplished from less than 1 second actual exposure time at the telescope!

The residual effects of the seeing must be removed to yield the maximum accuracy. Even though the bands (fringes) are readily visible in raw speckle power spectra, their spacing is effected by the residual seeing effects. Labeyrie's method uses observation of point source stars to determine these seeing effects and remove them. If $P_i(x)$ are point source speckle photos with a mean power spectrum $<|P(s)|^2>$, and $<|I(s)|^2>$ the mean power spectrum of the object speckle photos $i_i(x)$ then the diffraction limited power spectrum of the object is given by:

$$|O(s)|^2 = \frac{\langle|I(s)|^2\rangle}{\langle|P(s)|^2\rangle} \qquad (2)$$

Point source data is usually derived from speckle observations of point source stars situated near on the sky to the program objects. Since these point source objects are not in general observed within the same isoplanatic angle and not at the same time their power spectrum can only represent the residual seeing effects in a statistical sence. Worden et al. (1977) have developed a method to calibrate for residual seeing effects using the same set of speckle photos as used to study the program objects.

We illustrate the Worden et al. (1977) method in Figure 7. The method proceeds as follows: the mean autocorrelation function of a series of speckle, $i_i(x)$ photos is computed.

$$\langle AC(\Delta x)\rangle = \langle \int_{-\infty}^{\infty} i_i(x) \cdot i_i(x-\Delta x)dx\rangle$$

$$= \langle i_i(x) * i_i(x)\rangle \qquad (3)$$

(The autocorrelation is the Fourier transform of the power spectrum - see Bracewell 1965 for details). As we see in Figure 7, the mean autocorrelations are dominated by the seeing background. This background may be accurately removed by computing and subtracting the mean cross-correlation between consecutive speckle photos of the same set of data used to compute the auto-

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correlation. The cross calculation between the $i\underline{\text{th}}$ and $i\underline{\text{th}} + 1$ speckle photo is given by

$$\langle XC(\Delta x)\rangle = \langle \int_{-\infty}^{\infty} i_i(x) \cdot i_{i+1}(x-\Delta x)dx \rangle$$

$$= \langle i_i(x) * i_{i+1}(x)\rangle \qquad (4)$$

Welter and Worden (1978) showed that the resulting subtraction in the object autocorrelation as it would appear with virtually all seeing effects removed.

Current photographic speckle cameras are generally limited to objects brighter than +7. Thus the photographic recording systems are being replaced with high quantum efficiency digital recording systems. These systems record individual photon events. The University of Arizona speckle camera uses a CID (Charge Injected Device) television system to record photon arrivals. This system simply replaces the photographic emulsion and it can record data for objects faint enough so that only a few photons arrive in a 20 milli sec exposure. In Figure 8 we show data from this system for Saturn's moon Rhea which is a $10\underline{\text{th}}$ magnitude object. For faint objects like this, only the few hundred photon locations are recorded, rather than the entire frame. This allows such systems to run at the maximum speckle data rate of one speckle frame every 20 ms. This form of data is ideal for the correlation data reduction method described above, since the correlation functions are simply

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the sum of vector differences between photon locations. Consequently a direct computer interface may compute the results in real time at the telescope. The limiting requirement for this method is that at least two photons arrive in a 20 ms exposure. This translates to about a +16 stellar magnitude limit. Although angular diameters are more difficult to derive than binary separations, we have used this system to derive angular diameters for 13th magnitude objects accurate to ± 5% with less than 5 minutes total observing time.

The Amplitude Interferometer obtains the high angular resolution information in a somewhat different fashion than the Speckle Interferometer. In this case, the light is sampled at the entrance aperture of the telescope where the effect of the atmosphere has been to introduce only an error in the phase delay. The light from two separate apertures on opposite sides of the telescope is then interferometrically combined. Such a combination is illustrated in Figure 9.

By appropriate choice of the size of the interferometric aperture, one component of the atmospheric correction becomes negligible. The magnitude of the combined coherence function appears as the magnitude of the fringes in the combination of the interferometer two beams. In the case of high coherence one gets a varying signal as indicated in Figure 10. The fluctuations in this signal are caused by the motion of the wind. These fluctuations, or, more precisely, the autocorrelations and cross correlations of individual photo-electrons are used to elevate the fringe visibility.

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The currently operating Amplitude Interferometer is illustrated
in Figure 4.   The light from the telescope is sampled for two apertures
which have a diameter of 4 centimeters.   This has been used in a regular
program to measure star diameters down to about 6th magnitude (Currie
et al., 1974, Currie et al., 1976, Braunstein, 1977).   Although some
work has been done on binary stars (Braunstein, 1978) most of the work
has been on stellar diameters.   In order to illustrate the current
performance of the Amplitude Interferometer on the telescope we consider
Figure 11, which shows a typical set of data for a resolved star and for
an unresolved star which is used as a reference or check.   This shows the
visability of the fringes.   From this measure, the diameter of the star
is derived.

Taking successive measurements on different nights, we have
 seen   a high degree of stability, even though there have been
significant changes in the atmosphere.   This illustrates the general
validity of the atmospheric model and amplitude interferometric para-
meters in assuring independence of atmospheric fluctuations.

In order to permit the observation of fainter objects, we wish to
simultaneously use all the light entering the telescope aperture, i.e.
the data from many thousands of pairs of apertures. (i.e. a Multiple
Aperture Amplitude Interferometer or MAAI).   This may be done by
replacing each of the two photomultipliers with a "television camera"
in which each resolution element acts as a separate channel interferometer.

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The light then operates as shown in Figure 12. When an array detector is used, an inverting prism is required which causes every separation to be sampled. The overall design of this instrument is indicated in Figure 13.

The description of such an instrument, as might be used on a space telescope, has been given by Currie (1974) while a more detailed discussion of certain aspects appears in (Braunstein, 1978). A photograph of the MAAI is shown in Figure 14.

IV. ACCURACY

McAlister has had a substantial speckle program to derive binary star
parameters underway at Kitt Peak for the last several years. This program's
results provide preliminary information with which to estimate the precision
possible with speckle interferometry (McAlister 1978).

Internal errors in speckle interferometry are divided into the basic
uncertainty in the data itself, and the error due to uncertain calibration of
the image scale. Based on 46 pairs of binary star observations for 5 stars,
each pair separated in time by one day to one month, McAlister has computed
errors. One observation is defined as the result from a single fifty frame
set of speckle photos. For this data (with binary separations of 0.2" to
3".25) McAlister concludes that the error due to basic uncertainty in the
data is $\pm$ .3% in separation and $\pm$ 0°2 in position angle for each fifty frame
data set. If the calibration errors are included the angular separation
measurement reduces to $\pm$ .6%.

Calibrations of image scale and position angle are made by placing a
double slit with known slit separations over the telescope aperture. Since
the telescope is then effectively a two-slit interferometer, the fringe spacing
and position angle in power spectra of data taken through this slit provides
accurate calibrations of angular separations and position angles. Calibrations
are generally made only several times per night. If a set of built-in

calibration double slits were used to calibrate each star after every

observation, calibration errors could be reduced to much less than the

inherent error in the data. For binaries with separations less than

1", accuracies of ± ".002 are already obtainable and accuracies of

± ".1 are obainable for stars of 5" separation, in single observations.

A similar level of accuracy has been obtained using the Amplitude

Interferometer for the measurement of stellar diameters (Currie, 1976).

Although such measurements are not identical to the binary measurements

this does provide an evaluation of the general ability of the amplitude

interferometer to obtain high accuracy. The reproductivity in angular

diameters from one year to the next on the stable stars is of the order

of one to two milliarcseconds. Most of this error may be related to

aspects of the current Amplitude Interferometer with a single pair of

apertures and would not occur in the Multi-Aperture Amplitude Interferometer

(MAAI). The MAAI has been used to resolve of stellar diameters as

small as 10 milliarcseconds, and is expected to provide 5 milliarcseconds

on the 5-meter telescope or 33 milliarcseconds on a 60-inch telescope.

McAlister ahs computed possible external errors in his results by

comparing binary orbits he has derived from speckle interferometry with

high quality published orbits. He concludes that speckle orbits match

the published orbits to within the accuracies of these orbits, this re-

sult precludes large systematic errors in speckle binary star measurements.

The above analysis for speckle interferometry is based on photographic

data recording systems. An advanced photoelectric data acquisition system

has several advantages. Since the new systems run at essentially television rates (60 frames per second), a single fifty frame sample takes less than 1 second to obtain! McAlister observes about 150 stars per night with several minutes spent on each star. We might expect that fifty observations of five minutes duration would be possible in an observing session with a dedicated telescope. If we assume errors may be reduced as the square root of observing time then the over 10^4 fifty frame data sets obtained per year would refine the accuracies a factor of 10^2 over the McAlister's values. This corresponds to 2×10^{-5} arc second per year on binaries with separations smaller than 1 arc second and 10^{-4} arc second per year on a binary with five arc seconds separation. The higher quantum efficiency and linearity of the digital system should indicate that these numbers apply to stars brighter than about +9, as compared to McAlister's limit of +7. The accuracies on binaries near the faint limit at +14 would probably be a factor of ten worse for the same observing time.

The isoplanatic angle is another limitation. Conventional wisdom, not based on many real observations, places the isoplanatic angle at about 3 arc-seconds, meaning interferometry of binary stars with separations much larger than this would be impossible. However, recent measurements by McAlister (1979) and Hubbard et al (1979) of binary stars with larger separations places this angle closer to 6 arc-seconds and perhaps as large as 10 arc-seconds. It may therefore be possible to use as a reference star an unrelated background star rather than the other binary component. This may extend interferometric position determinations to wider binaries and some single stars.

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Photographic speckle systems have been limited to binary stars where the two components are within five magnitudes of each other. Photoelectric systems may extend this limit to 7 or 8 magnitudes. However, the requirement of two photons in each exposure may practically limit one to systems where both stars are brighter than + 16 magnitudes.

The maximum size of the detector array is another possible limitation. Since we desire to oversample the telescope diffraction spot size by at least a factor of four and to cover 10" on the sky we would need a 700 x 700 element array for a 2 meter aperture telescope (diffraction limit ".06). However, 800 x 800 element arrays are to become available soon, so detector size should not limit speckle interferometry.

V.   SUITABLE TARGET BINARY SYSTEMS

In this section we examine a set of possible program binary systems
and discuss detection probability. As a data source we have used Gliese's
Catalogue of Nearby Stars (1969) which includes all stars with known
parallaxes equal to, or greater than ".045, plus borderline cases.

There is some conjecture that binary star formation inhibits
planet formation. However, definitive models for planetary formation
are not available. At present, there is absolutely no reason to,
a priori, dismiss binary systems as possible planetary systems. It
is of particular interest to study the frequency of these occurances
and mass distribution of companions in order to further illuminate
the physical processes of star formation and of planetary system
formation. Moreover, the extensive satellite systems of Jupiter
and Saturn point strongly to the hiarchial formation of such systems.
There are, however, dynamical constraints on possible planetary orbits
in binary systems. Harrington (1977) has examined dynamical stability
of a planetary third body in a binary system in terms of the restricted
three body problem. He concludes that stable planetary orbits are
possible in two classes of binary systems: Those in which the planetary
orbit is large compared to the binary orbit, and those in which it is
small. In both cases the planetary orbit must be a factor of three to
four larger (or smaller) than the maximum (or minimum) binary separation.
Since there are no detectable effects of a planet in the case where the

binary separation is small compared to the planetary orbit we restrict
our discussion to the opposite case. If we use Jupiter's orbit at
approximately 5 AU radius as a benchmark we can examine which binaries
may have a stable Jovian orbit. Table I lists the separations for a
stable Jovian orbit as a function of parallax.

Table I

Angular Size of Binary Orbits for a Stable Jovian Orbit

Parallax ("):	Size of Jovian Orbit (")	Minimum Binary Orbit Size for Stable Jovian Orbit (")
.2	1.000	4.000
.1	.500	2.00
.075	.375	1.500
.050	.250	1.00

Table II shows the effects of a Jovian planet ($m = 10^{-3}M_\theta$) in a Jovian
orbit (5 AU) and a large terestrial planet ($m = 10^{-5}M_\theta = 3M_\bullet$) at 1 AU.
These effects are shown as a function of the reflex motion on a solar
type primary (1 M_θ) and a late type M dwarf (.15 M_θ).

Table II

Effects of Planets on the Primary Star
Orbital Amplitude as a Function of Distance

Parallax (")	$10^{-3}M_\odot$ Effect on $1M_\odot$ (")	$10^{-3}M_\odot$ Effect on $.15M_\odot$ (")	$10^{-5}M_\odot$ Effect on $1M_\odot$ (")	$10^{-5}M_\odot$ Effect on $.15M_\odot$ (")
.2	2×10^{-3}	1.3×10^{-2}	2×10^{-6}	2.6×10^{-5}
.1	1×10^{-3}	6.7×10^{-3}	1×10^{-6}	1.3×10^{-5}
.075	7.7×10^{-4}	5×10^{-3}	7.5×10^{-7}	9.7×10^{-6}
.050	5×10^{-4}	3.3×10^{-3}	5×10^{-7}	6.5×10^{-6}

Based on the calculations of 10^{-4} arc-second accuracy in section IV. We see that Jovian planets are detectable for all binary separations out to 20 pc. In the special case of nearby M dwarf stars it may even be possible to detect large terrestrial planets.

In the Gliese (1969) catalog there are 248 star systems with binary separations between ".2 and 15".0. 188 of these systems lie north of -30°. In Table III we list the binary separation distributions for these 188 star systems.

Table III

Binary Separations of Stars North of -30° in the Gliese Catalog

Separation (")	Number of Systems
.2 - .5	23
.5 - 2.0	64
2.0 - 6.0	64
6.0 - 10.0	19
10.0 - 15.0	18

Table IV lists the parallax distributions of these 188 systems.

Table IV

Parallaxes of Northern Binary Stars with Separations

Less Than 15" in the Gliese Catalog

Parallax (")	Number of Systems
> .200	9
.200 - .100	24
.100 - .075	21
.075 - .050	76
< .050	58

Using Harringtons stability criterion we find that roughly half of the 188 systems would have a stable Jovian orbit, while almost all of them would have a stable terrestrial orbit. The sample therefore permits large numbers of planetary orbits at distances similar to those in the solar system.

For the 182 systems which list magnitudes for both components we report the following magnitude differencies between the two components.

Table V

Magnitude Differences for 182 Northern Binary Systems
in the Gliese Catalog

Δm	Number of Systems
0 - 1	74
1 - 3	48
3 - 5	28
> 5	32

Almost half of the systems have nearly equal magnitudes, while 82% have less than the 5 magnitude difference needed for the present photographic system. These magnitude differences should be about 1 magnitude less if observations were made around 8000Å, since the secondary is almost invariably redder than the primary. The magnitudes for 375 of the component stars are in Table VI.

Table VI

Magnitudes of Component Stars in Northern Gliese Catalog Binary Stars

Apparent V Magnetude	Number of Stars
0 - 5	35
5 - 7	79
7 - 9	68
9 - 11	90
11 - 13	74
> 13	29

50% are brighter than +9, the magnitude limit for the maximum accuracy. 251 of these stars have spectral classification which are catalogued in Table VII.

Table VII

Spectral Types of Northern Gliese Catalog Binary Stars

Spectral Type	Number of Stars
A	10
F	40
G	43
K	59
M	99

As may be expected, the spectral types, which are generally for the primary component only, are weighted heavily toward M types. The secondary components should be weighted even more heavily towards later spectral types. Almost all of these stars are main sequence (Luminosity Class V), 16 are subgiants (Luminosity Class IV), 2 are giants (Luminosity Class III).

We conclude that there are a sizeable sample of binary candidates for planetary detection. Even if we apply the restrictive requirements that one component be brighter than +9, that the system have a stable Jovian orbit, that the magnitude difference be less than $\Delta m = 5$, and that the separation be less than 6", we have nearly fourty candidate systems.

We hasten to note that the results of a systematic long term search of these systems would be extremely valuable in their astrophysical importance. Orbits derived from the binary orbits which would be a by-product of a planetary search allow a very accurate calibration of lower main sequence masses, and solar neighborhood distance scale. The program should also turn up large numbers of low mass, but not planetary, stellar components. This data will be essential for calibrating binary star mass functions.

VI. A DEDICATED INTERFEROMETRIC TELESCOPE

To study over 100 binary systems to the accuracy desired requires substantial time on a large telescope. In this section we discuss the possibilities for a low cost telescope which could serve as a dedicated interferometric instrument. Such an instrument may also be usable for other aspects of a planetary detection program, such as certain radial velocity programs.

With the advent of computer controlled telescopes and lightweight optics, telescope costs may be substantially reduced. The University of Wyoming recently constructed a computer controlled 92" telescope for 1.8 million dollars. We include here a design proposed by the Kitt Peak National Observatory for a low cost 2-meter telescope which serves as an example of an instrument which could serve as a dedicated interferometric telescope. We provide the preliminary discussion of this instrument in Appendix A. Telescope drawings are shown in Figure 15. The Nasmyth foci are particularly appealing since they eliminate flexure changes in the instrument as the telescope moves to different positions on the sky. This feature is desirable for both interferometric and spectroscopic instruments. The design shown has several features which are not needed for a planetary detection telescope, such as a chopping secondary or prime focus capability. These items could be eliminated to save costs. Kitt Peak's cost estimates are shown in Table VIII. The estimates for constructing a digital speckle camera are based on an Air Force Geophysics Laboratory program to construct such a device at the University of Arizona.

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It is recommended that the detached telescope be used with both
a multi-aperture amplitude interferometer and a speckle interferometer.
While there are unique advantages and classes of separation which may
be done with each separately, there is a large domain which they may
confirm each other and detect systematic errors which occur with both.
The speckle interferometer is less expensive and less
complicated to operate. On the other hand, the multi-aperture amplitude
interferometer has a resolution which is almost a factor of 2 larger,
it is less affected by atmospheric phenomena, and has a much simpler
data reduction. However, it may not work in as bad seeing as the speckle
interferometer.   The data obtained by the two techniques are signi-
ficantly independent. The question of ultimate sensitivity and limiting
magnitude will primarily involve the modes of implementation but the
ultimate sensitivity and accuracy of the two systems should be comparable.

The construction costs for a dedicated interferometric facility
should be less than 1.4 million dollars. Operating costs may be estimated
based on costs for the Sacramento Peak Observatories operation of a dedicated
photometric 48" telescope in Cloudcroft, New Mexico. The annual operating
costs for this instrument are $170,000 per year. Operating costs for a
dedicated interferometric telescope, including observers, data reduction
personnel, and maintainance personnel should be similar.

SUMMARY

We have shown that a small aperture stellar interferometry can obtain accuracies of better than 10^{-4} arc-seconds per year on binary star orbits. There are 188 accessable binary star systems within 20 pc of the sun. About half of these systems should have stable orbits for a Jovian type planet which would be easily detectable with the accuracies possible. We have discussed a possible interferometric system for observing these binaries. A dedicated interferometry telescope could be contructed for 1.4 million dollars and operated for $170,000 per year.

We conclude that stellar interferometry is a viable option for detecting extra-solar planets, and it is an option which could be easily implemented. In fact, interferometry is ideal for precisely those systems which conventional astrometry has some difficulty, the close binary systems.

Table VIII

Estimated Costs for A Low Cost
Dedicated Interferometry Facility

I. Telescope and Building (Kitt Peak Estimates)

	Budget Estimates ($1000 units)
Optics	200
Optics Support	50
Secondary Assembly	60
Tube, Altitude Bearings	100
Azimuth Yoke and Bearings	200
Drives	250
Telescope Controls (including computer which may also be used for data reduction)	100
Dome and Building	170
Miscellaneous (instrumentation, auxilliary equipment, etc.)	120
TOTAL	1250

II. Interferometer (speckle) and Data Reduction Equipment (Based on AFGL Estimates for University of Arizona Speckle System)

	Budget Estimates ($1000 units)
Optical and Mechanical Components	30
Image Intensification	20

Table VIII (continued)

Estimated Costs for A Low Cost
Dedicated Interferometry Facility

II. Interferometer (speckle) and Data Reduction Equipment (continued)

	Budget Estimates ($1000 units)
Photoelectric Array and Interface	50
Two-Dimensional Array Processor and Computer Interface	50
TOTAL	150

III. Interferometer (Amplitude) and Data Reduction Equipment (Based Upon Projections from the Current Instrument)

	Budget Estimates ($1000 Units)
Optical and Mechanical Components	80
Photodetectors	65
Two Dimensional Memory, Electronics and Computer Interface	60
TOTAL	210

Table VIII (continued)

Estimated Costs for A Low Cost

Dedicated Interferometry Facility

IV. Annual Operation and Maintainance (Based on Sacramento Peak Estimates for a Dedicated 48" Photometric Telescope)

	Budget Estimates ($1000 units)
Personnel	
2 Observers	30
1 Maintainance (electronics)	15
1 Maintainance (facility)	15
1 Astronomer	20
Overhead on Personnel	40
Utilities	25
Computer Maintainance	15
Miscellaneous Equipment	10
TOTAL	170

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APPENDIX A

Kitt Peak National Observatory
Functional Requirement and General Specifications
For New Generation 2-M Telescope

Preliminary   December 1, 1978

I. TELESCOPE

A. Introduction

The general concept is that of a low-cost, highly efficient

telescope, which does not require frequent instrument changes.

The telescope will be carefully optimized for O/IR photometry

and spectrometry. It will provide a powerful research tool

for attacking many key astronomical problems.

A number of design features are directly related to aspects of

the Next Generation Telescope (NGT)program studies, and hence,

much valuable information will be gained in support of this

program.

B. Mounting

1. The telescope shall utilize an altitude-azimuth mount configur-
    ation. (See attached concept sketch).

2. The telescope should be contained in an approximately 32-foot
    diameter dome.

C. Focus Positions

The telescope shall provide for two 3-mirror Nasmyth foci,

two 3-mirror bent Cassegrain foci (90° from the Nasmyth and not

a fixed gravity position), a 2-mirror Cassegrain, all parfocal,

and a prime focus (future).

D. Instrumentation Potential

1. Nasmyth - major fixed instruments: moderate-resolution optical spectrometer, infrared echelle spectrograph.

2. Cassegrain - lightweight instruments for O/IR photometry and spectrophotometry.

3. Prime - cooled solid-state detector arrays.

4. Provision for acquisition TV's should be provided for all foci.

5. Field rotation compensation by instrument rotation will be included at Cassegrain and prime focus. The optical Nasmyth position will have instrumentation or field rotation as part of the instrument package.

E. Optics

1. The design shall incorporate a primary mirror of at least 2-m diameter and provide the following nominal focal ratios:

   Prime   f/1.5 with 10' (9 mm) field of view.
                          Scale 15 μ/1".

   Nasmyth, Cassgrain   f/15 with 5' (44 mm) field of view.
                          Scale 145 μ/1".

2. The design of the upper structures of the tube will provide for easy interchangeability of several specialized structures. These will include:

   a) f/15 chopping secondary with or without sky baffles

   b) prime focus structure

   c) other Cassegrain/Nasmyth secondaries, fixed or chopping, f/15 or slower

Only the f/15 chopping secondary shall be provided with the initial telescope facility.

3. The f/15 secondary mirror shall be undersized, using a diameter of (TBD) cm of the primary mirror, thereby providing a 2.5 cm-wide low-emissivity ring around the main part of the primary.

4. For infrared observations, the secondary shall be physically larger in diameter than its associated supporting structure.

5. For optical observations, easily removable sky baffles around the secondary shall be provided. Provision for baffling elsewhere may be required.

6. The telescope design shall provide for easy checking and alignment of the optical axis of the various foci.

7. The telescope design shall provide for easy washing and cleaning of the optical components.

8. Provision for easy removal of the tertiary for use of the 2-mirror Cassegrain shall be provided. Future tertiaries with internal fused silica prisms for visual work are possible and should be allowed for.

F. Environment

The telescope must be fully functional with no degradation of specifications under typical ambient conditions found on Kitt Peak: 10-90° F, 2-99% RH, 0-25 mph wind (shutdown at 40 mph).

II. PERFORMANCE SPECIFICATIONS

A. Optical Quality

At the Cassegrain/Nasmyth foci, 90% of the light from (TBD) cm diameter shall fall within a circle of $0\overset{\frown}{.}6$ in diameter at a wavelength of $0.5\,\mu$ for zenith angles less than $60°$. Neglecting diffraction and obscuration, 99.5% of the light shall fall within a circle of diameter $1\overset{\frown}{.}0$. For a zenith angle of $80°$, image quality shall not degrade to more than twice the above specifications.

B. Sky Coverage

1. No structure shall vignette the telescope above $10°$ from the horizontal in any direction.

2. Azimuth rotation of $+270°$ from the south shall be allowed for.

3. Electrical limit switches and mechanical stops shall be provided as necessary for telescope protection.

C. Absolute Pointing Accuracy

The absolute pointing error goal shall be $0\overset{\frown}{.}5$ rms for zenith angles less than $60°$. The 24-hour repeatability shall be better than 1".

D. Tracking

The goal shall be tracking an object to within $0\overset{\frown}{.}1$ rms for periods of time up to 2 hours for zenith angles less than $60°$.

E. Motions

1. The slewing speeds shall be at least 2°/second.

2. Tracking speeds shall be at least 0°5/second.

3. Setups on a new object within 90° should be possible within a time of 2 minutes.

F. Cone of Avoidance at the Zenith

The telscope shall operate as specified to within 5° of the zenith.

G. Chopping Secondary Characteristics

1. Chopping direction: Remotely adjustable 270° from the center position and should include the capability for automatic field rotation compensation.

2. Amplitude: Remotely adjustable continuously from zero to 3'.

3. Frequency: 0 to 40 Hz.

4. Performance: For a chopping amplitude of 20". the 10-90% rise time will be < 3 msec with < 1% overshoot.

H. Nasmyth Platforms

Size (TBD, at least 5 feet long beyond focus, 8 feet is preferable); instrument weight limits (TBD); location of best focus (TBD, at least 18 inches beyond bearing); instrumentation, electrical, vacuum, displays, controls, and other needs (TBD).

STAR 1   STAR 2

ATMOSPHERIC
TURBULENCE

α

ISOPLANATIC
ANGLE

TELESCOPE
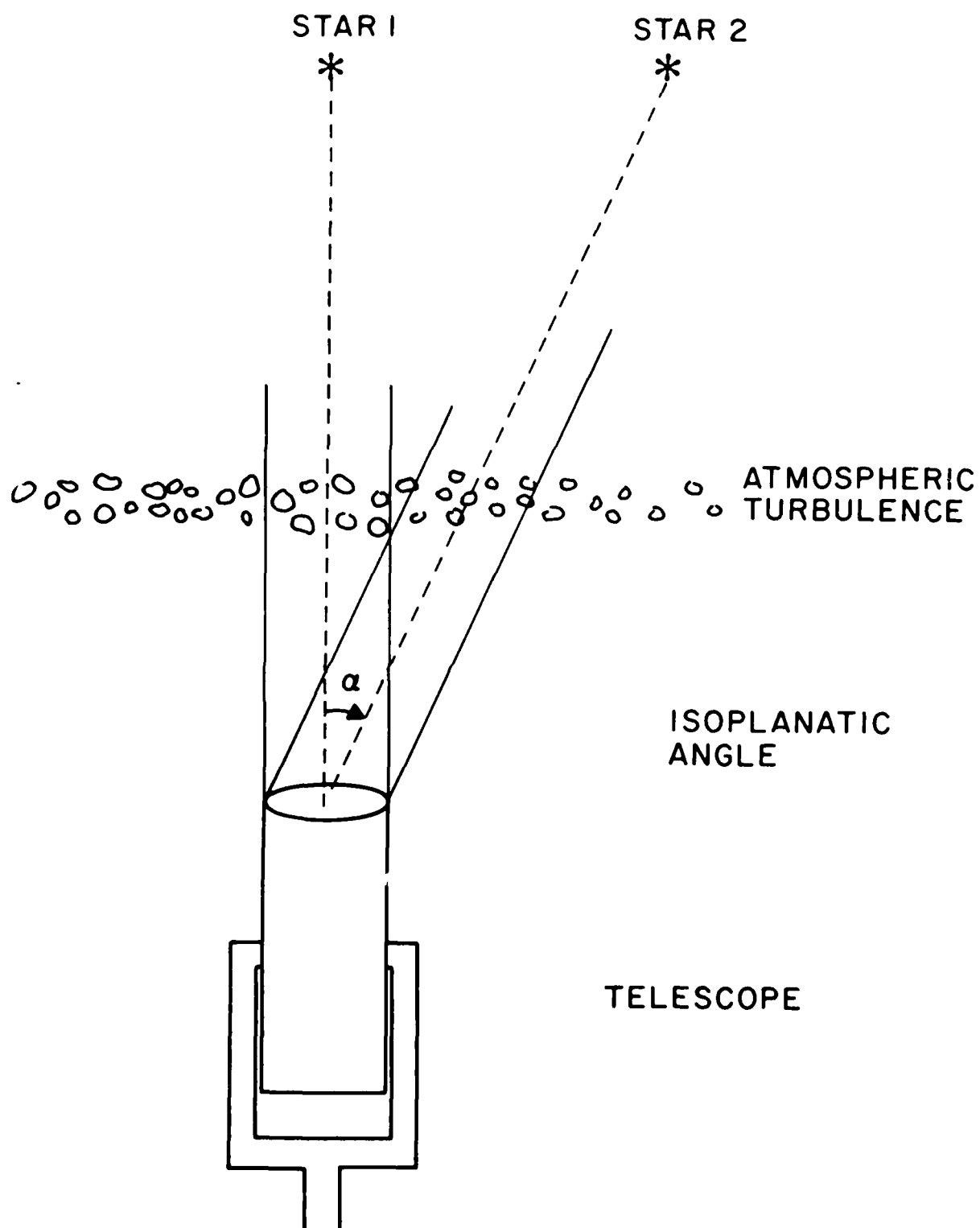
Figure 1.- The isoplanatic angle - the maximum angle separating two objects so
that light from the two objects passes through the same column of turbulent
atmosphere.
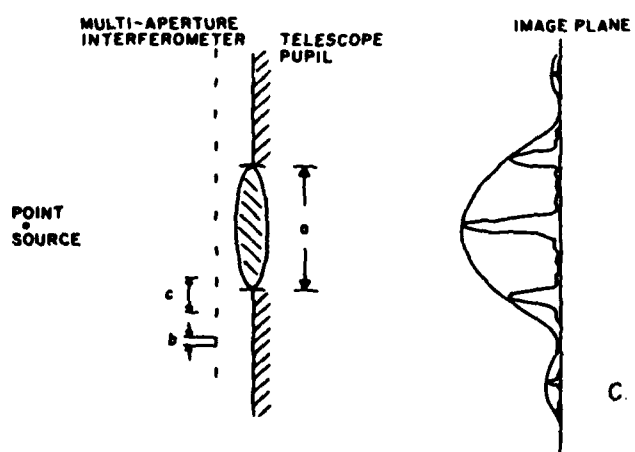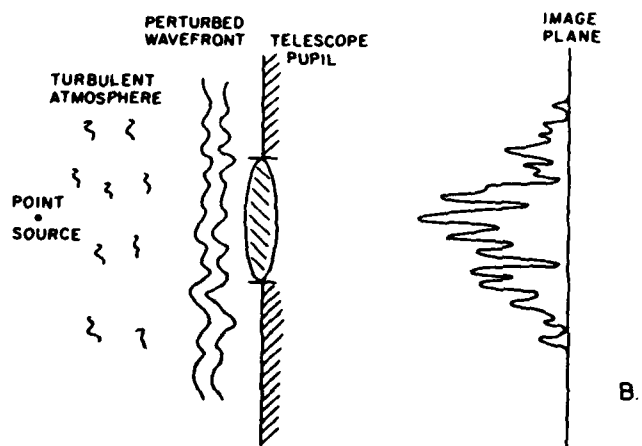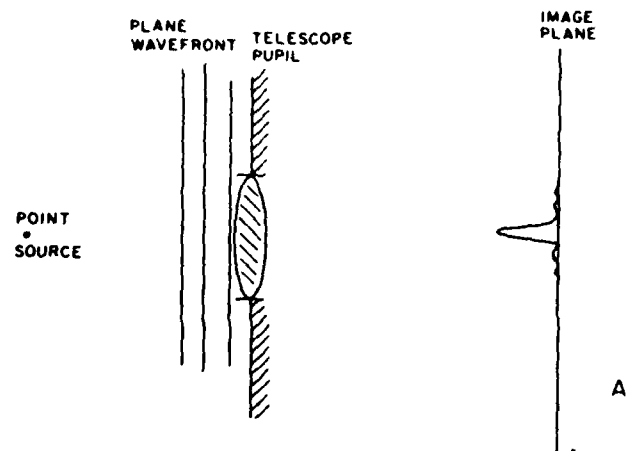
Figure 2.- Schematic diagram of image formation through a turbulent atmosphere. (a) Image formation outside the atmosphere; the image is diffraction limited.
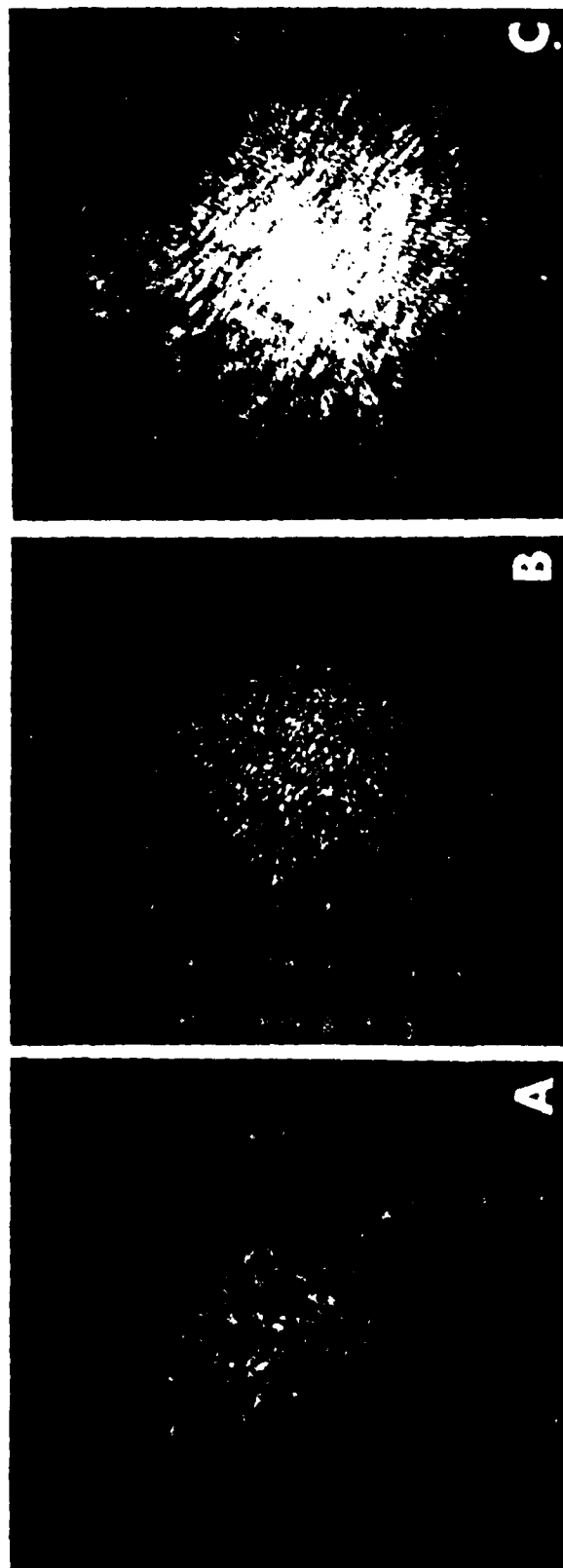
40

Figure 3.- Speckle photographs for three stars from the Kitt Peak 4-m telescope. Note the different character for the three objects. (a) The resolved supergiant star α Orionis (Betelgeuse), (b) a point source star γ Orionis (Bellatrix), (c) a close double star, separation ".05 ι Aurigɑ (Capella).

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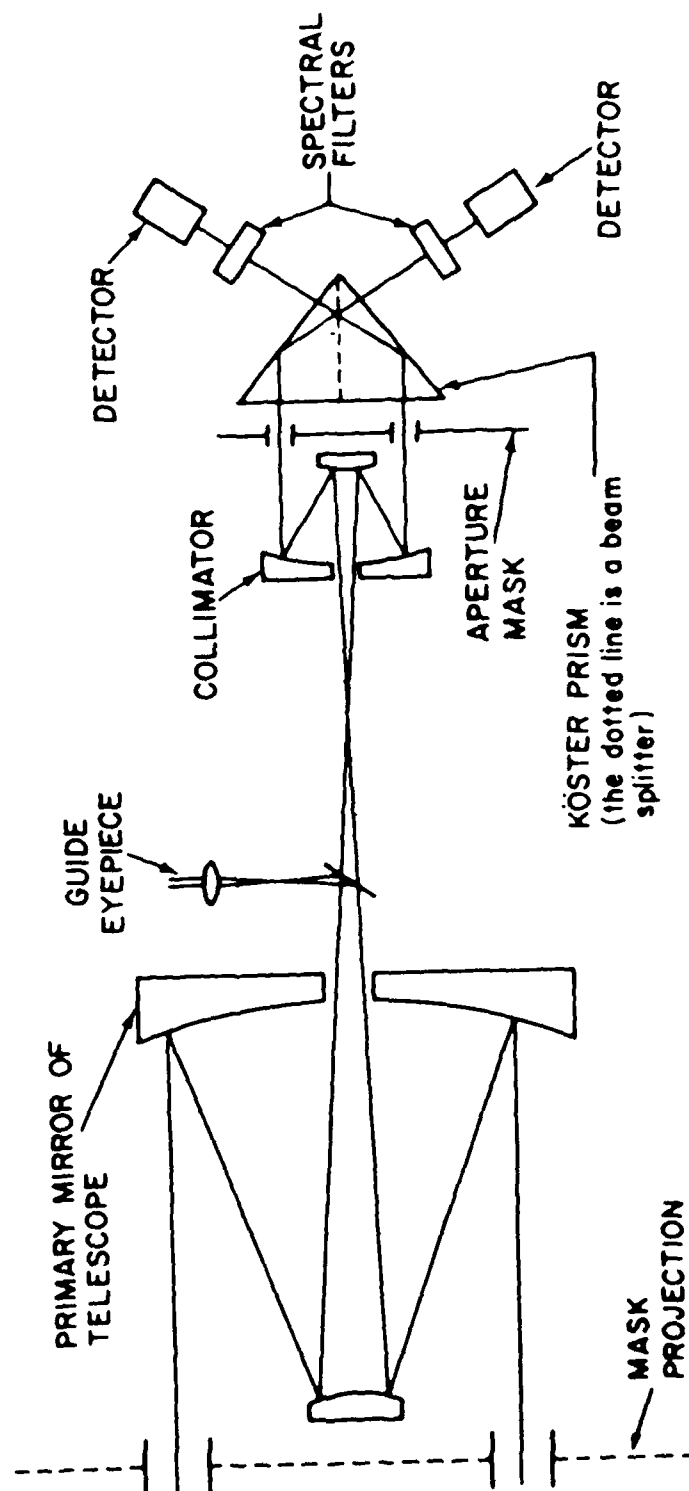
Figure 4.- A diagram of Currie's amplitude interferometer.
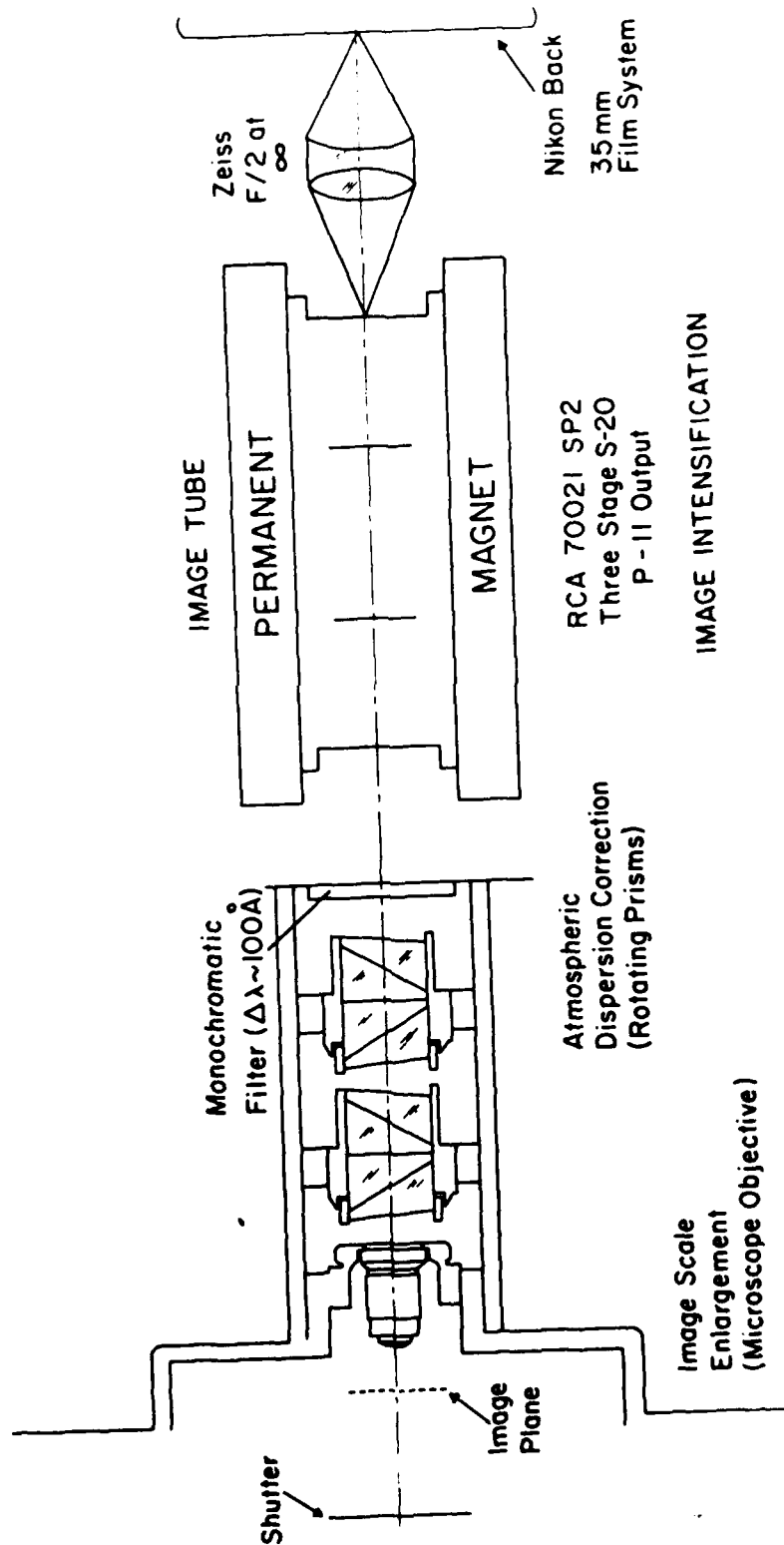
Figure 5.- A diagram of Kitt Peak's photographic speckle interferometry camera.

Shutter

Image Plane

Image Scale
Enlargement
(Microscope Objective)

Monochromatic
Filter (Δλ~100Å)

Atmospheric
Dispersion Correction
(Rotating Prisms)

IMAGE TUBE

PERMANENT

MAGNET

RCA 70021 SP2
Three Stage S-20
P-11 Output

IMAGE INTENSIFICATION

Zeiss
F/2 at
∞

Nikon Back

35mm
Film System
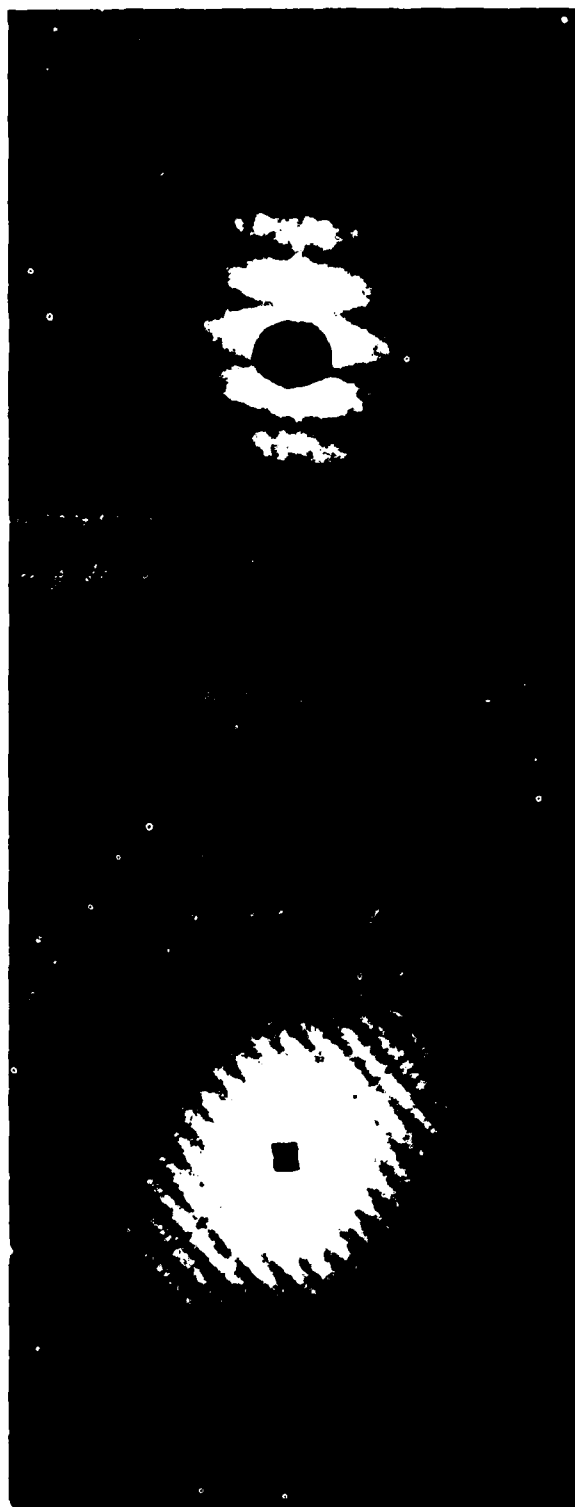
Figure 6.- Mean speckle power spectra for two binary stars. The larger separated fringes are those of Serpertis (separation "1), the smaller fringes are those of...
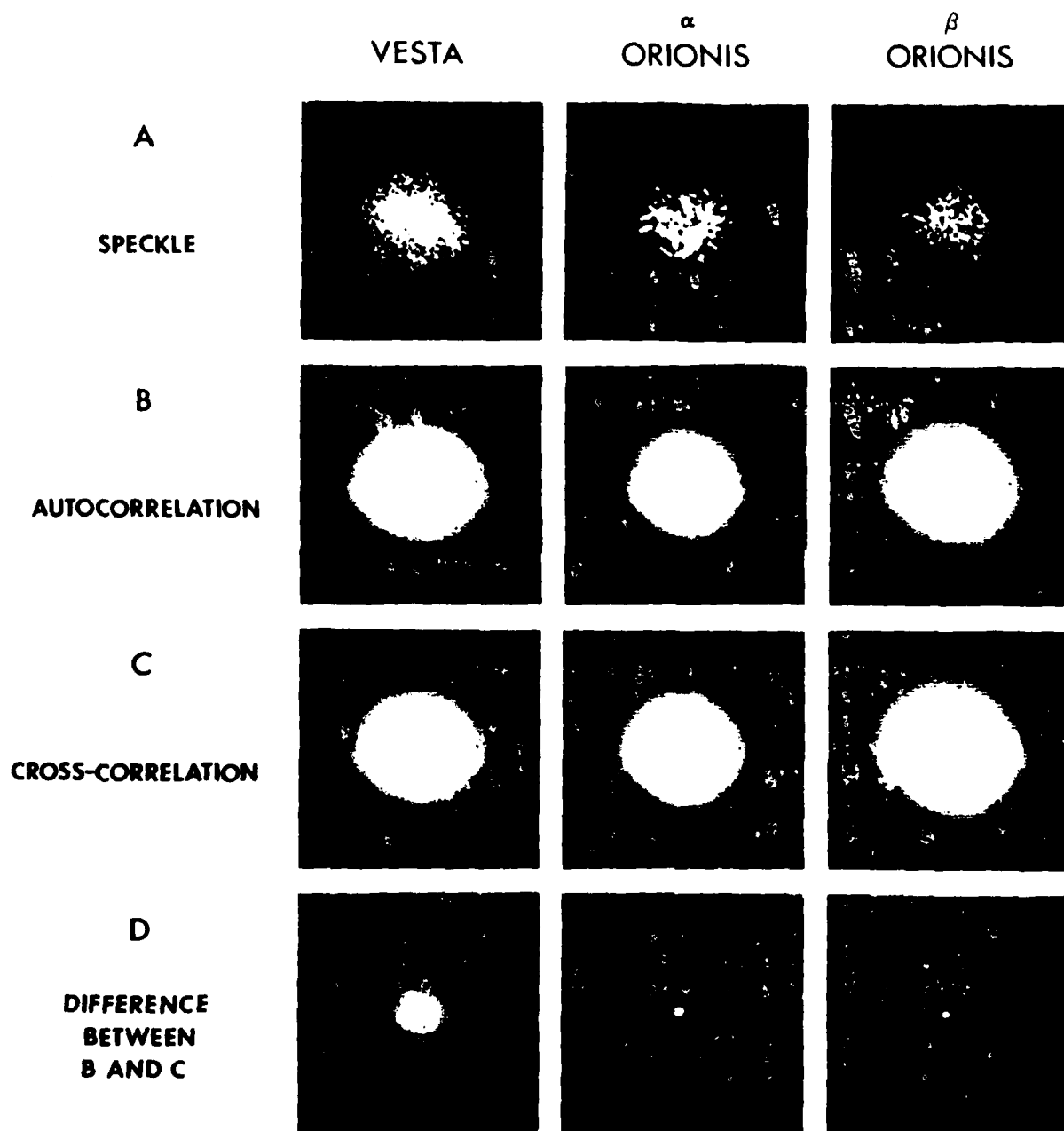
Figure 7.- Schematic representation of Worden et al. (1977) method for reducing the effects of seeing in final speckle interferometry results.
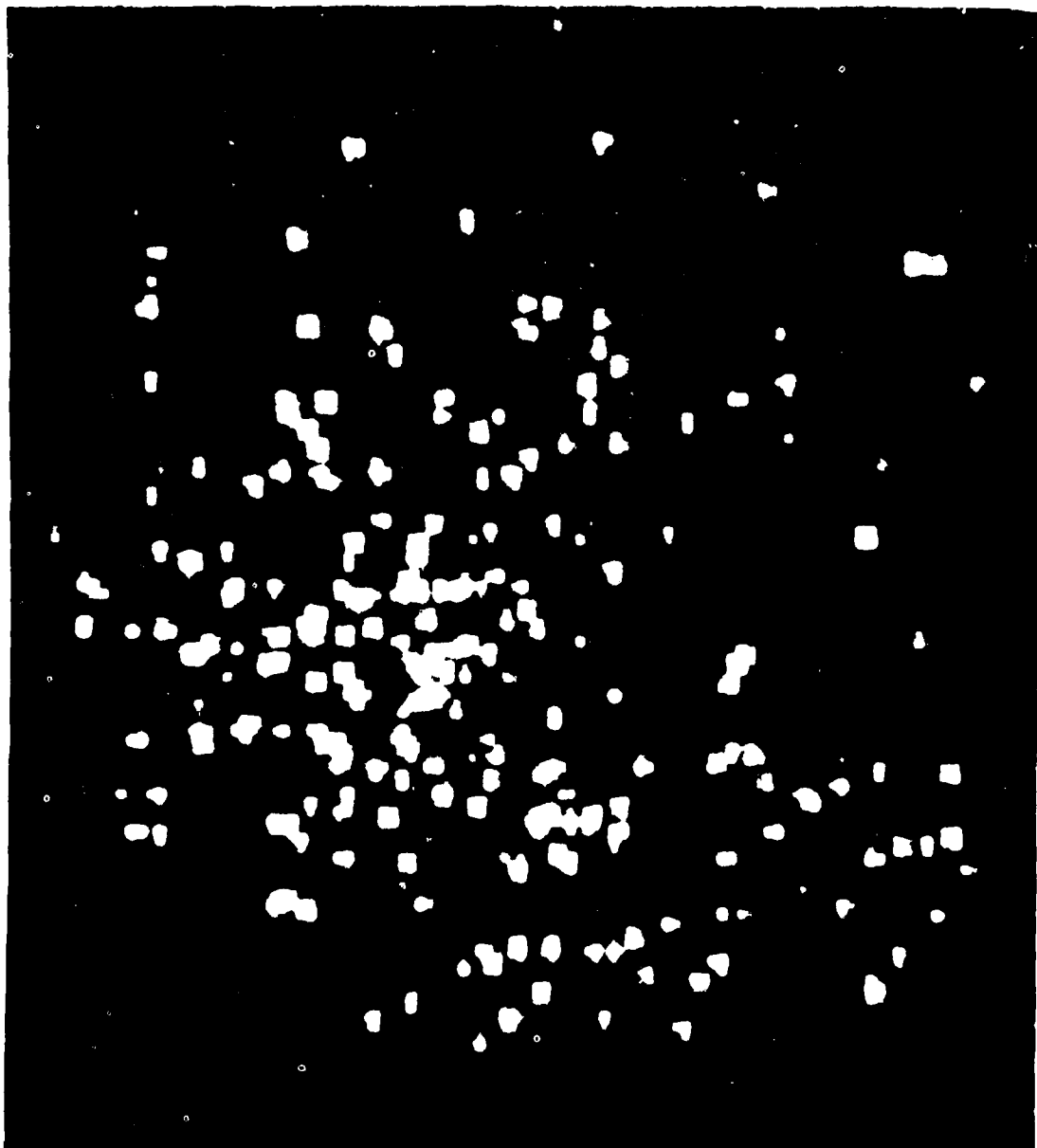
Figure 8.- Speckle data showing individual photons for Saturn's moon Rhea
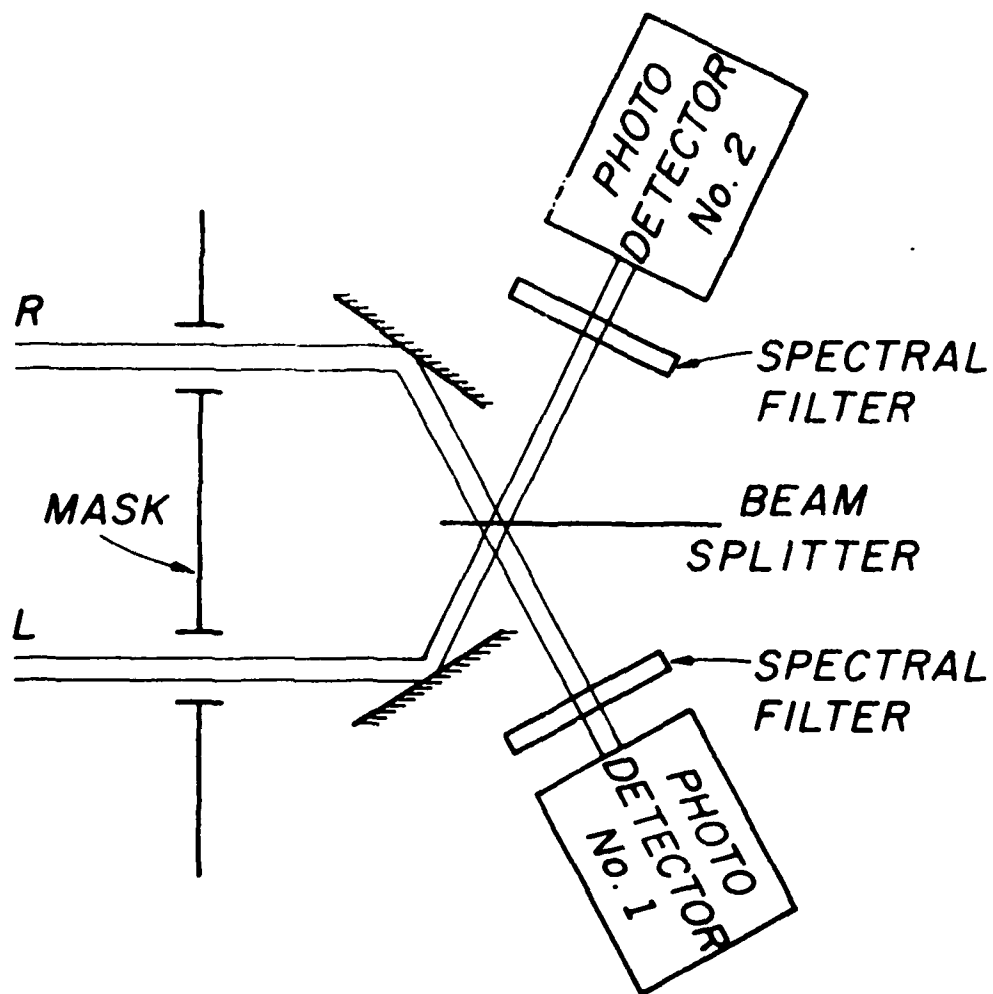(M. 10) taken with University of Arizona CID speckle camera.

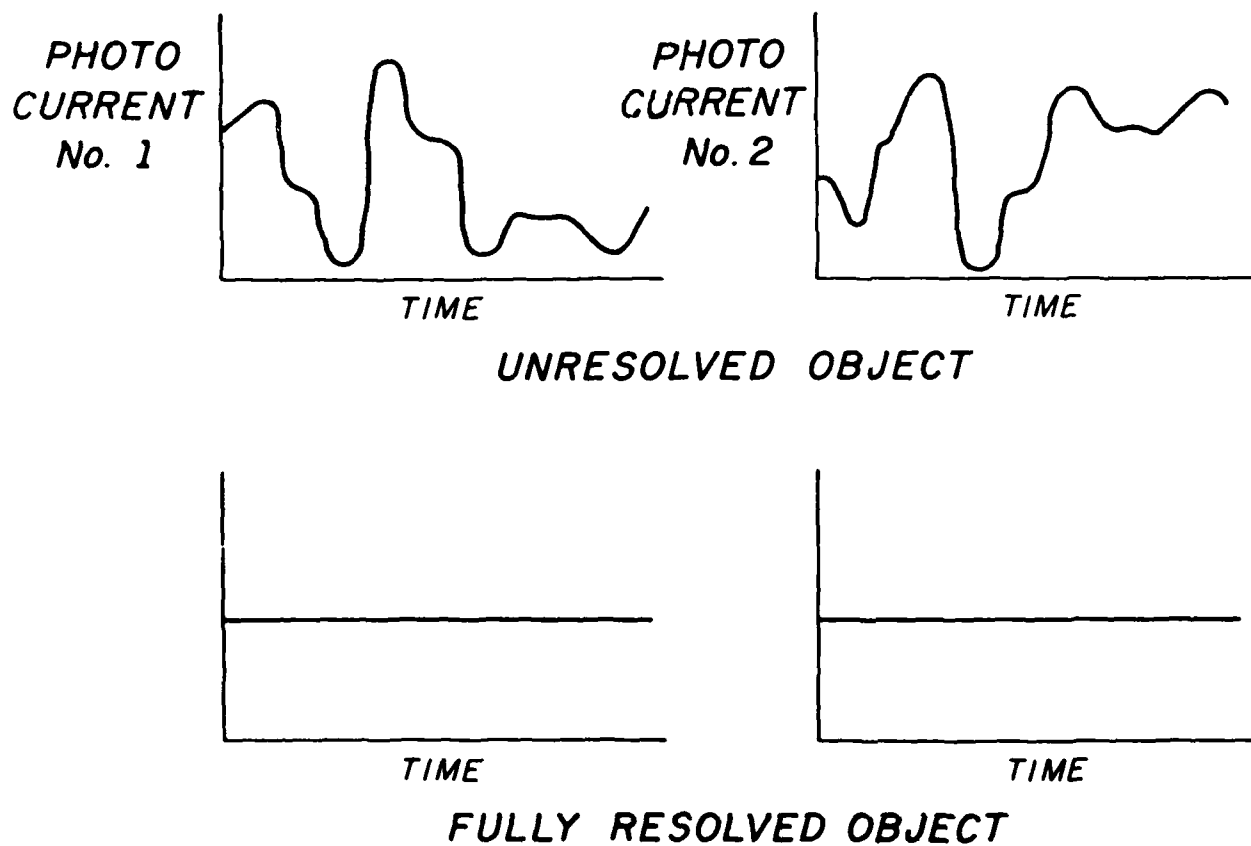Figure 9.- Combination of the starlight from the separate apertures for an Amplitude Interferometer.

Figure 10.- Variation of photomultiplier outputs for a bright source with high coherency and low coherency in a two-beam Amplitude Interferometer.
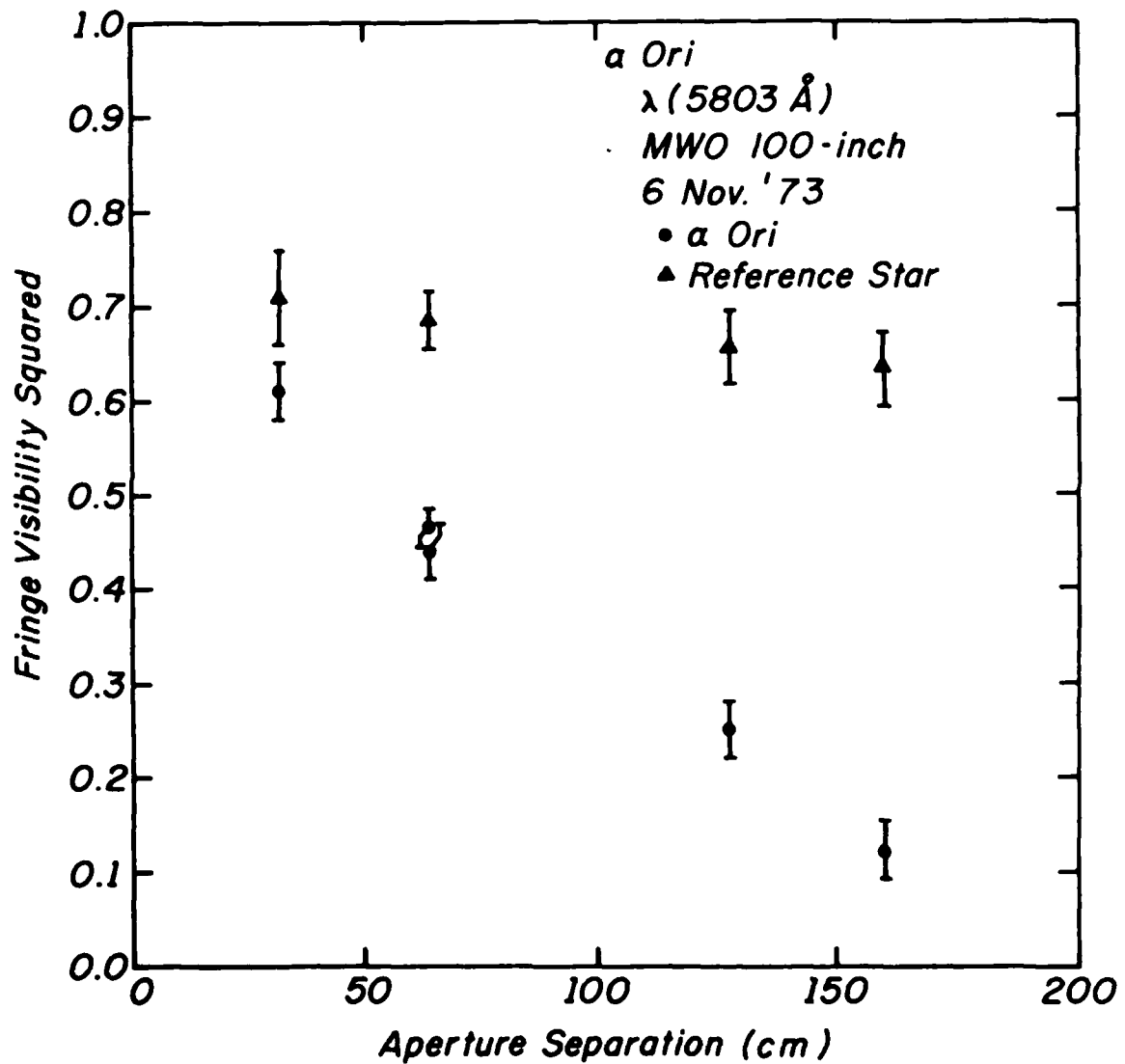
a Ori
λ(5803 Å)
MWO 100-inch
6 Nov. '73
• a Ori
▲ Reference Star

Fringe Visibility Squared

Aperture Separation (cm)

Figure 11.- Amplitude Interferometer outputs for a resolved star (α Orionis) and an unresolved star.

MULTI-ELEMENT
PHOTO DETECTOR

KÖSTER PRISM

COLLIMATED BEAMS
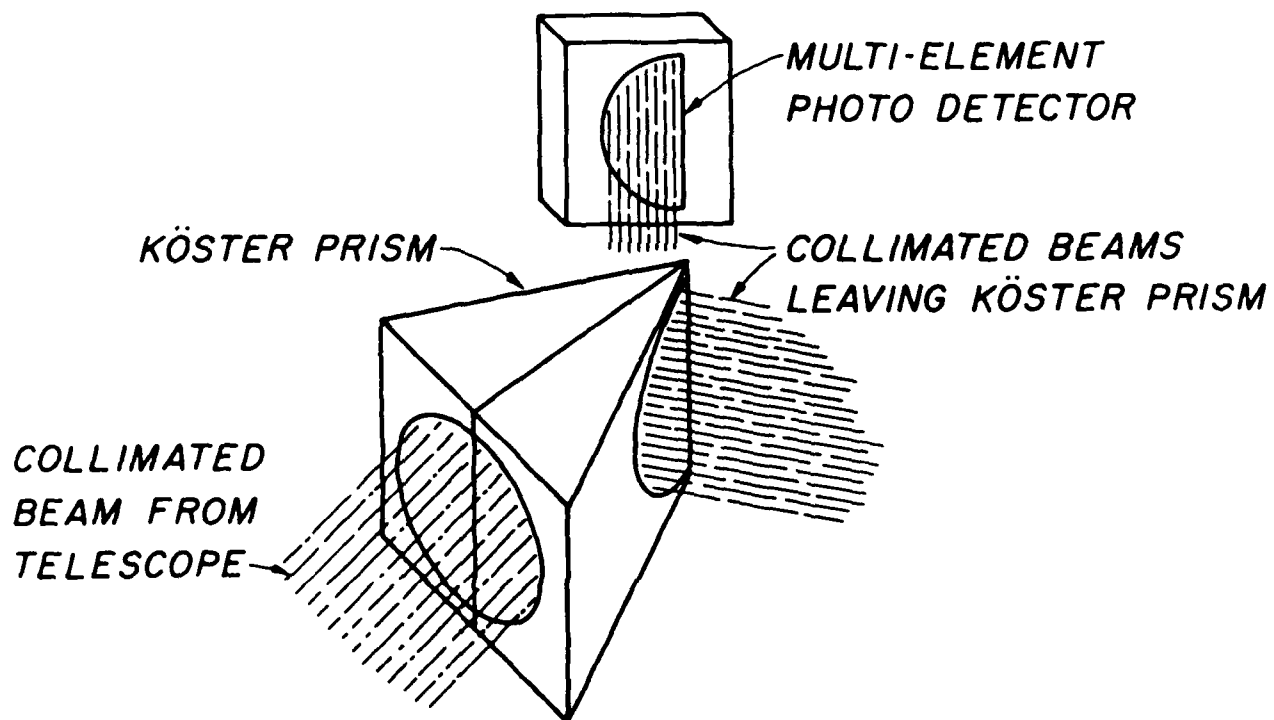LEAVING KÖSTER PRISM

COLLIMATED
BEAM FROM
TELESCOPE

Figure 12.- Multi-element detector scheme for a Multiple Aperture Amplitude
Interferometer.
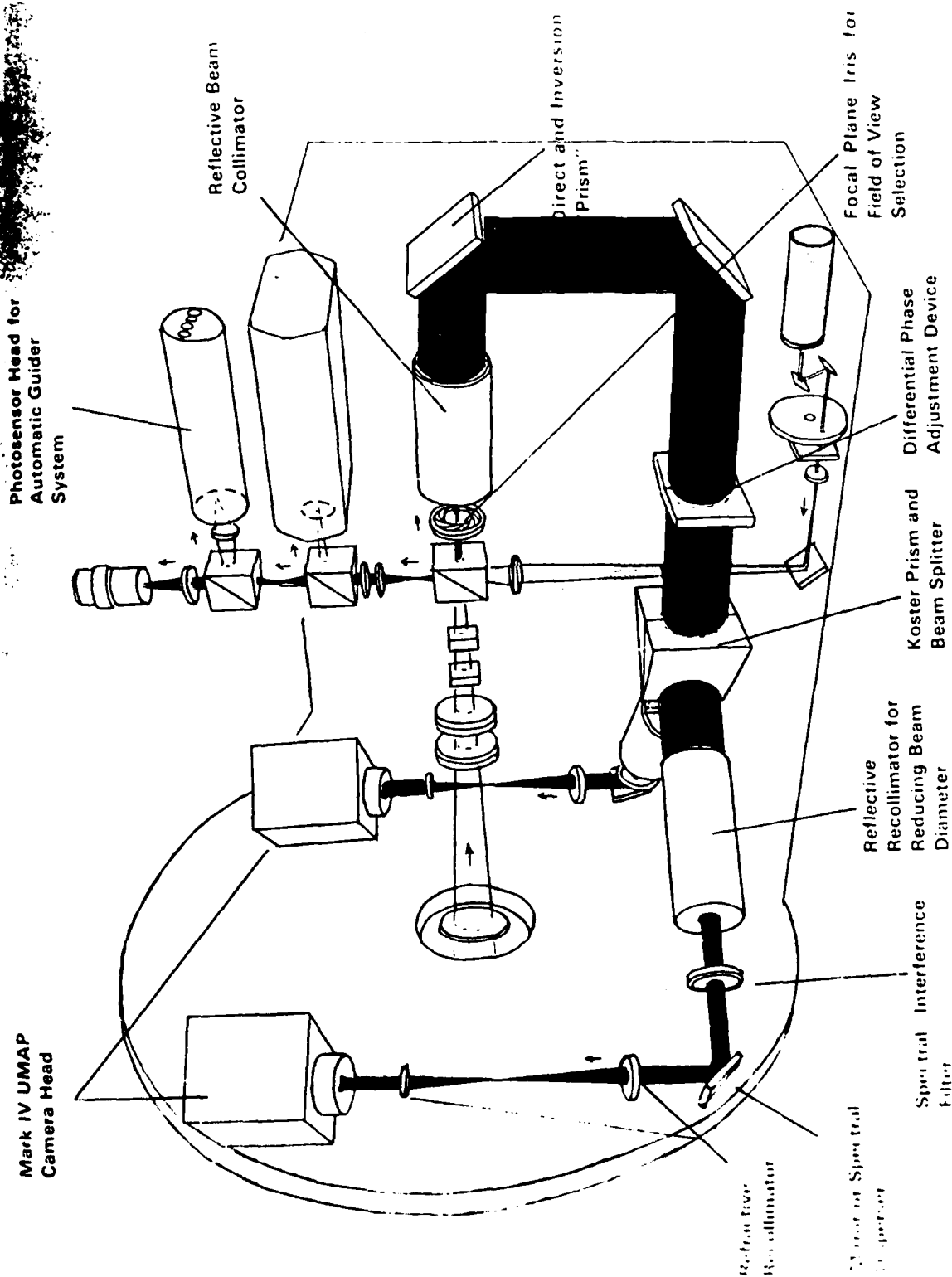
Figure 13.— Multiple aperture interferometer design.

Reflective Beam
Collimator

Direct and Inversion
Prism

Focal Plane Iris for
Field of View
Selection

Photosensor Head for
Automatic Guider
System

Differential Phase
Adjustment Device

Koster Prism and
Beam Splitter

Reflective
Recollimator for
Reducing Beam
Diameter
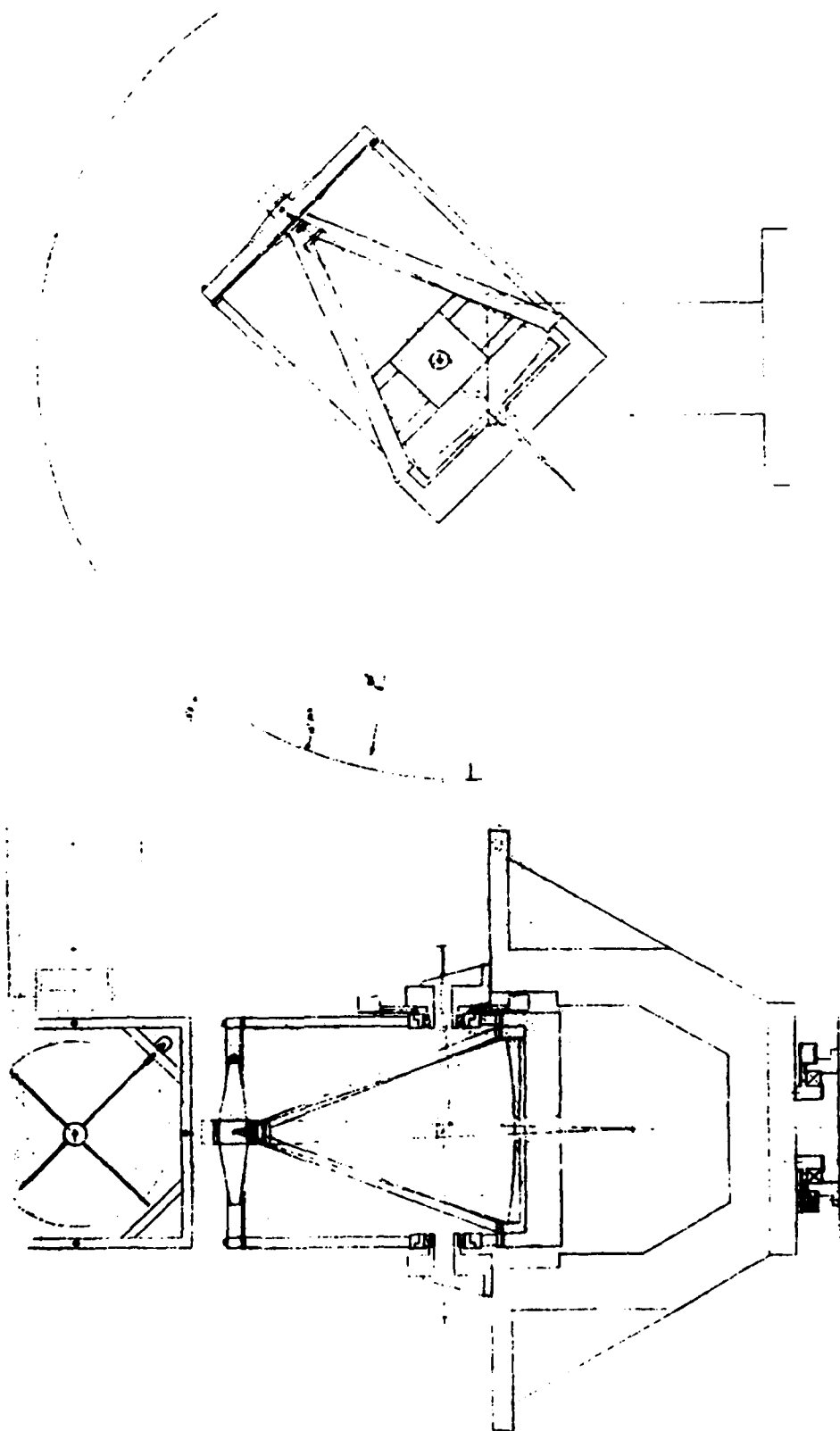
Mark IV UMAP
Camera Head

Spectral Interference
Filter

Reflective
Recollimator

Direct or Spectral
Aperture

AMPLITUDE INTERFEROMETRY PROGRAM
UNIVERSITY OF MARYLAND

Figure 14.- Photograph of a multiple aperture amplitude interferometer, as may be used in a space telescope.

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Figure 15.- Preliminary Kitt Peak National Observatory design for a low-cost 2-meter telescope.

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