(NASA-CR-163393) HIGH RESOLUTION IMAGING AT LARGE TELESCOPES (Harvard Univ.) 18 p CSCL 03A N80-29217

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G3/89 26388

KITT PEAK NATIONAL OBSERVATORY CONFERENCE

OPTICAL AND INFRARED TELESCOPES FOR THE 1990s

TUCSON, ARIZONA

7-12 JANUARY 1980

PROCEEDINGS

VOLUME I

EDITED BY

ADELAIDE HEWITT

MAY 1980

KITT PEAK NATIONAL OBSERVATORY, TUCSON, ARIZONA

HIGH RESOLUTION IMAGING AT LARGE TELESCOPES

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ABSTRACT

Image recovery at a resolution limited only by diffraction is now possible at large telescopes. We give a brief review of one approach to high resolution imaging and cite recent results to give the reader an appreciation of its current state of development. We also summarize potential applications of the process when used with very large telescopes and list the constraints on telescope design imposed by these techniques.

1. THEORY OF SPECKLE IMAGE RECONSTRUCTION

Speckle imaging is derived from speckle interferometry. In both cases the input data consist of large numbers of images recorded with the exposure times short enough to "freeze" the atmospheric blur. In speckle interferometry, spatial power spectra of the individual images are summed directly and the result is a power spectrum whose higher spatial frequency components, out to the diffraction limit, characterize, not the atmosphere or telescope aberrations, but the source. This technique is well known and has been extensively demonstrated.[1] Power spectrum analysis does not allow recovery of true images, however.

Several procedures have been devised to permit full image recovery.[2,3,4] In the one we describe here, based on a technique first suggested by Knox and Thompson,[5] the objective of obtaining a diffraction-limited fourier transform of the source, which can then be inverted to give an image, is naturally separated into two problems: finding the amplitude and finding the phase of the transform.

In this process, each image, $I(\bar{x})$, is fourier transformed $(t(\vec{\omega}))$ and the ensemble average of four separate quantities is performed:

$$< t(\vec{\omega}) > = < a(\vec{\omega})\ e^{i\phi(\vec{\omega})} > \tag{1}$$

$$< |t(\vec{\omega})|^2 > = < |a(\vec{\omega})|^2 > \tag{2}$$

$$< t^*(\vec{\omega})t(\vec{\omega} + \Delta\omega_x) > = < a(\vec{\omega})a(\vec{\omega} + \Delta\omega_x)\ e^{i[\phi(\vec{\omega} + \Delta\omega_x) - \phi(\vec{\omega})]} > \tag{3}$$

$$< t^*(\vec{\omega})t(\vec{\omega} + \Delta\omega_y > = < a(\vec{\omega})a(\vec{\omega} + \Delta\omega_y)\ e^{i[\phi(\vec{\omega} + \Delta\omega_y) - \phi(\vec{\omega})]} > \tag{4}$$

where

$t(\vec{\omega}) = \int I(\vec{x})e^{-i\vec{\omega}\vec{x}}\,d\vec{x}$, and < > is the expected value.

In the first quantity, the effects of image shifts are removed from the fourier transform phase before ensemble averaging. This yields the recentered direct sum which is used both for reweighting the low frequencies in reconstruction and for estimating the biases introduced by photon noise.

The second quantity is the standard speckle power spectrum, from which the reconstruction amplitudes are obtained.

The third and fourth quantities are used to save and ensemble average the transform phases. $\Delta\omega_x$ and $\Delta\omega_y$ may be arbitrarily chosen to be small enough so the phases in each realization of quantities (3) and (4) never exceed π (or $\pm \pi/2$). This avoids 2π ambiguities during the ensemble averaging and allows the phase errors introduced by atmospheric aberrations to average to zero. After averaging, the "phase differences" obtained in this way must be reintegrated to obtain the reconstruction phases, and since there is always residual noise after averaging, we have found it useful to use an iterative least squares fitting technique such as that developed for active optical systems.[6] This approach uses the redundancy in the fourier transform to average out errors in any given phase path. The phases thus derived are then combined with the reweighted amplitudes, obtained from quantities (1) and (2), to produce the reconstruction fourier transform, which is finally retransformed to obtain an image. A flow diagram of the entire process is shown in Figure 1. The bias subtraction operation refers to compensation for photon noise and only applies in the low light level regime.

2. CURRENT STATUS

Our recent work has concentrated on algorithm testing, processing of actual data, and development and testing of a video recording and digitization system.

Laboratory tests have successfully demonstrated the aberration insensitivity of the process and its usefulness at low light levels.

Figure 2 is a demonstration of the reconstruction procedure at a relatively high light level. 2a-b show the input test object, the

SPECKLE IMAGE RECONSTRUCTION

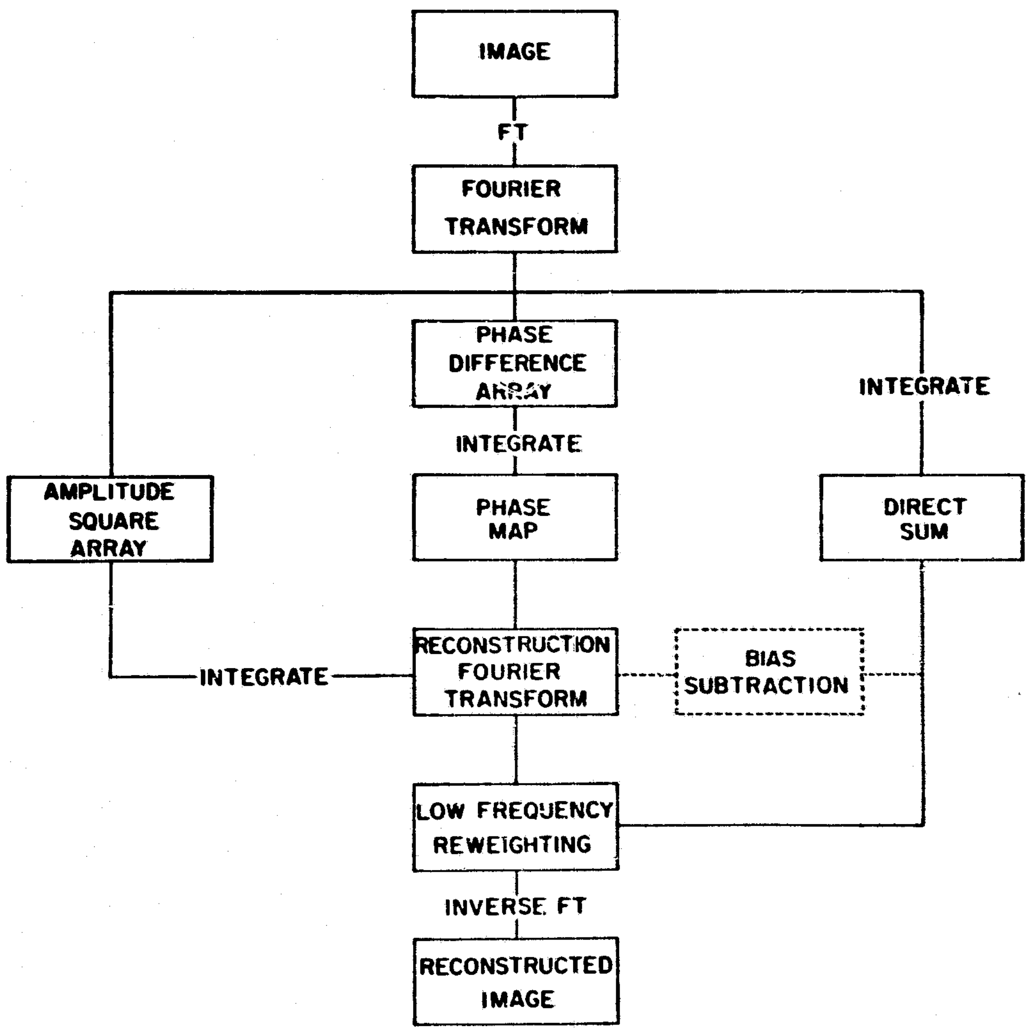

Figure 1

Greek letter *gamma* and a point and the diffraction-limited image, respectively. 2c is an image of an unresolved 6th magnitude star taken on film at the 2.1-meter Kitt Peak telescope, and 2d is the result of convolving 2c with the test object. 2d is formally equivalent to a single speckle frame taken at the telescope. 2e is the direct sum of 100 such frames, and 2f is the 100 frame reconstruction obtained from speckle processing. The recovered image is quite similar to 2b, the aberration-free diffraction-limited image.

Other results, to be published elsewhere, include reconstruction of the 0.05 arc-second separation binary star Capella, from data taken at the 5-meter Palomar telescope, recovery of an improved resolution image of a complex solar feature from images taken at the 0.75-meter Sacramento Peak telescope, and diffraction-limited reconstruction of binary stars from speckle data taken with a laboratory device simulating telescope aberration and atmospheric turbulence.

All of the data described in the foregoing were recorded on film and digitized with the aid of a microdensitometer. Electronic recording and real time digitization and processing have obvious advantages. Eventually, particularly with array processing, on-telescope data reduction should be a straightforward matter. At present, we and others, perform the reconstruction process only with data returned to the laboratory, although on-telescope speckle interferometry has been demonstrated by several groups.

In our approach, an effort was made to keep the field equipment extremely simple, light and reliable. An ISIT video camera, operating at 60 fields per second, and a video-tape recorder are used at the

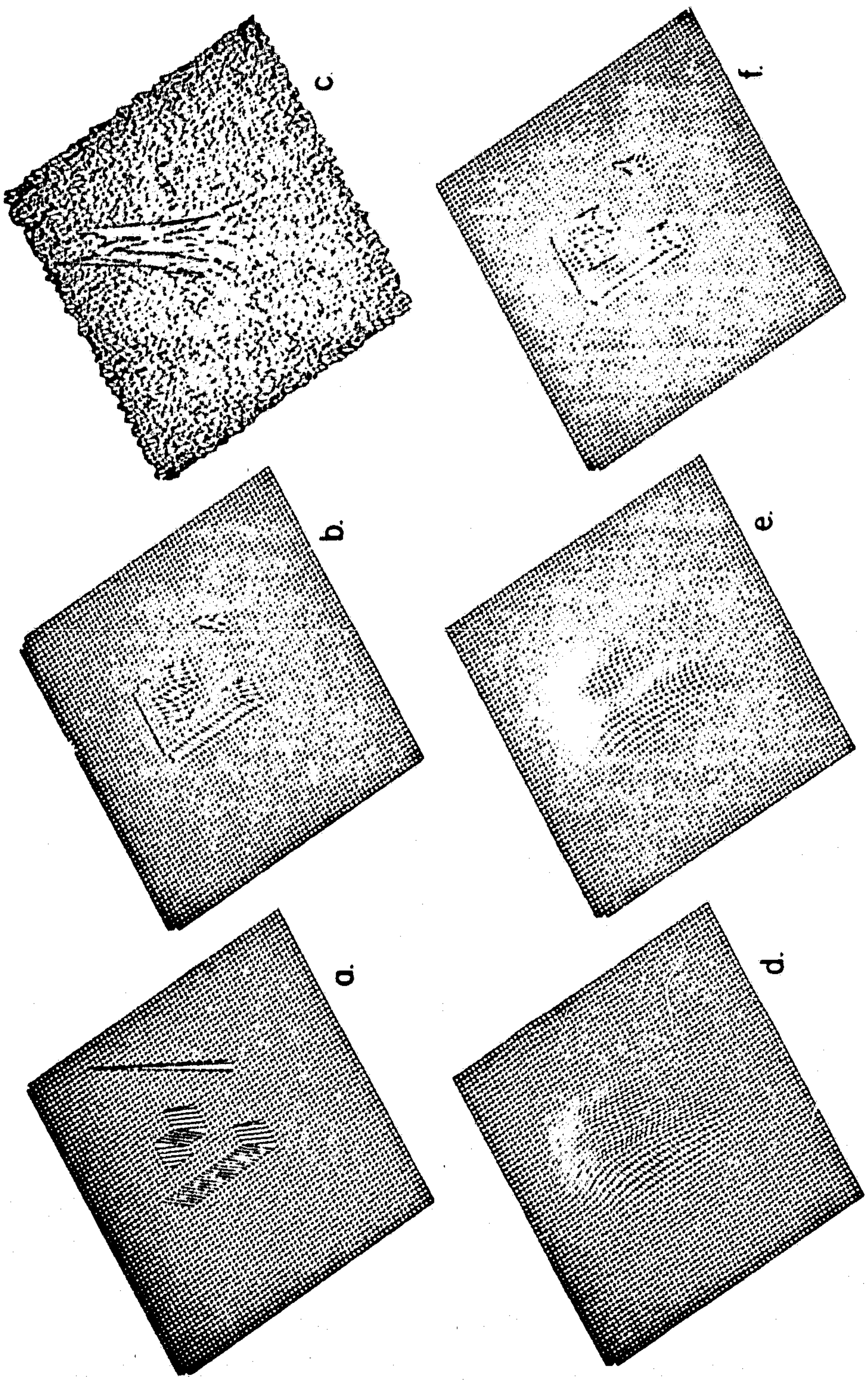

Figure 2

telescope, and the data are digitized and recorded on a 9-track tape in the laboratory for subsequent processing. A shutter exposes 1 field in 8 (although the erase beam operates for 7 fields out of 8) and a light source is used to saturate the target between exposures. Both precautions are taken to insure complete erasure of the silicon surface between exposures. The particular choice of 1 field in 8 for exposure was set by the rate at which at 125 i.p.s., 1600 b.p.i. tape drive will accept $(128)^2$ 8-bit digitized images. A tone on the audio track marks exposed frames for the laboratory digitizer. Figure 3 includes schematic diagrams of the camera and digitizer.

A very brief discussion of the low light level case is in order, at this point, because of the number of interesting objects at that light level and because it is in this regime that a very large telescope may be expected to make important contributions.

The individual frames upon which one operates are affected by photon noise even for relatively bright sources. This is the case because exposures are short ($\sim$ 0.01 second), spectral bandpasses must be restricted (for a 25-meter aperture, $\Delta\lambda \approx 4$ nm), and magnifications are high (typically, at very large telescopes, hundreds of resolutions elements are required across the seeing disk). At the 5-meter Palomar telescope, one records only 100 photons per frame for a 10th magnitude source. Furthermore, the relevant parameter for determining rate of convergence is not the integrated source brightness, but surface brightness. A 10th magnitude 1 arc-second source will require many more frames for convergence than a 10th magnitude 0.2 arc-second source.

Analysis shows that the introduction of photon noise leads to the presence of phase and amplitude bias terms in the reconstruction fourier

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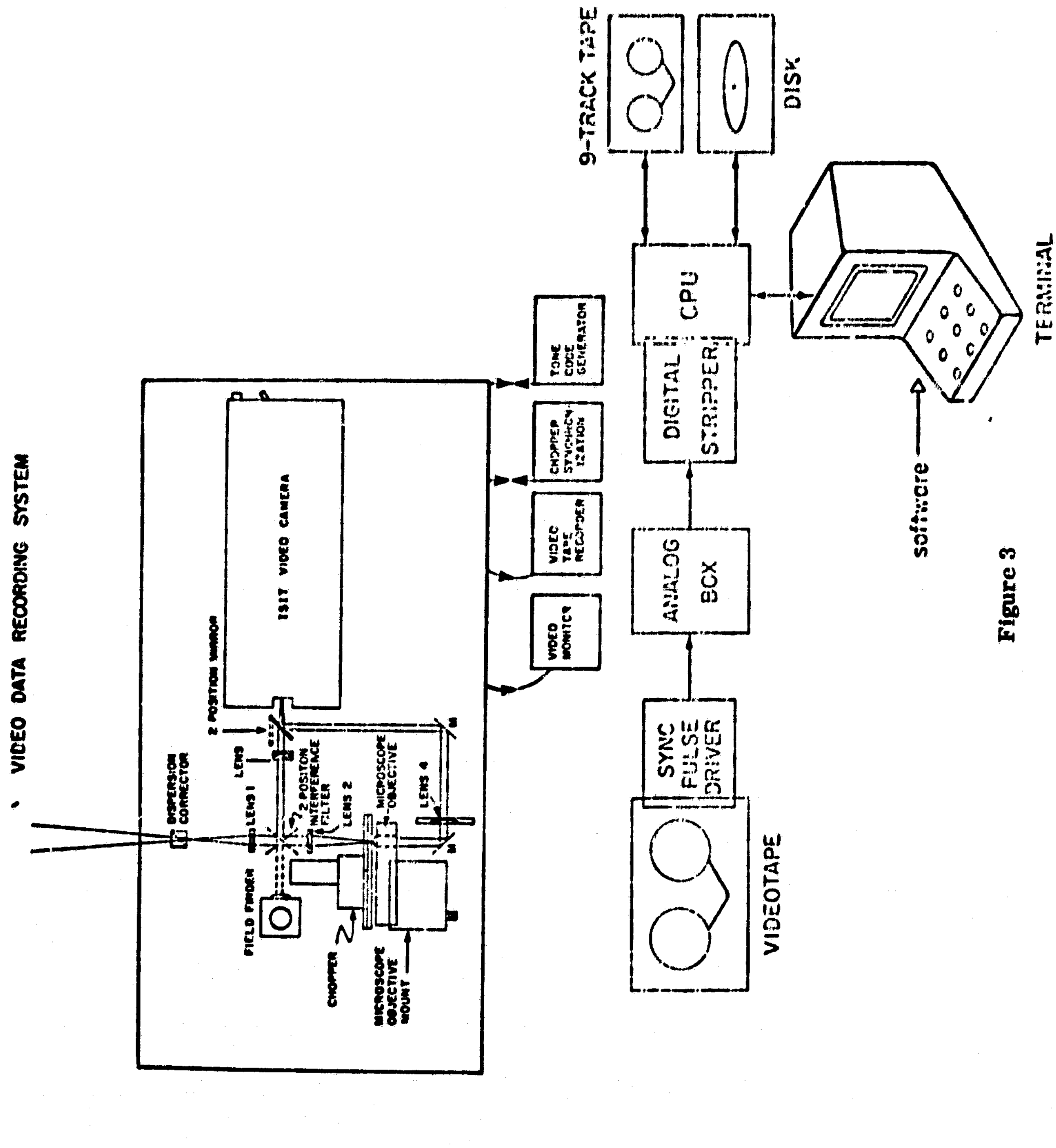

Figure 3

transform. Images recovered from such transforms are severely degraded. However, it is possible to deduce the bias terms from the fourier transform of the direct sum of the images (Eq. 1) and to compensate for the influence of photon noise. A demonstration showing experimental verification of this fact is reproduced as Fig. 4.

4a is a double Gaussian test object. 4b is the same double Gaussian convolved with an actual film-recorded 2.1-meter telescope point spread function (unresolved star speckle image) and poisson-distributed photon noise to simulate an object with 3 x 10^3 photons per frame. 4c is a reconstruction attempted without noise bias compensation, and 4d includes bias compensation. The bias parameters were derived from the direct sum transform.

This figure demonstrates that photon bias compensation is necessary and that it can be quite successfully implemented. It should be noted that at very low light levels both the data recording and processing constraints may be considerably relaxed. Recording bandwidths become smaller and innovative photon position-cataloging detectors may be used in place of devices which record large 2-D arrays that are mostly null. Processing is simplified by the fact that one deals with correlations of small numbers of events rather than with complex, large-array, 2-D fourier transforms. Problems of low light level detection and processing are actively being investigated.

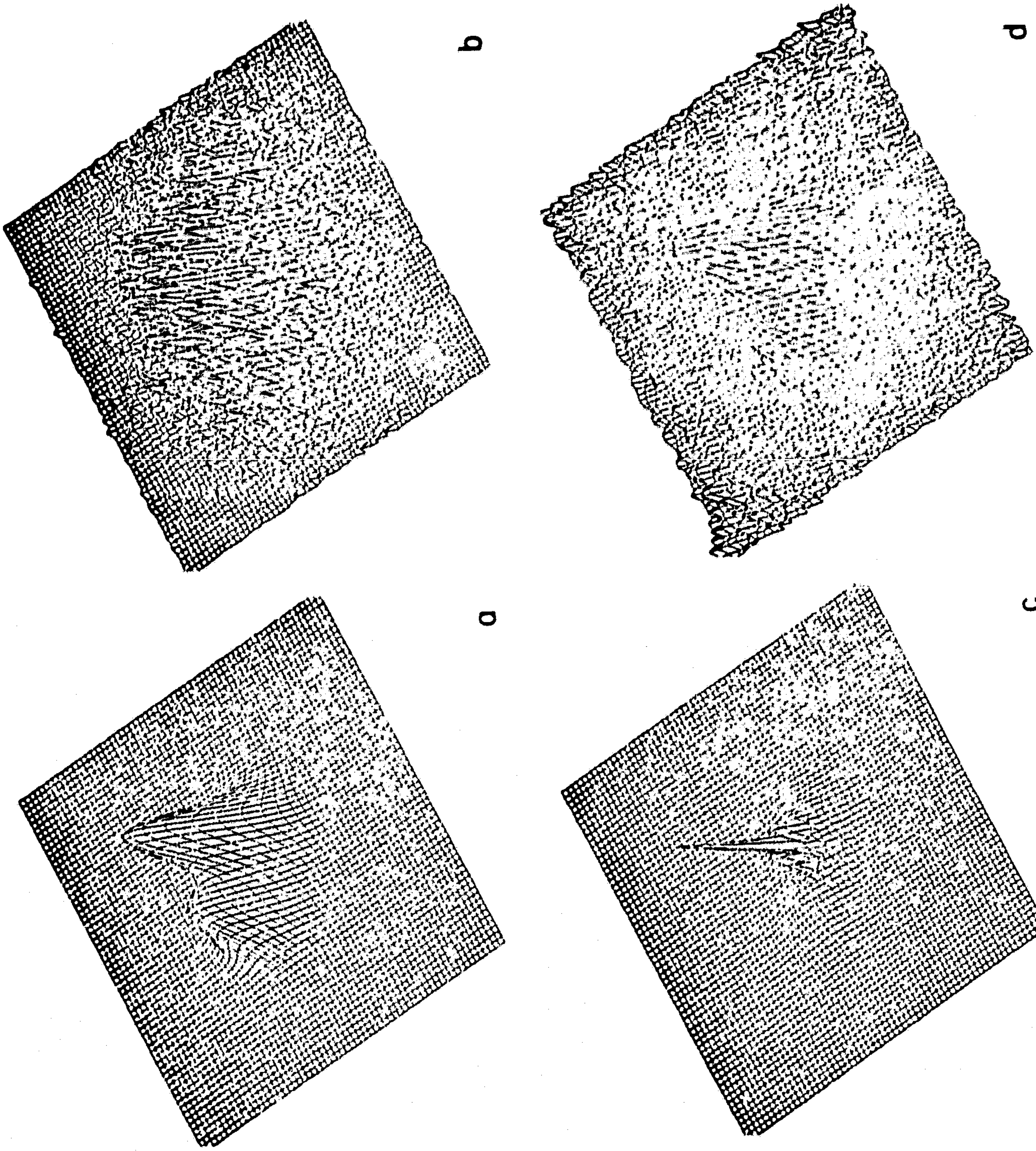

Figure 4

3. LARGE TELESCOPE CONSIDERATIONS

The telescope design requirements set by speckle imaging are identical to those appropriate to any of the high resolution image reconstruction techniques known to us, and are most easily understood in terms of the data taking constraints.

The data consist of direct images having:

- Exposure times short enough to freeze atmosphere-associated image structure changes (∿ 0.1 to 0.01 second);
- Limited spectral bandpass, so that the diffraction-limited speckles (interference fringes) are sharp over the seeing disk of an unresolved star;
- Adequate intensification and magnification to record the diffraction-limited structure;
- No object structure change during the record sequence.

Only the first and second requirements have implications for telescope design. The exposure time requirement suggests that high frequency vibrations moving the telescope through more than a diffraction spot width (0.005 arc-second at a 25-meter telescope) must not occur on a time scale shorter than that set by the atmosphere change time. Note that there is no strict requirement on guiding accuracy, only that individual exposures not be blurred.

The second requirement, on bandpass, implies an obvious assumption: that adequate coherence is present to insure that speckles are visible at all. At a given telescope, in 1 arc-second seeing, the second requirement is met if the bandpass is held to approximately $2\lambda\ell_o$, where λ is the wavelength of observation and ℓ_o is the diffraction resolution limit in arc-seconds. At a hypothetical 25-meter telescope, the requisite bandpass is 4 nm. A 4 nm bandpass implies that the telescope-induced wavefront error may approach 50-100 waves before coherence loss becomes very serious. It has already been demonstrated that high resolution image recovery is possible as long as the telescope aberrations are small enough to allow resolution of the seeing disk.

While we have yet to experimentally verify the number of frames of data required to assure convergence to a diffraction-limited reconstruction characterized by a particular signal-to-noise ratio, we do have analytical estimates substantiated by our digital simulation. These indicate that a 6th magnitude, 1 arc-second source, observed at a 2-meter telescope, will converge in 400 frames. This number scales with the inverse square of the number of photons per resolution patch, a number which can be computed for different telescopes, source surface brightnesses and patch sizes. It should be noted that, by opting for a resolution lower than the diffraction limit, one can greatly reduce the number of frames required.

At very large telescopes, the full diffraction-limited resolution can be achieved at an acceptable signal-to-noise in a reasonable number of frames only for high surface brightness objects. Even such relatively high surface brightness objects as the outer planets require a sufficiently large number of frames for diffraction-limited resolution that rotational blurring becomes a problem. For planetary sources, one is forced to accept a lower recovered resolution; nevertheless, for a typical object, Titan, the scaling law indicates rotation-limited resolution at a 25-meter telescope would be about half the diffraction-limited resolution. This is still very high resolution. Synoptic observations of planetary meteorology will be possible at resolutions exceeding that of the space telescope. Even for the Pluto, the resolution will be 0.02 arc-seconds.

Surface features, if any, on stars of large angular extent will be quite readily observable because of the very high surface brightness of the sources. Figure 5 shows the result of plotting a selection of the 100 brightest stars on a color magnitude diagram together with lines of constant angular diameter determined from an expression given by Warner.[7] The figure demonstrates that while a relatively small number of stars are resolvable at the 5-meter, many more are open to study at a larger telescope. At a 25-meter, about 300 resolution elements are present over the surface of the star Mira. Many more candidate stars would appear on Figure 5 if the list were extended beyond the 100 brightest.

In a list due to McAllister,[8] it is estimated that $\sim$ 250 binary stars with spectroscopically-determined orbits would be resolvable at a 25-meter telescope. Combination of the visual orbit with spectroscopic elements would double or triple the number of stars on the mass-luminosity diagram and extend it to include stars from O9 to M2. 13 supergiant masses would be measurable. Perturbations in precisely-determined binary star orbits could also be used to reveal the presence of low-mass, non-luminous components.

Image reconstruction of circumstellar shells, quasars, seyfer galactic nuclei and expanding nova shells (which, combined with spectroscopy, give distances) are also possible.

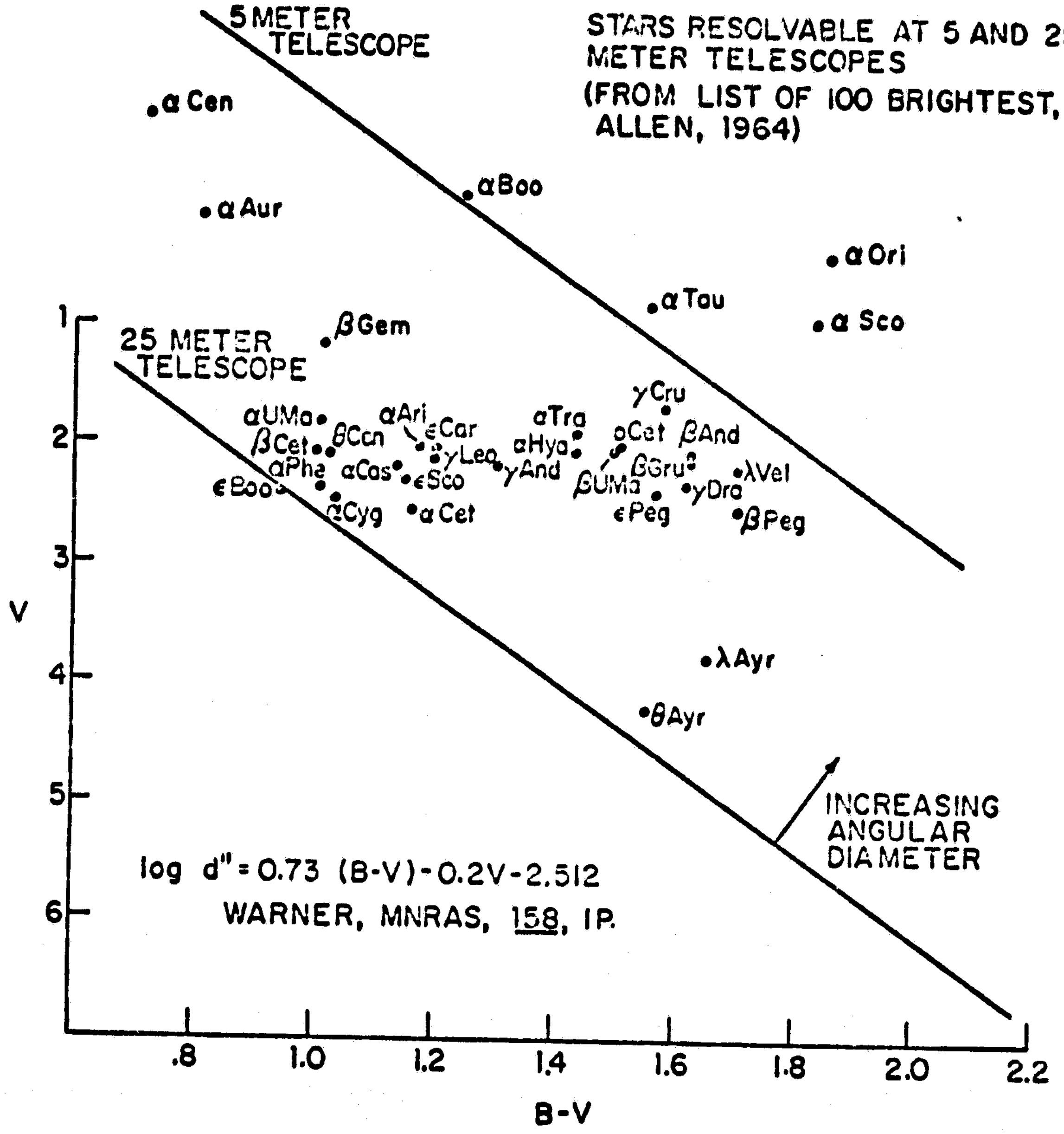
5 METER TELESCOPE
STARS RESOLVABLE AT 5 AND 25 METER TELESCOPES
(FROM LIST OF 100 BRIGHTEST, ALLEN, 1964)
α Cen
α Boo
α Aur
α Ori
α Tau
α Sco
β Gem
25 METER TELESCOPE
γ Cru
α UMa
α Ari
ε Car
α Tra
β Cet
β Ccn
α Hya
α Cet
β And
α Phe
α Cas
γ Leo
γ And
β UMa
β Gru
λ Vel
ε Boo
ε Sco
γ Dra
α Cyg
α Cet
ε Peg
β Peg
λ Ayr
θ Ayr
INCREASING ANGULAR DIAMETER
log d" = 0.73 (B-V) - 0.2V - 2.512
WARNER, MNRAS, 158, IP.
V
1
2
3
4
5
6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
B-V

Figure 5

The success of high angular resolution interferometry and imaging techniques gives added justification for the construction of telescopes of greatly increased aperture size. For certain classes of objects, angular resolution could be obtained well beyond that projected for space telescopes of the foreseeable future. The principal telescope design constraint imposed by these techniques is optical system coherence to within, perhaps, 50 wavelengths in the visible.

ACKNOWLEDGEMENT

We gratefully acknowledge the interest and support of Richard Goody, Robert Noyes, and Jerome Apt, and express our thanks to Paul Horowitz for his design and construction of the video digitizer. This work was carried out with NASA and Air Force support under Grants NGL-22-007-228, and F19628-78-C-0026, respectively.

FIGURES

1. Flow chart outlining the speckle image reconstruction process. Details are given in the text.

2. (a) is an input test object, a *gamma* and a point. (b) is the test object filtered to have the appearance of a telescope diffraction-limited image. (c) is an actual 2-meter telescope point spread function (stellar image), which, in (d), is convolved with (a) to produce an image degraded in a highly realistic way by atmospheric seeing. (e) is a direct sum of 100 realizations like (d) and (e) is the image reconstructed from the same 100 frames.

3. Schematic diagrams of the on-telescope video image recording system and laboratory-based video-tape data digitizer.

4. A demonstration of the photon-noise bias subtraction procedure described in the text.

5. A color magnitude diagram on which are plotted a selection of objects from a list of 100 brightest stars as well as curves of constant angular diameter for diameters equal to the diffraction resolution limit of 5-meter and 25-meter telescopes.

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