Phase Referencing

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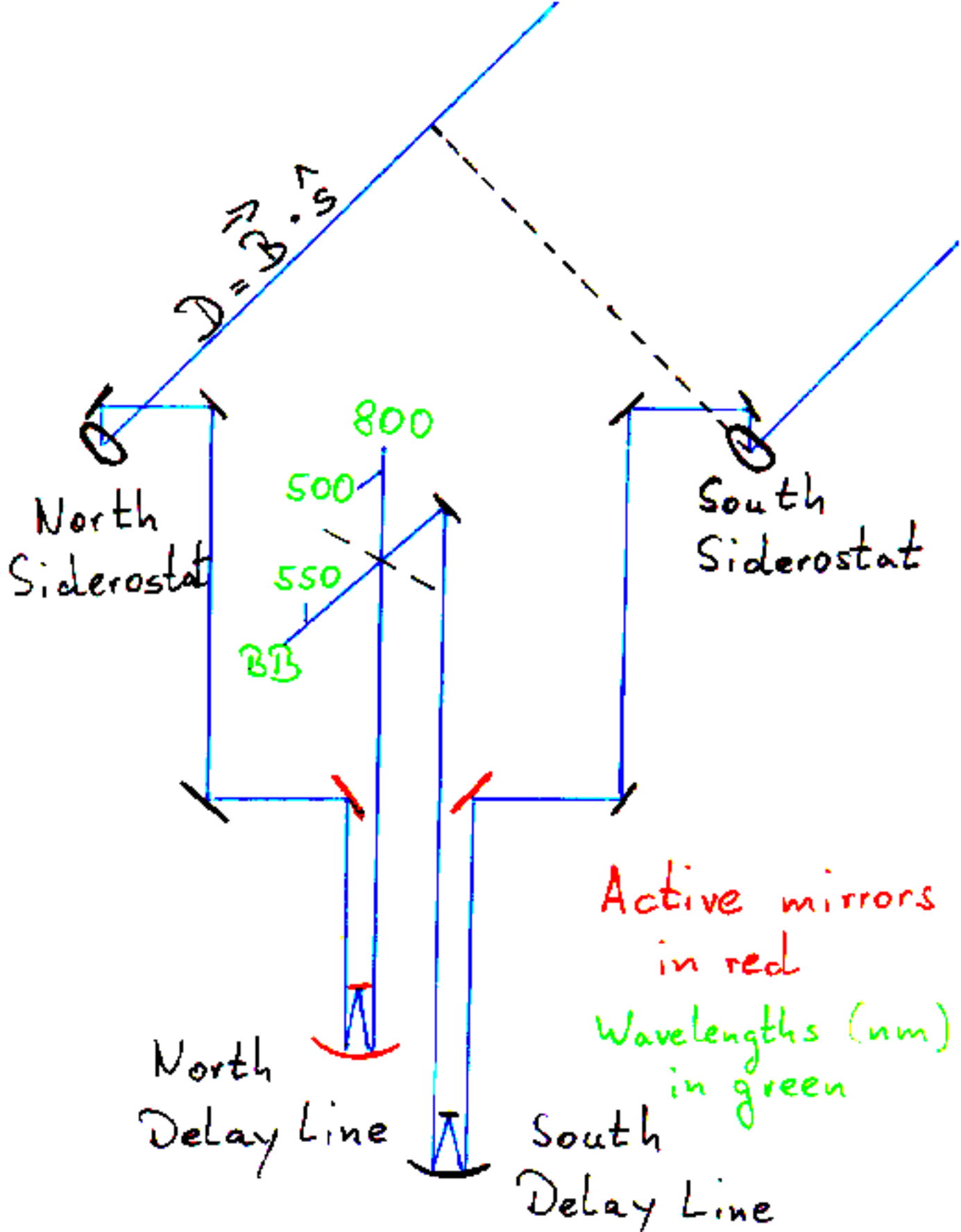
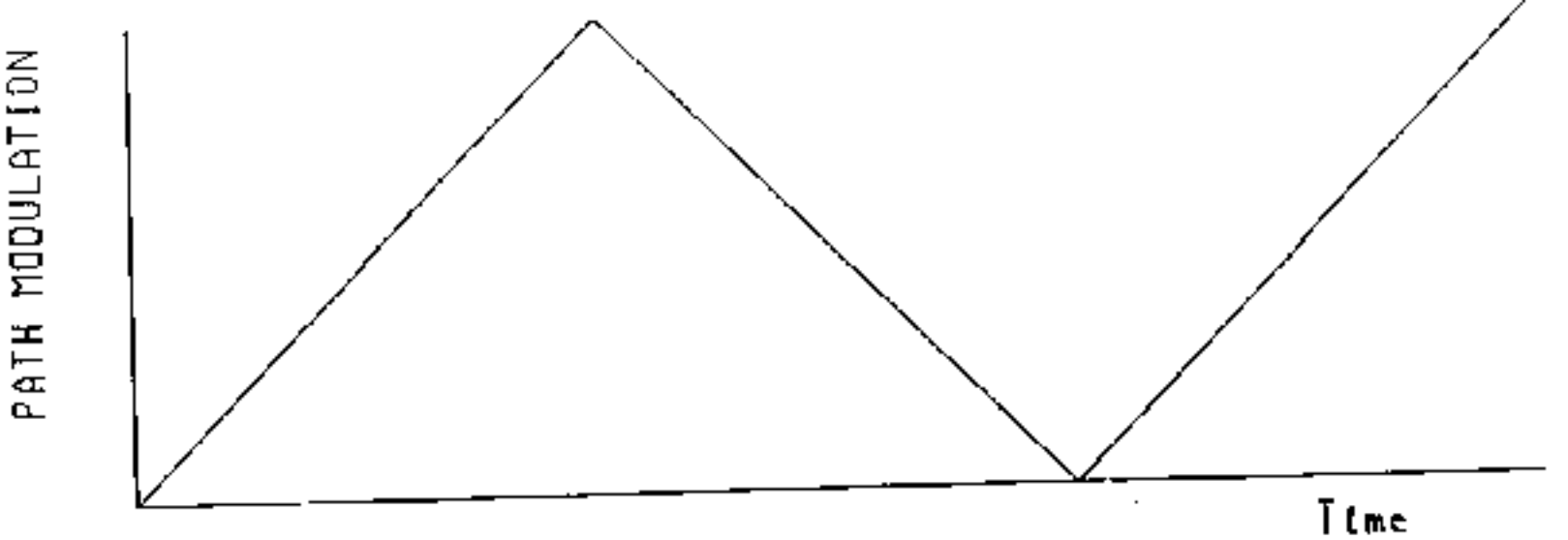
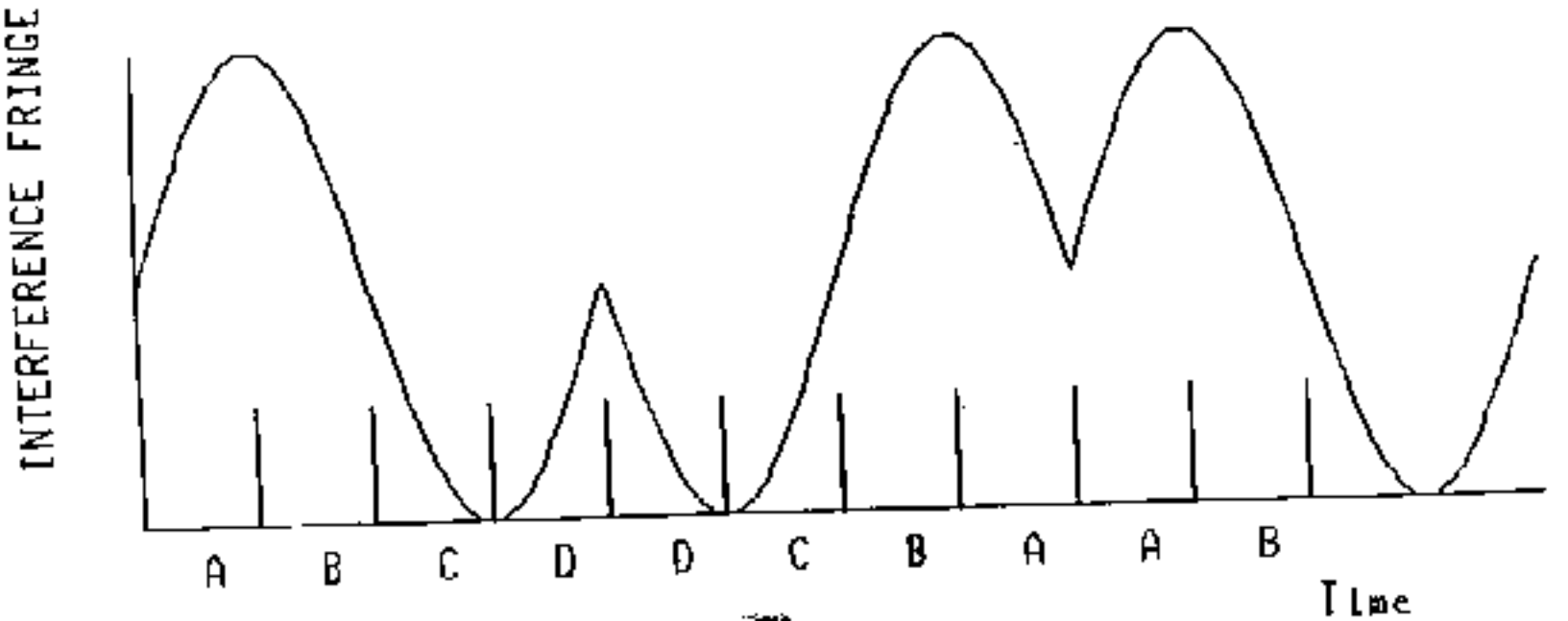

$D = \vec{B} \cdot \hat{s}$
800
500
550
BB
North Siderostat
South Siderostat
Active mirrors in red
Wavelengths (nm) in green
North Delay Line
South Delay Line


PATH MODULATION
Time


INTERFERENCE FRINGE
A B C D D C B A A B
Time

Basic Fringe Quantities

Fringe sine and cosine: $X := A - C \qquad Y := B - D$

Visibility: $$V^2 = \frac{\pi^2}{2} \frac{\langle X^2 + Y^2 - N \rangle}{\langle N - N_{dark} \rangle^2}$$

Phase: $$\tan\phi = \frac{\langle Y \rangle}{\langle X \rangle} - \frac{\pi}{4}$$

Signal-to-noise: $$SNR = \frac{1}{4} \frac{\sqrt{M}\, NV^2}{\sqrt{1 + 0.5\, NV^2}}$$

Photon-Rich and Photon-Starved Observations

- Photon-rich regime: $NV^2 \gg 1$
  $\mathrm{SNR} \propto \sqrt{MN} \propto \sqrt{t_{\mathrm{obs}}}$
- Photon-starved regime: $NV^2 \ll 1$
  $\mathrm{SNR} \propto \sqrt{M} \times N = \sqrt{MN} \times \sqrt{N} \propto \sqrt{t_{\mathrm{obs}}} \times \sqrt{t_{\mathrm{coh}}}$
- The bottom line: you need two photons to do interferometry!
- Sensitivity of interferometer is limited by the number of photons in coherence volume (e.g., $\frac{\pi}{4} r_0^2 \times c\,\tau_0$)

Table Ib. Source-referenced Mode Sensitivity
Phasing & Cophasing. *Long-Term Case*
Telescope Diameter 2-m

Seeing	H	K	L	M	N	Q
0.5"	11.2	12.3	10.4	8.1	5.3	2.4
	35	8	21	110	320	1 100
1.0"	8.9	10.1	8.5	6.7	4.9	2.0
	280	59	120	390	460	1 600

Units: upper lines are magnitudes ; lower are milliJy
Phasing: $V = 1$ or $V \neq 1$. Cophasing: $V = 1$.
1.0" seeing $\Leftrightarrow r_o(0.5\mu m) = 10$ cm.

Table Ib. Source-referenced Mode Sensitivity
Phasing & Cophasing. *Long-Term Case*
Telescope Diameter 8-m

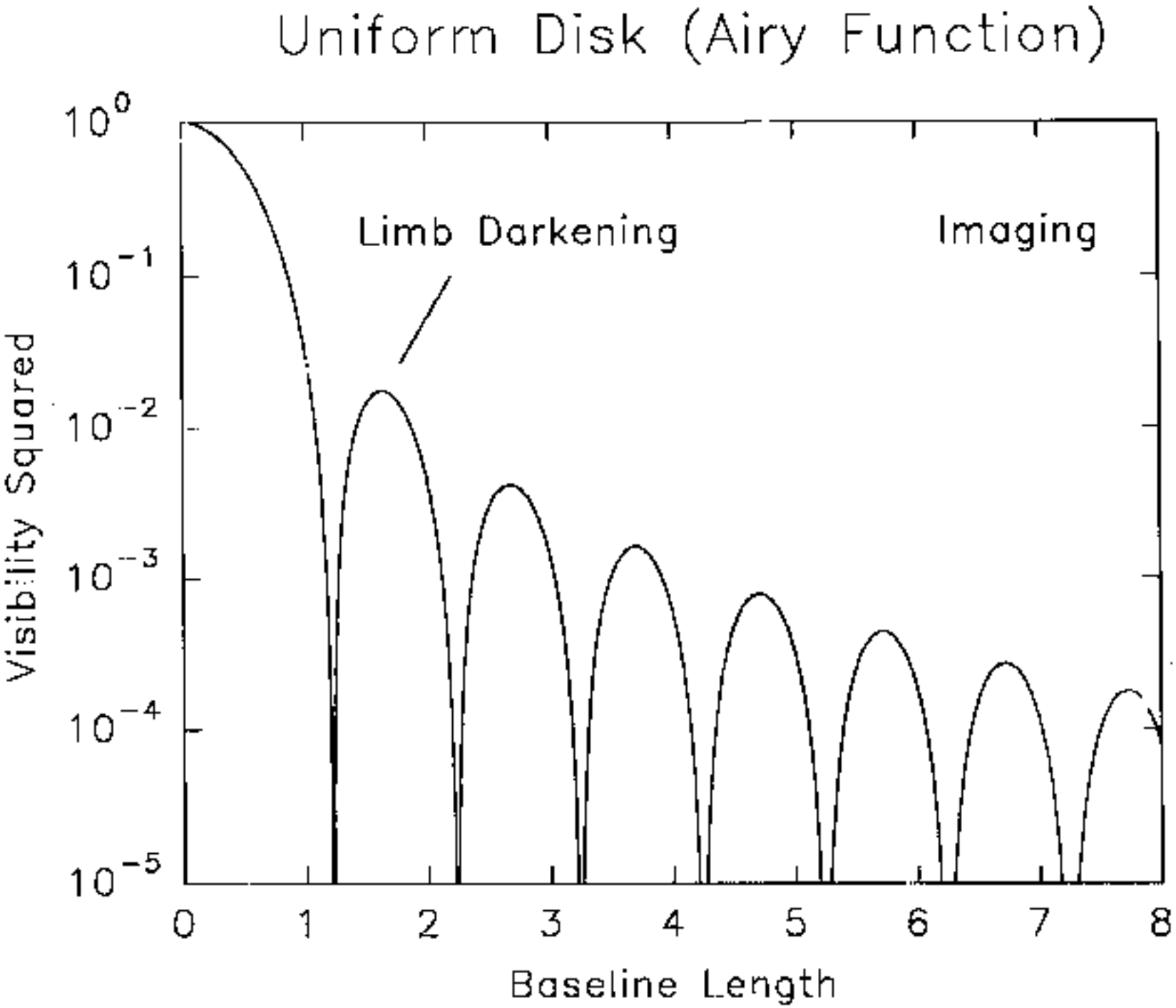
Seeing	H	K	L	M	N	Q
0.5"	11.2	12.3	10.4	8.6	7.6	5.4
	35	8	21	69	38	70
1.0"	8.9	10.1	8.5	6.7	5.8	4.5
	280	59	120	390	210	150

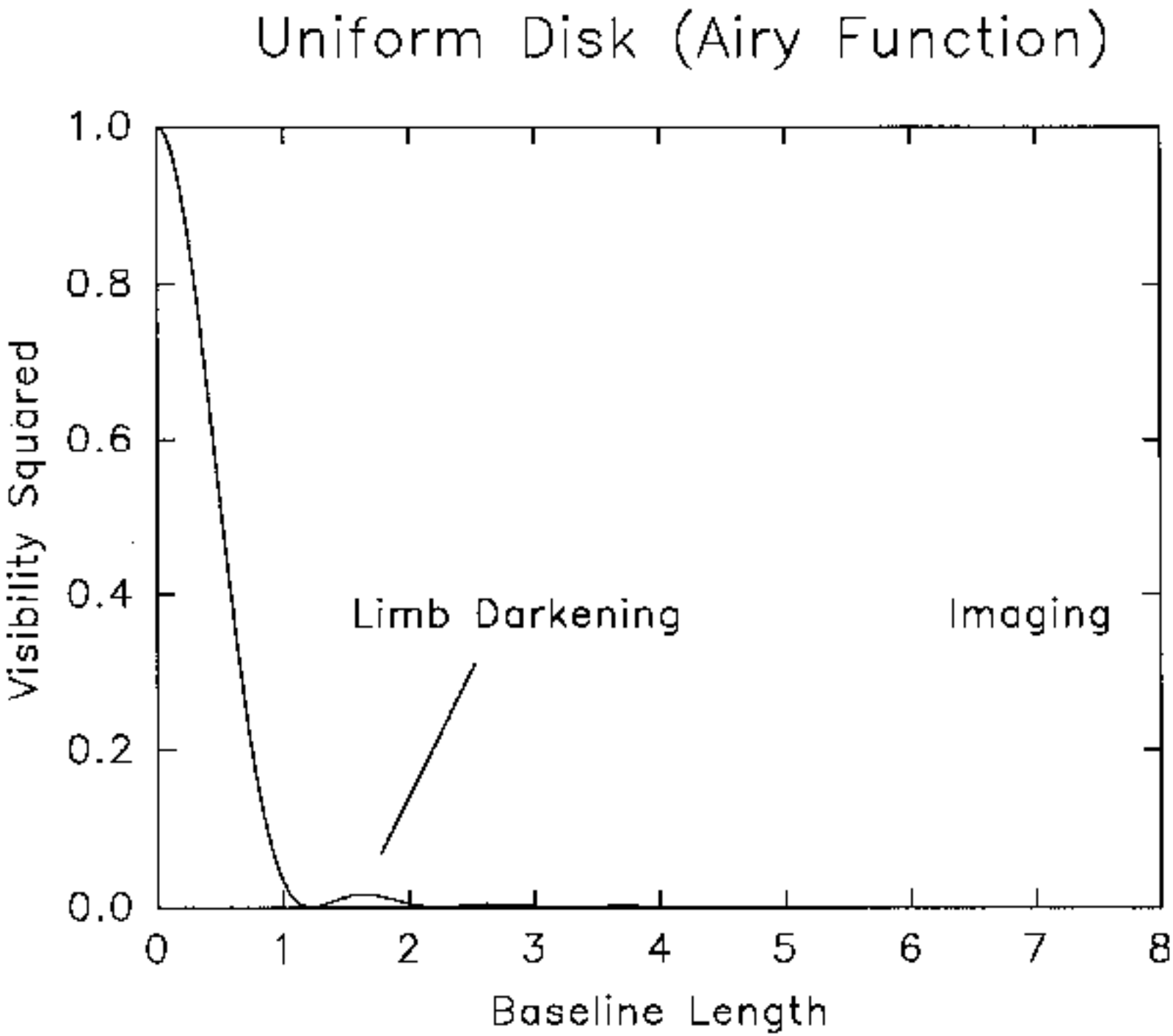
Units: upper lines are magnitudes ; lower are milliJy
Phasing: $V = 1$ or $V \neq 1$. Cophasing: $V = 1$.
1.0" seeing $\Leftrightarrow r_o(0.5\mu m) = 10$ cm.

Table III. Off-source Referenced Mode Sensitivity
Integration Time $\Delta T = 10$ minutes. *Long Term case*

Telescope	H	K	L	M	N	Q
2-m + 2-m	21.1	20.4	15.3	12.2	8.9	5.6
	.004	.005	.24	2.5	11	59
8-m + 8-m	24.1	23.4	18.3	15.2	11.9	8.6
	.0002	.0003	.015	.15	.72	3.7

Units: upper lines are magnitudes ; lower are milliJy


Uniform Disk (Airy Function)
Limb Darkening
Imaging
Visibility Squared
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
3
4
5
6
7
8
Baseline Length


Uniform Disk (Airy Function)
Visibility Squared
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Baseline Length
Limb Darkening
Imaging

Fringe Tracking

Fringe tracking requires SNR $\gtrsim 10$ *within one coherence time of the atmosphere* (a few milliseconds in the visible, scales with $\lambda^{6/5}$).

What can be done if NV^2 is too small?

- Wavelength bootstrapping or baseline bootstrapping gives larger V^2 on the same source.
- Off-source fringe tracking can be used if a bright reference is available.

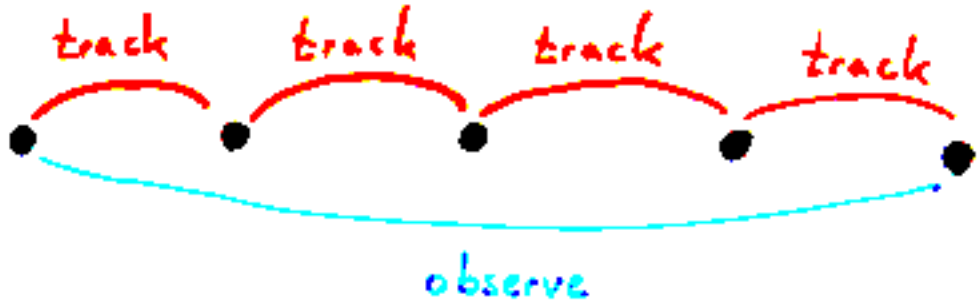
Off-Source Fringe Tracking

The reference source must be within the isoplanatic field of the science target (a few arcseconds in the visible, scales with $\lambda^{6/5}$).

The reference source can also be used for wavefront sensing in an adaptive optics system.

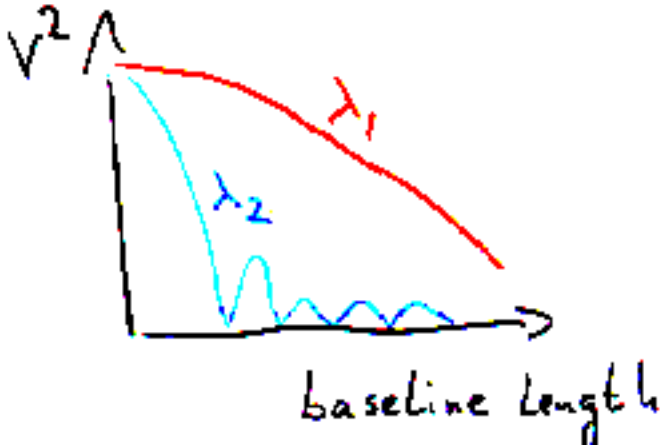
In this case the sensitivity of the interferometer is essentially identical to the sensitivity of a single telescope with the same diameter.

baseline bootstrapping



wavelength bootstrapping

$\lambda_1 \gg \lambda_2$



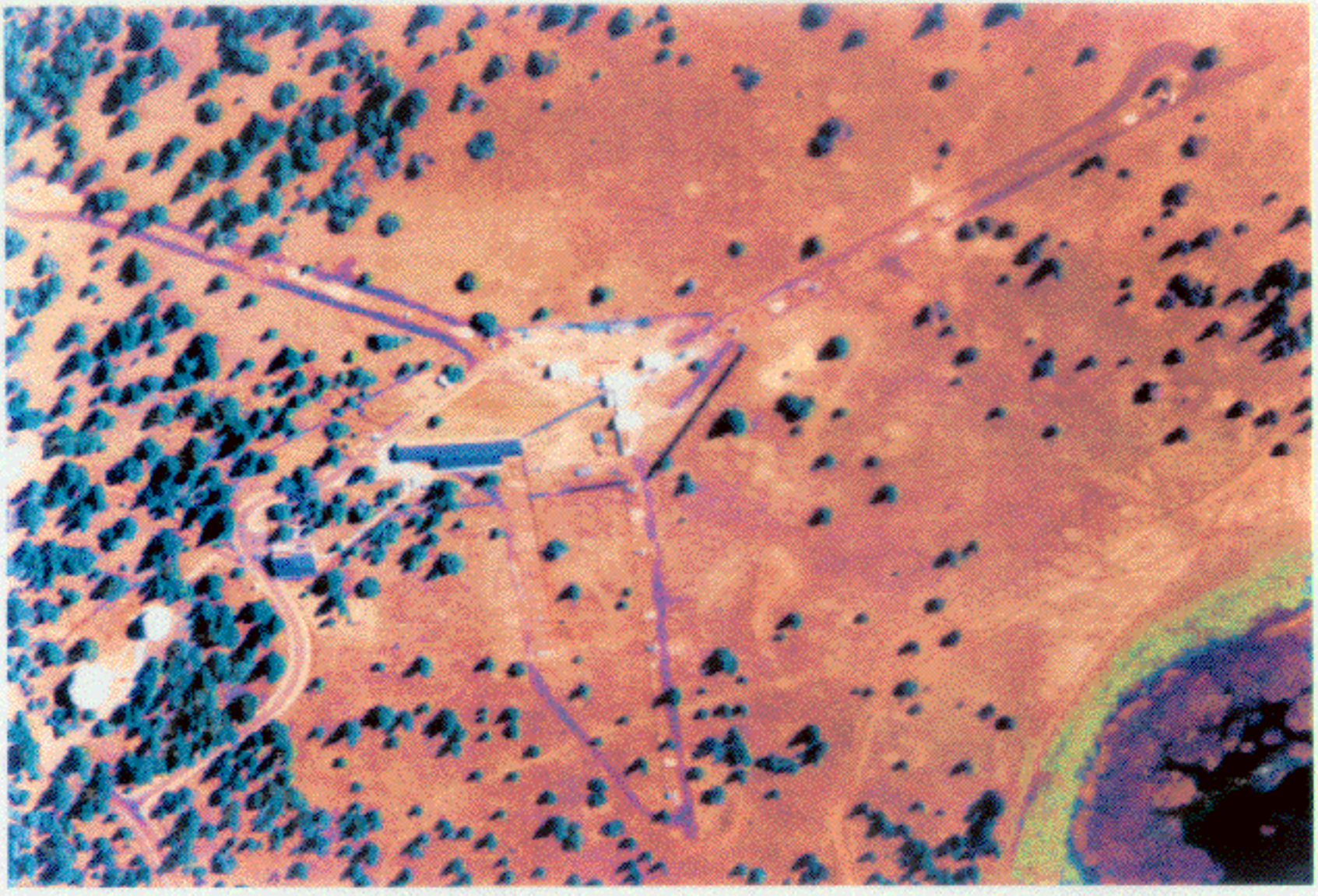
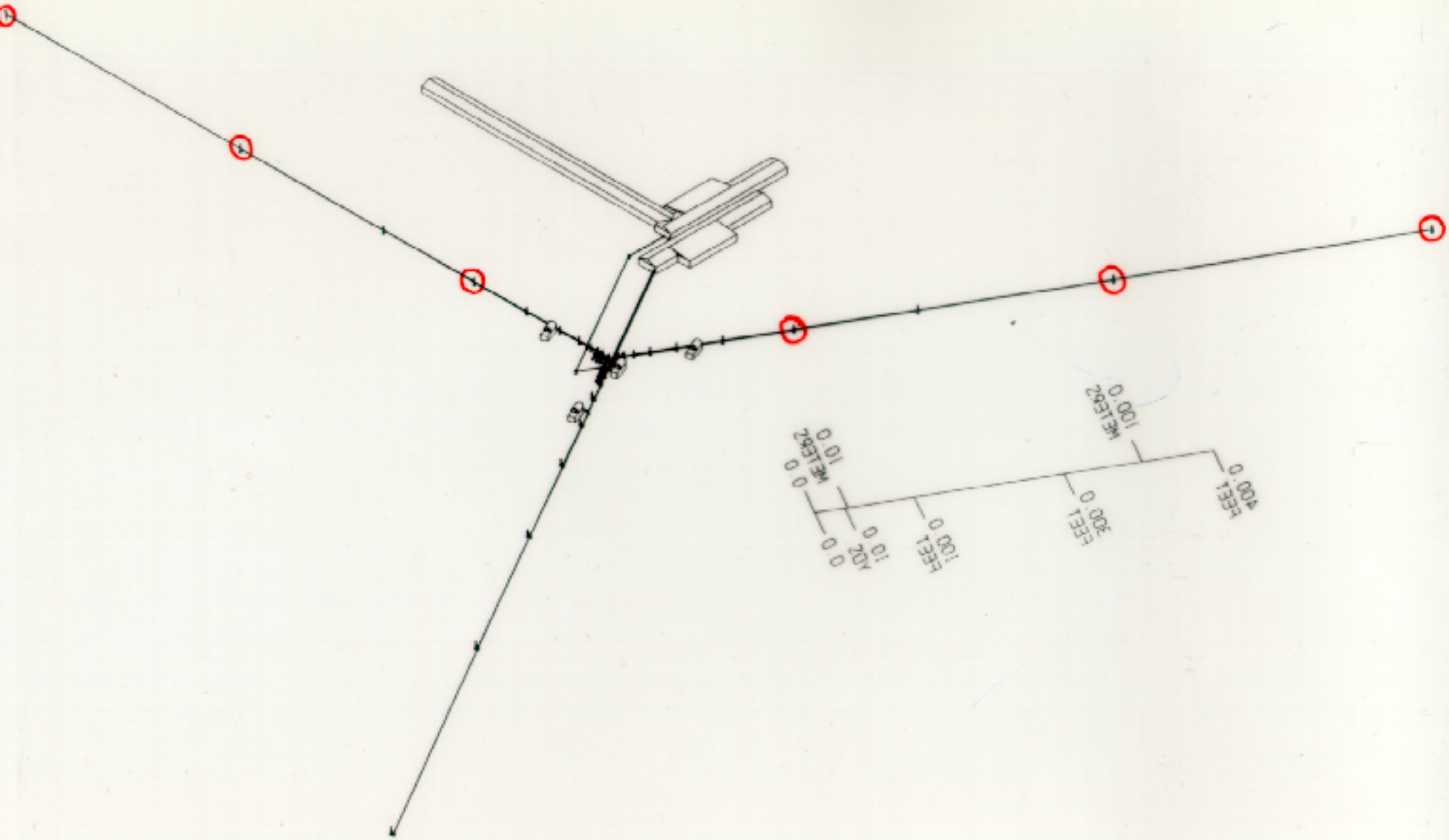


FIG. 1.—Aerial view of the NPOI as of 1996 October. North is toward the top of the photograph. Along the arms of the Y, small piers to support the feed beam vacuum pipes and larger piers to support the imaging siderostats can be seen. The furthest imaging siderostat piers are 250 m from the center of the array. The cluster of four white buildings at the center houses the four astrometric siderostats. The long building is the optics laboratory. Stretching north from the east end of the lab is the array of concrete piers on which the long delay lines will be placed. The control building is northwest of the lab. Also visible are two Lowell Observatory domes.

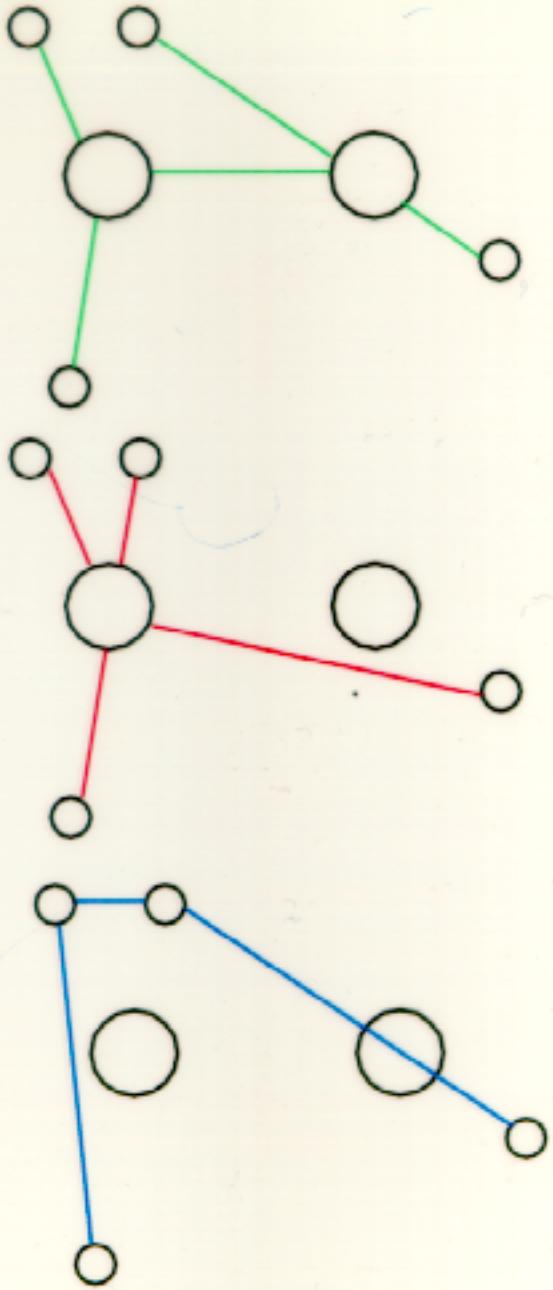
ARMSTRONG et al. (see 496, 551)


0.0
0.01
0.001
0.0001
0.00001
0.0
0.01
0.001
0.0001
0.00001

KECK INTERFEROMETER

Imaging - technical

- Maximum 6 telescopes
- Cophase on max. 6-1 baselines at H/K, on bright point source
- Image on max. 15 baselines



Applications of Phase Referencing

- Off-axis phasing of interferometer on nearby guide star
- Observation in narrow wavelength channel with fringe tracking in wide channel
- Observation in wavelength channel with low visibility (a.k.a. wavelength bootstrapping)
- Observation on long baseline with fringe tracking on short baselines (a.k.a. baseline bootstrapping)
- Measurement of phase shift as a function of wavelength

1994A&A...286.1019Q

Astron. Astrophys. 286, 1019–1027 (1994)

ASTRONOMY AND ASTROPHYSICS

Phase-referenced visibility averaging in optical long-baseline interferometry

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Abstract. In the photon-starved regime, the signal-to-noise ratio of interferometric data depends on the coherent integration time. To extend the integration time beyond the limit imposed by atmospheric fluctuations, the phases taken in a narrow "signal" channel can be corrected by referencing them to those taken in a wider "tracking" channel. A number of instrumental and atmospheric effects decorrelate the phases in the two channels and thus constrain the range of conditions under which the phase-referencing technique can be used. In the case of the MkIII stellar interferometer, differential refraction at intermediate to large zenith angles is the most important limitation. Tests with MkIII data in the photon-rich regime demonstrate that the phase-referencing technique works well at moderate zenith angles. In the photon-starved regime, the expected improvement of the signal-to-noise ratio is readily observed. We use phase-referenced data taken on the bright star α Boo close to the first null of the visibility function to show that the MkIII data are free from additive bias at the $V^2 \leq 10^{-4}$ level. The absence of any bias larger than this value is an important requirement for future imaging interferometers.

Key words: atmospheric effects – instrumentation: interferometers – methods: observational – methods: data analysis – techniques: interferometric

1. Introduction

The use of phases in astronomic interferometry is severely limited by the pathlength fluctuations of the earth's atmosphere. Two different approaches are widely used to deal with the problem of phase corruption: closure phase methods (or phase self-calibration), and phase-referencing. In the latter technique, the phase information from a reference object is used to determine the atmospheric phase, and to correct the phase of the target source accordingly.

While in radio astronomy the atmospheric coherence time is typically several minutes, and the coherence angle several degrees, the corresponding values in the optical regime are only of order ten milliseconds and a few arcseconds. These limitations preclude the use of source-switching strategies and require the simultaneous observation of target and reference object. While this might appear to be a very restrictive requirement, there are several important applications of phase-referencing to optical long-baseline interferometry. First, the phase difference can be used as a primary observable in "astrometric" applications, e.g. to determine the positional offset of a circumstellar envelope from the central star, or to search for the reflex motion of stars orbited by planets. (In the latter case, a suitable reference object is needed within the isoplanatic patch.) Second, the reference phase can be used to increase the effective atmospheric coherence time, allowing longer coherent integrations on the target source.

In this paper, we will discuss the coherent integration of visibility amplitudes in a "narrow" spectral channel, using the phase in a broader channel as a reference. This technique will be applied to data taken with the MkIII interferometer[1]. In Sect. 2 we will summarize the most important features of the MkIII instrument and describe the phase-referencing algorithm. In Sect. 3 we will review the sources of systematic errors and fundamental limitations to the technique. In Sect. 4 we will describe a test of phase-referencing using data with high signal-to-noise and compare the results with theoretical predictions. In Sect. 5 we will show the application of the algorithm to data with low signal-to-noise. Finally, we will summarize the results and discuss some future applications in Sect. 6.

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[1] The MkIII Optical Interferometer located on Mt. Wilson near Los Angeles, CA, is operated by the Remote Sensing Division of the Naval Research Laboratory (NRL).

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Visibility Reduction

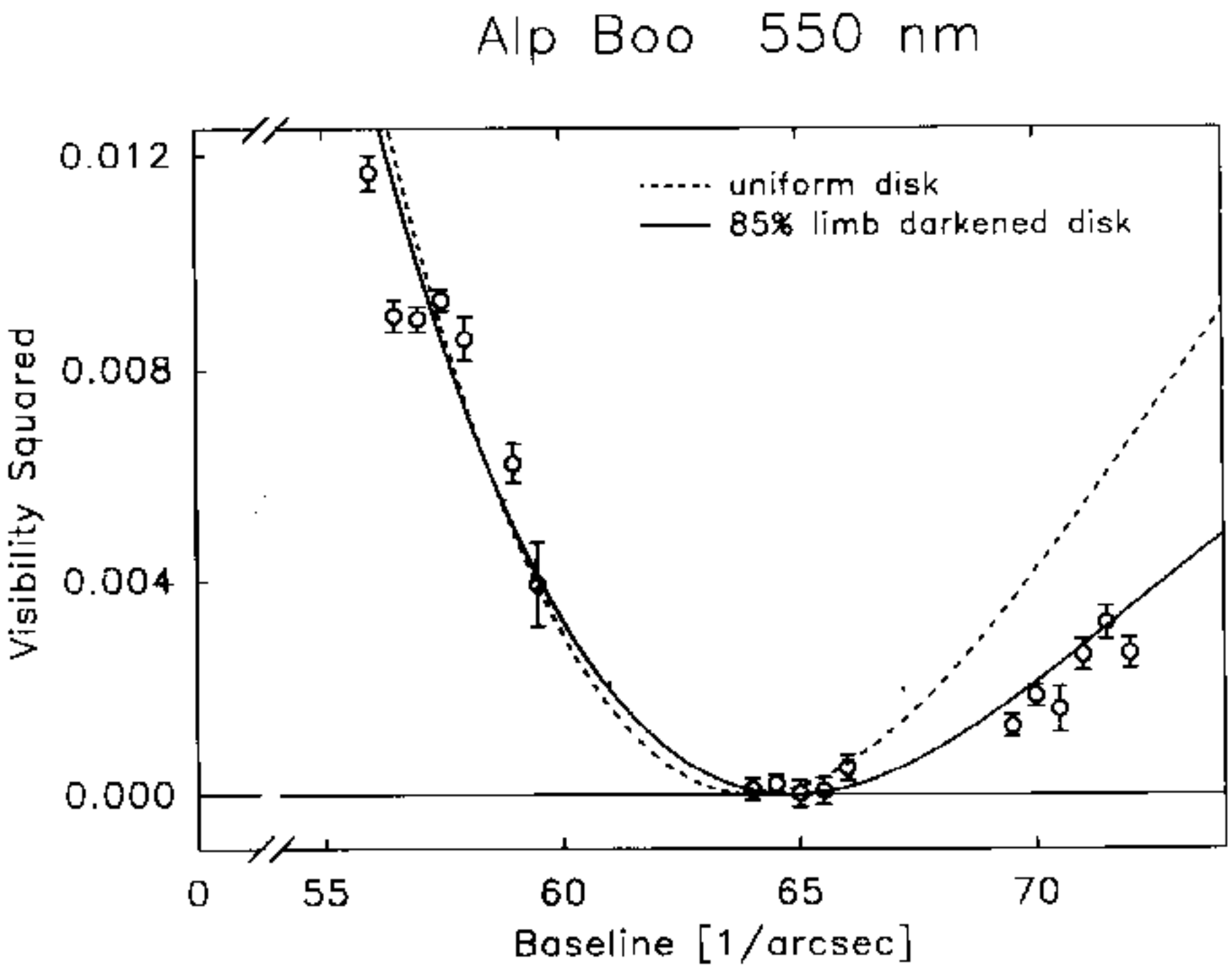
- Phase variations during the coherent integration time reduce the visibility
- If σ_ϕ^2 is the phase variance, $V^2 \rightarrow \eta V^2 = e^{-\sigma_\phi^2} V^2$
- Solution 1: keep phase variations small (requires many photons and fast servo for fringe tracking)
- Solution 2: break up total observing time in sections small enough to show no phase variations (incurs a signal-to-noise penalty)
- Solution 3: determine and correct phase fluctuations

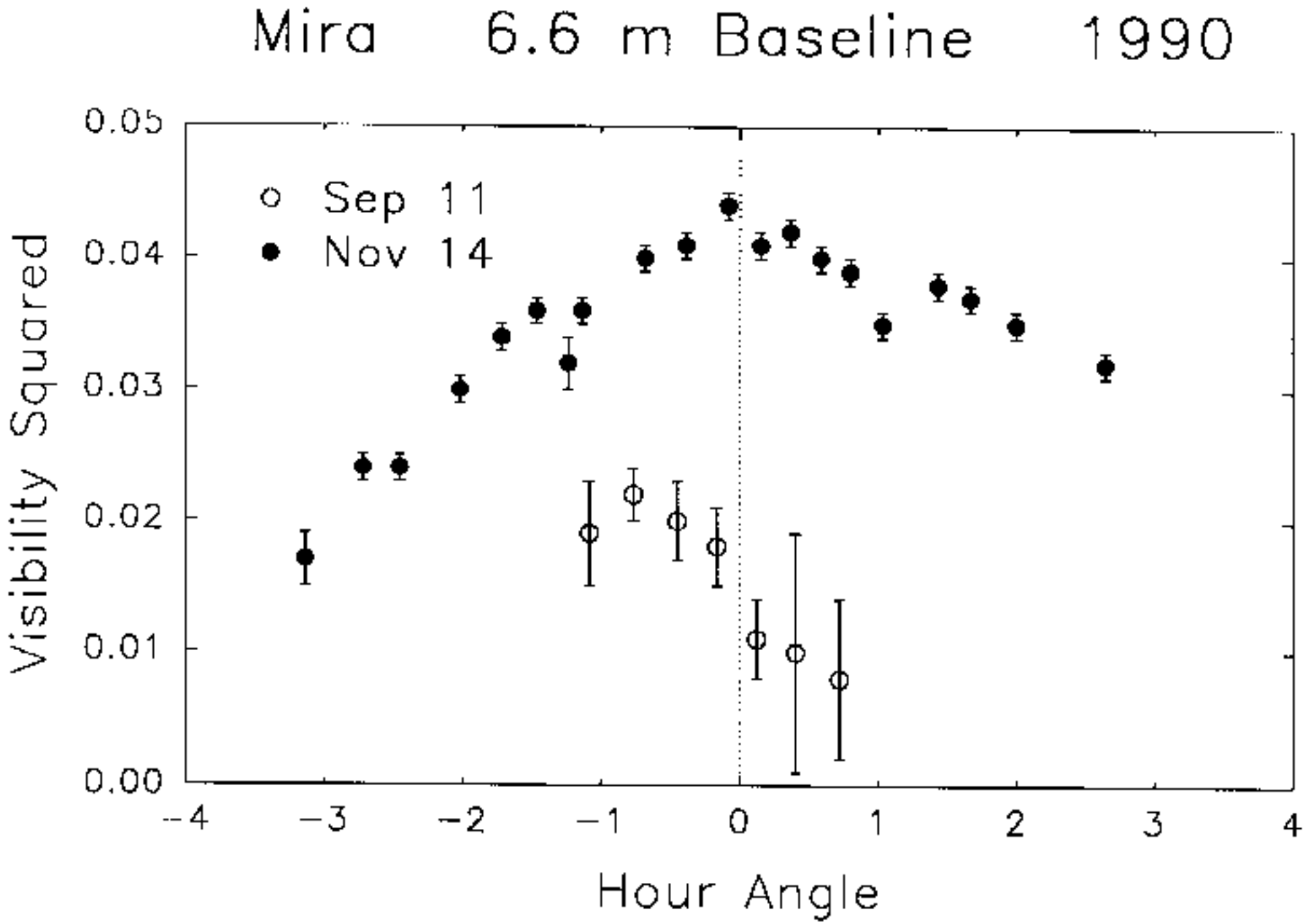
Mark III: Incoherent Averaging

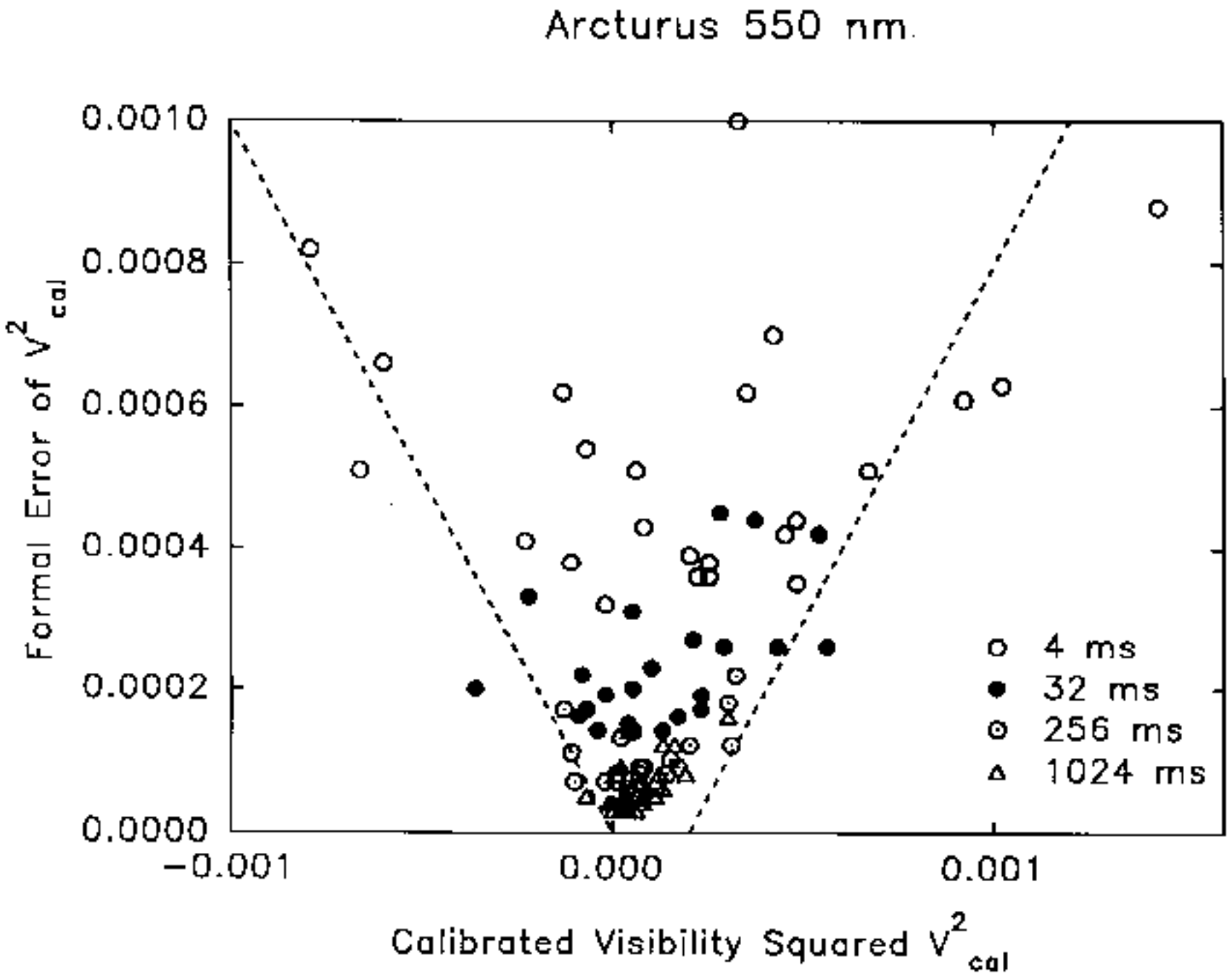
- Feed fringe tracker with wide-band light (centered at 700 nm)
- Get bin counts A, B, C, D in narrow signal channel for many 4 ms intervals
- Estimate V^2 from bin counts for each interval
- Average estimates of V^2 for each scan (75 s to 300 s)

Mark III: Phase-Referenced Averaging

- Feed fringe tracker with wide-band signal (centered at 700 nm)
- Get bin counts A, B, C, D in signal and tracking channels for many 4 ms intervals
- Estimate phases ϕ_s and ϕ_t in signal and tracking channels for each 4 ms interval
- Define $X_r + iY_r = V_r\, e^{i\phi_r} \equiv V_s\, e^{i(\phi_s - \frac{\lambda_t}{\lambda_s}\phi_t)}$
- Average X_r and Y_r for up to 1024 ms; calculate V^2 for each of these intervals
- Average V^2 for each scan (75 s to 300 s)


Alp Boo 550 nm
uniform disk
85% limb darkened disk
Visibility Squared
0.012
0.008
0.004
0.000
0
55
60
65
70
Baseline [1/arcsec]

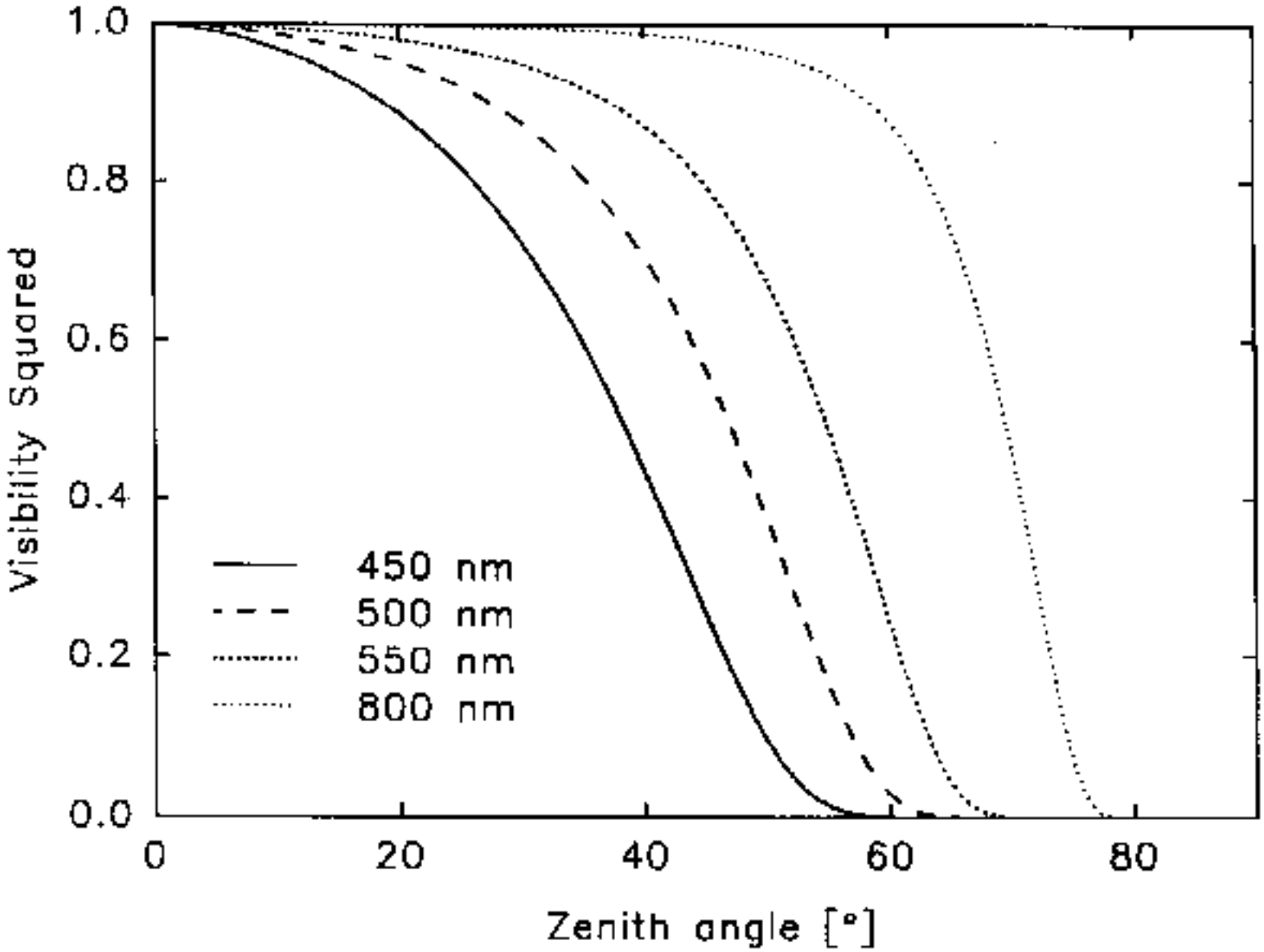

Mira 6.6 m Baseline 1990
Sep 11
Nov 14
Visibility Squared
0.05
0.04
0.03
0.02
0.01
0.00
−4
−3
−2
−1
0
1
2
3
4
Hour Angle

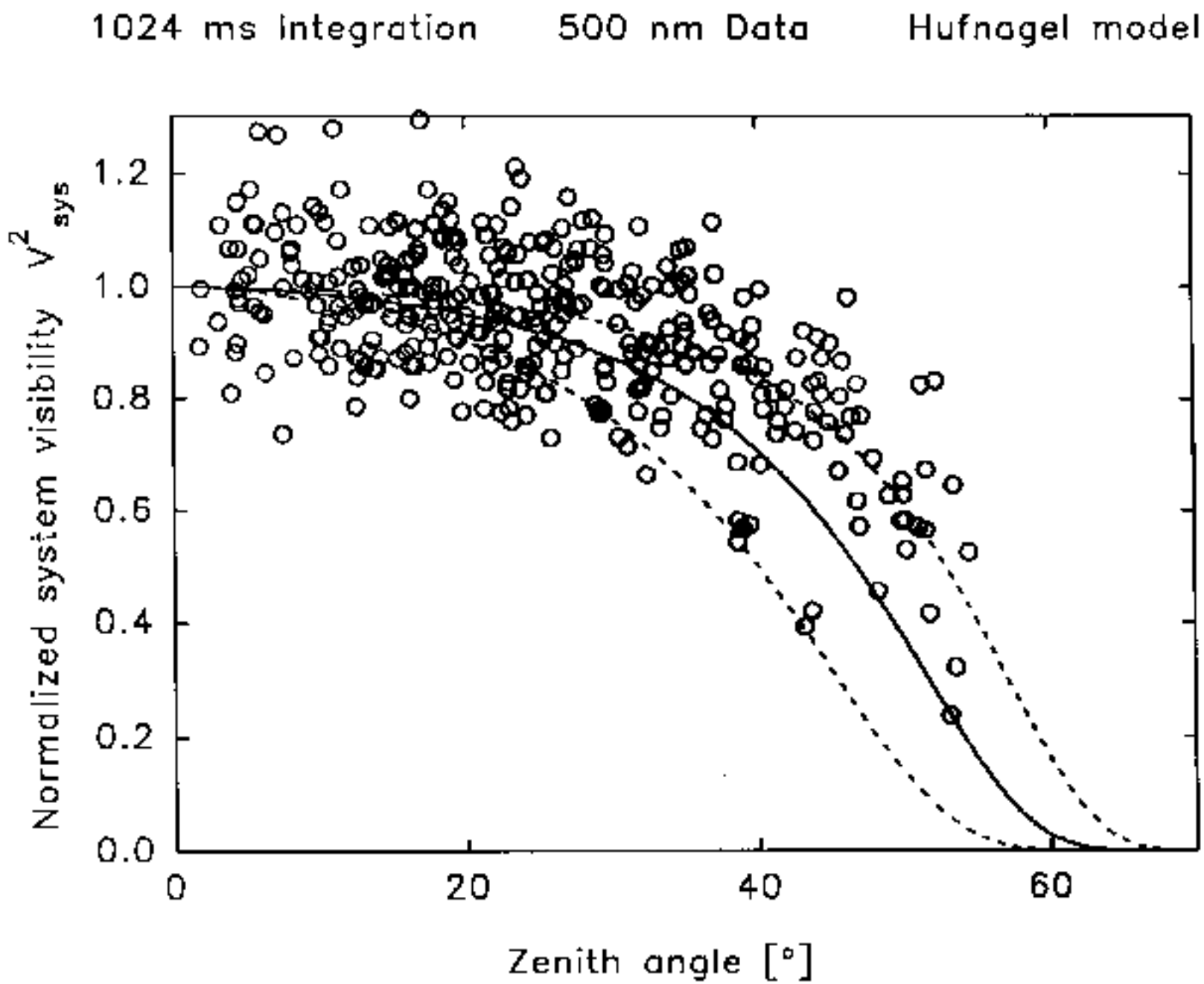

Arcturus 550 nm
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
Formal Error of V^2_{cal}
−0.001
0.000
0.001
Calibrated Visibility Squared V^2_{cal}
4 ms
32 ms
256 ms
1024 ms

Decorrelation Effects

- Photon noise in tracking channel
- Color and visibility dependence of effective tracking wavelength
- Stroke mismatch (A, B, C, D don't correspond exactly to $\lambda/4$)
- Fringe jumps ($\phi_t \rightarrow \phi_t \pm 360°$)
- Dispersion ($\phi_{\mathrm{atm},\,s} \neq \frac{\lambda_t}{\lambda_s}\phi_{\mathrm{atm},\,t}$), can approximately be taken into account in definition of referenced phase)
- Anisoplanatism (if tracking on off-axis source)
- Differential refraction (light at λ_t and λ_s takes different paths)
- Diffraction

Hufnagel model atmosphere 700 nm reference




1024 ms Integration
500 nm Data
Hufnagel model
Normalized system visibility V^2_{sys}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
Zenith angle [°]

Mourard et al., Nature 342, 520 (1989)

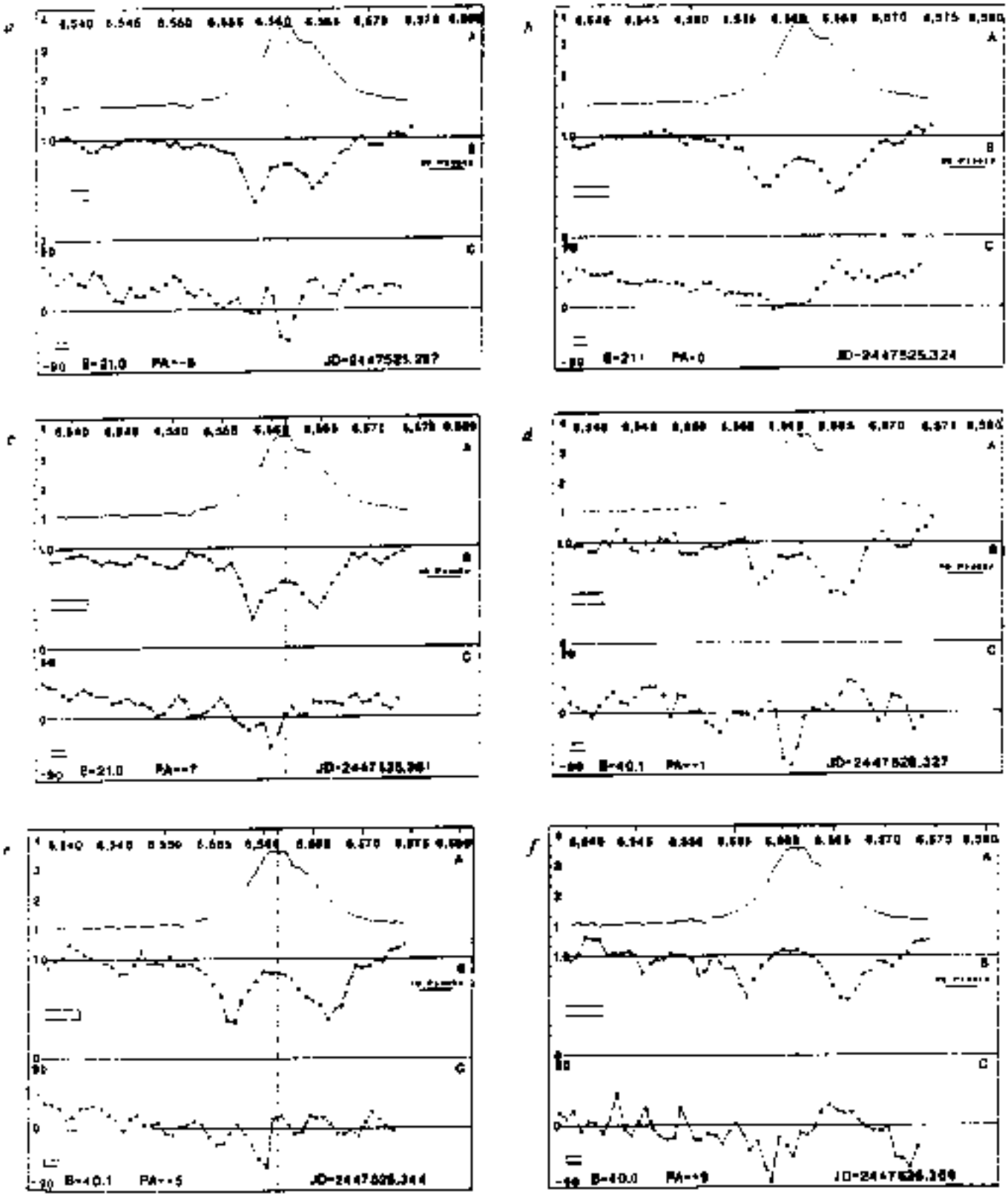
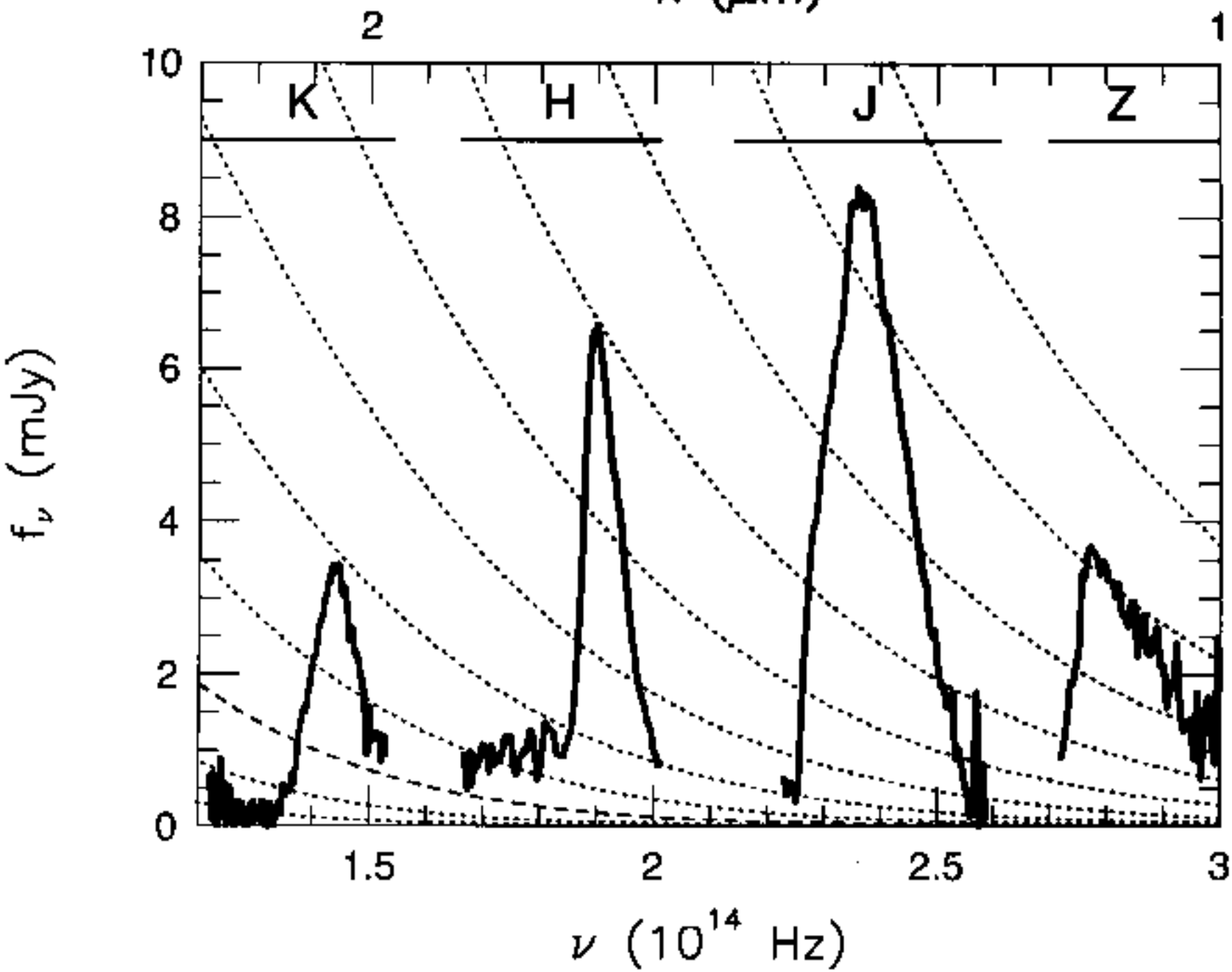


FIG. 1 Spectrum (A), with relative visibility structure (B) and phase (C) as a function of wavelength, across the hydrogen alpha emission of γ-Cas. B (in metres) is the baseline projected on the sky, PA (in degrees, from north to west) the position angle of the baseline and JD the julian date of the observation. The visibility drop in both wings of the line is evidence for a hydrogen structure rotating with high velocities. Among the noisy phase curves a significant disturbance also occurs at the line position. Because the line profile varied markedly from night to night, differences between corresponding curves may be linked to the changing morphology. The uncertainty boxes shown indicate, vertically, the r.m.s. noise level and, horizontally, the width of the sliding window used to reduce the spectral resolution. The signal-to-noise ratio is approximately twice as good at the centre of the line owing to the higher photon count.

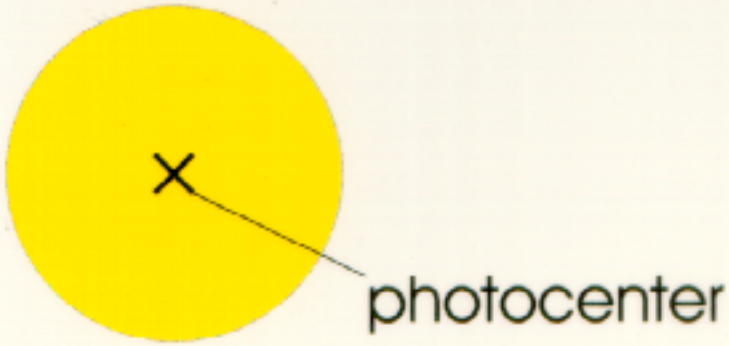
GL 229 B

Matthews et al. (1996)



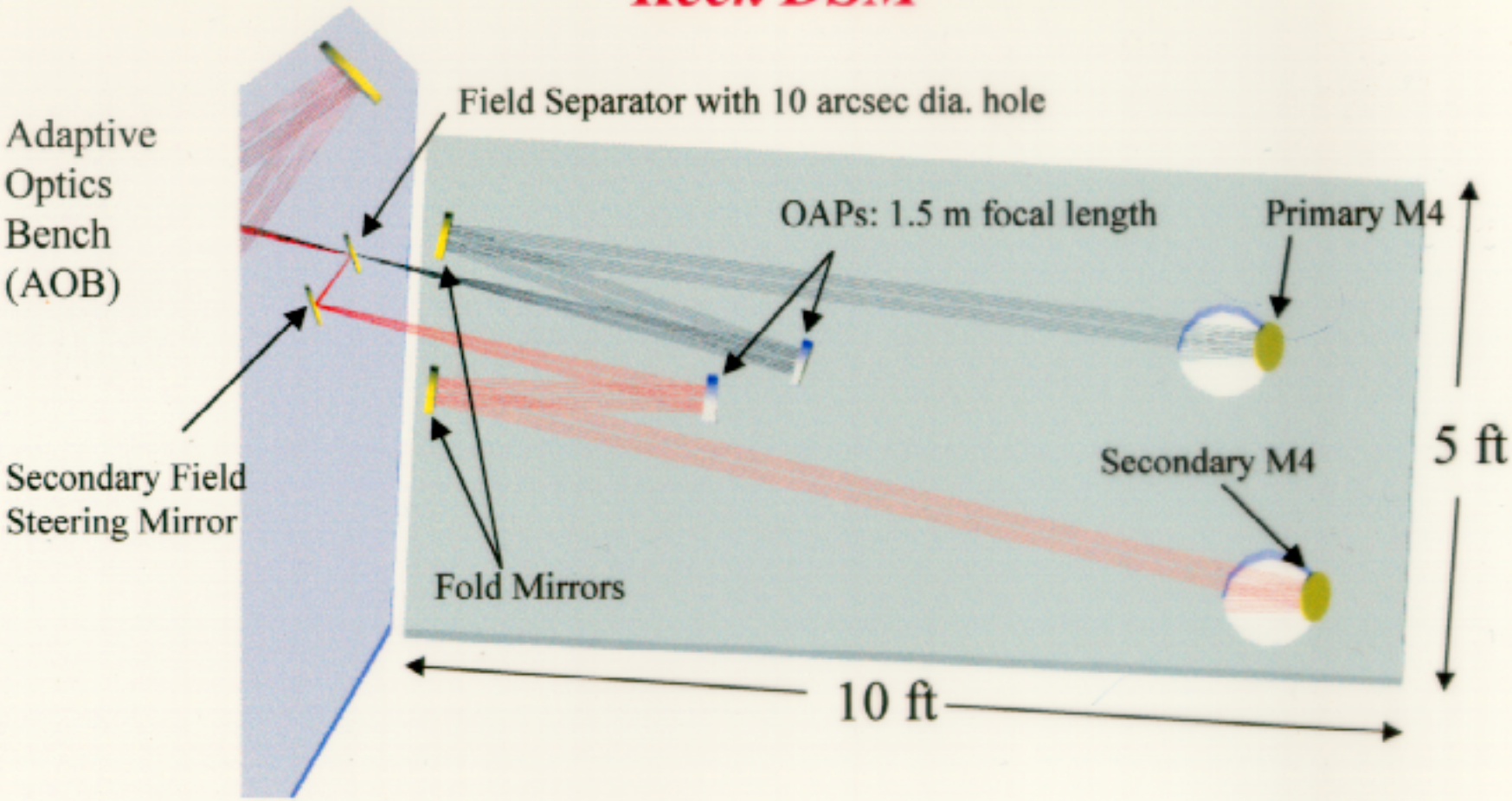
outside molecular band

inside molecular band



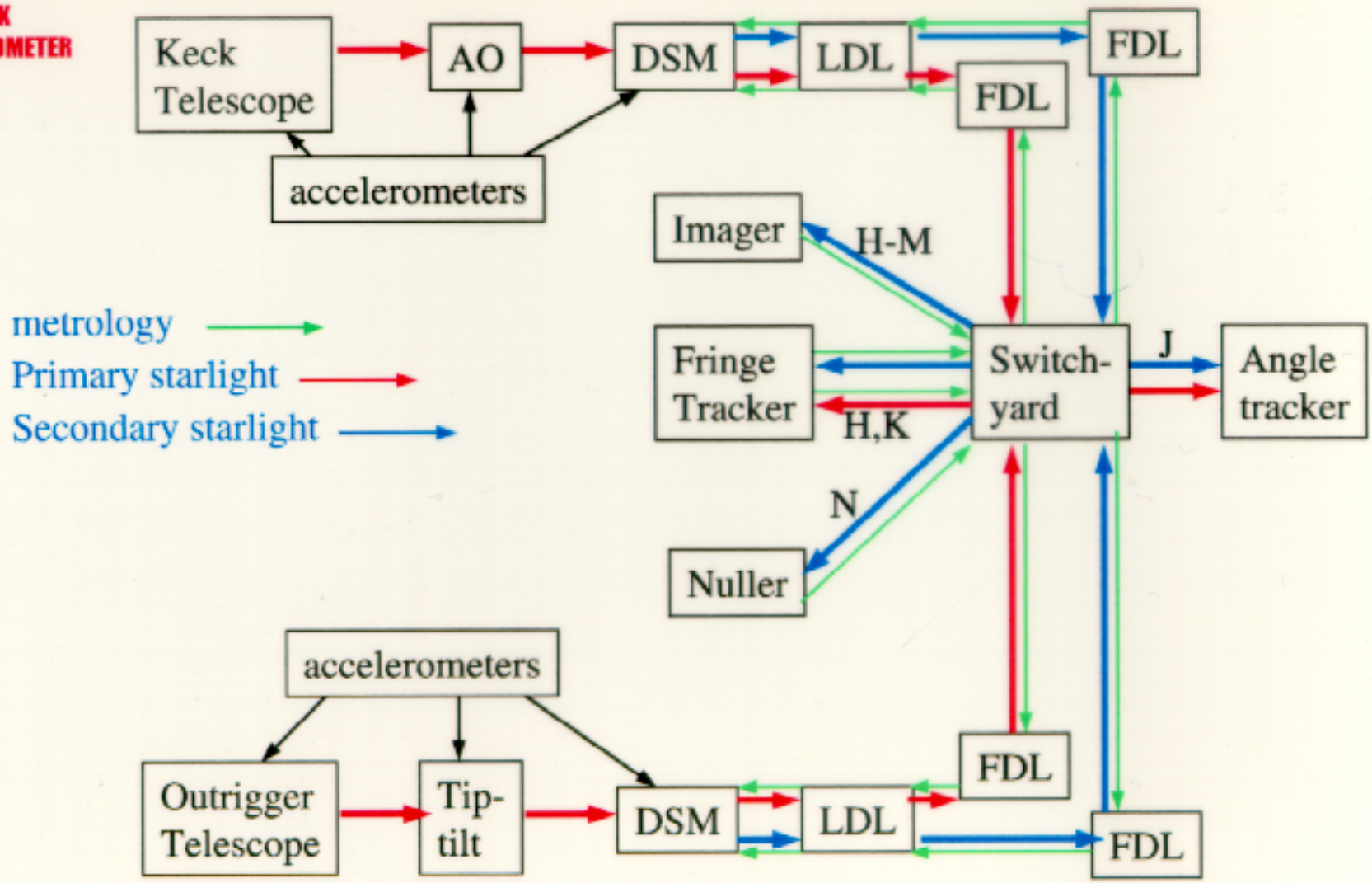
KECK INTERFEROMETER CDR

Keck DSM



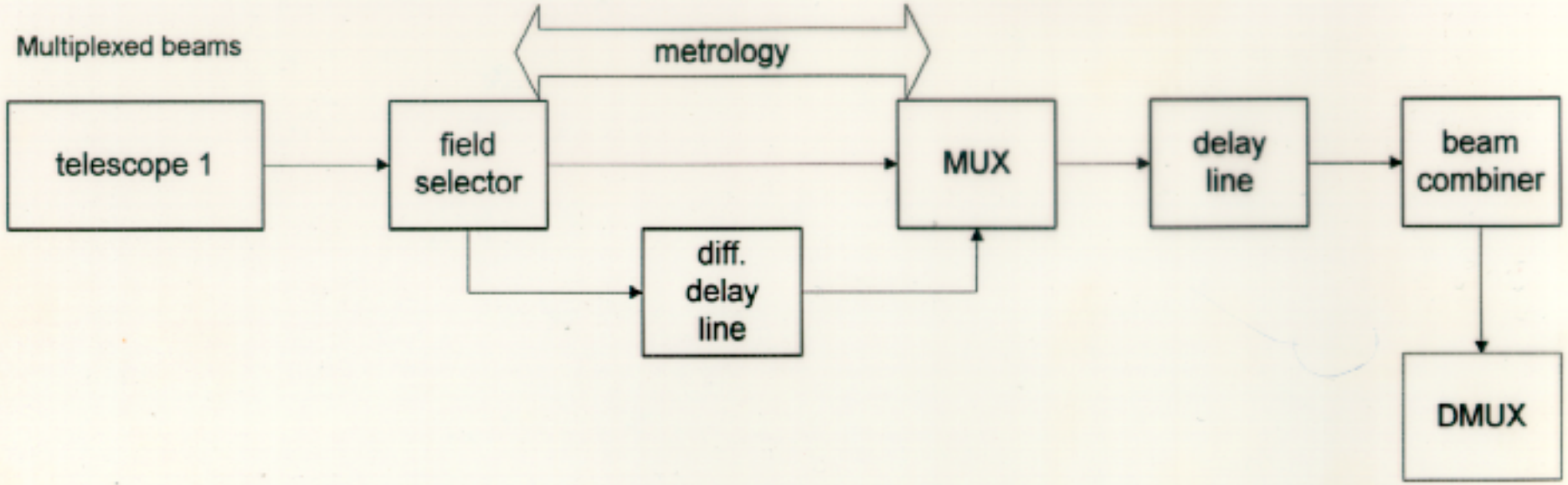
Instrument components

KECK INTERFEROMETER

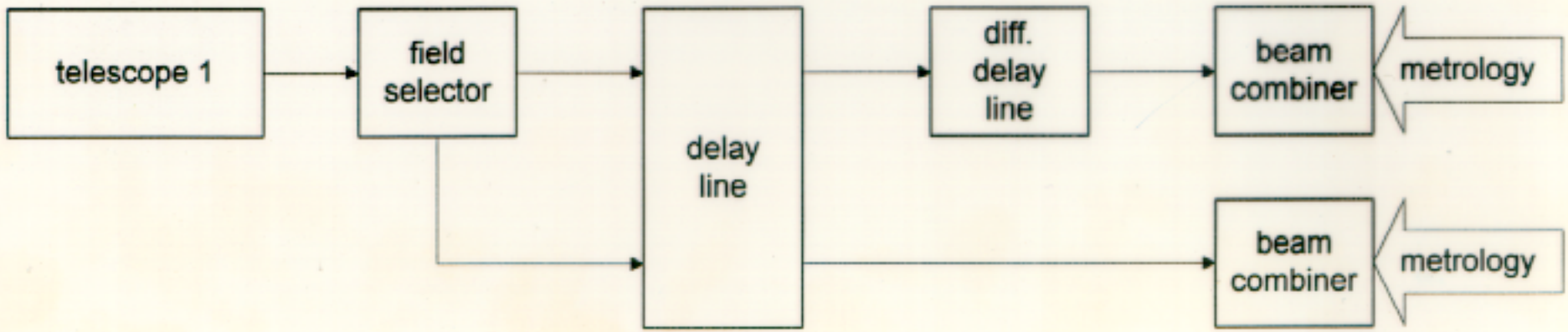


Layouts for the dual beam instrument

Multiplexed beams



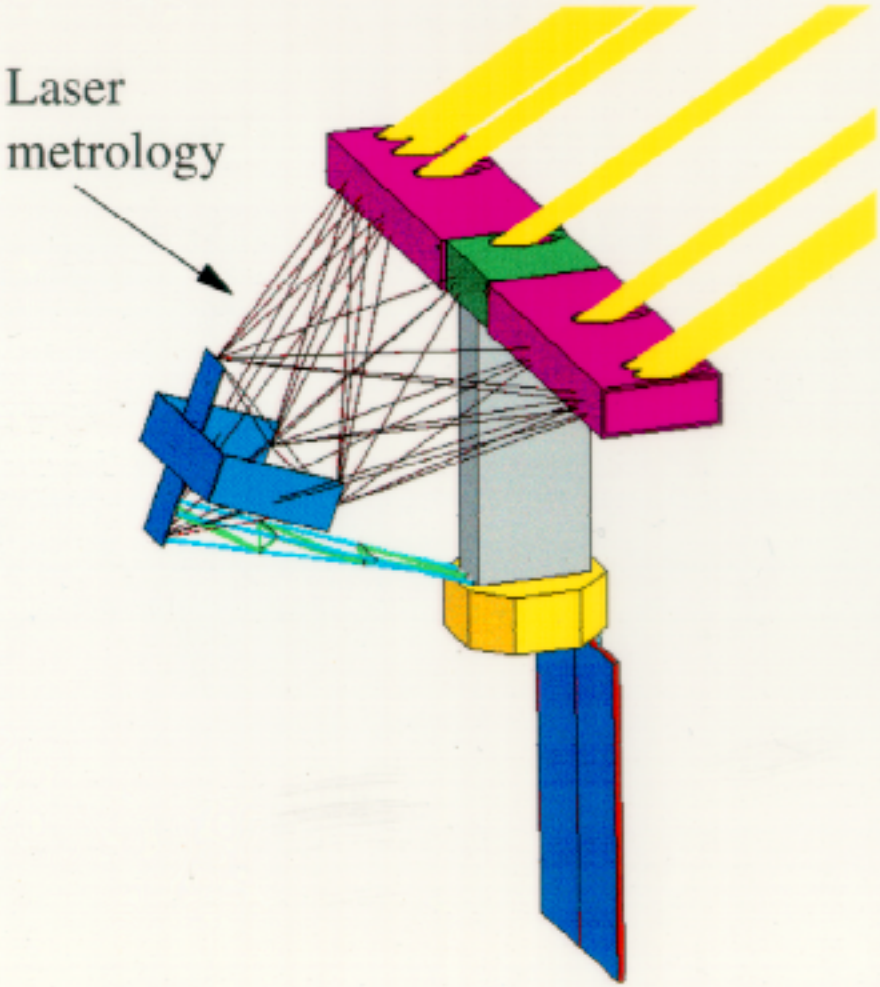
Separated beams



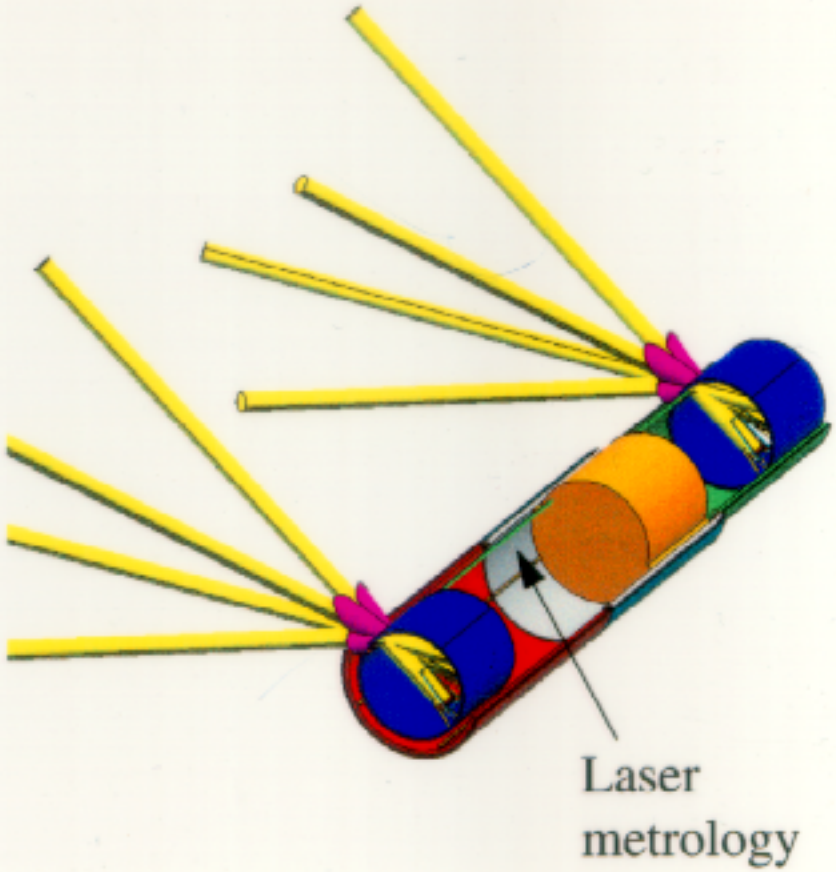
Key Science Topics for Phase-Referenced Imaging

- Active galactic nuclei, radio galaxies and quasars
- High-redshift galaxies
- Stellar population in the Galactic Center cluster
- In general: faint science close to guide stars
- In addition: observing and fringe tracking at different wavelengths

SIM Classic

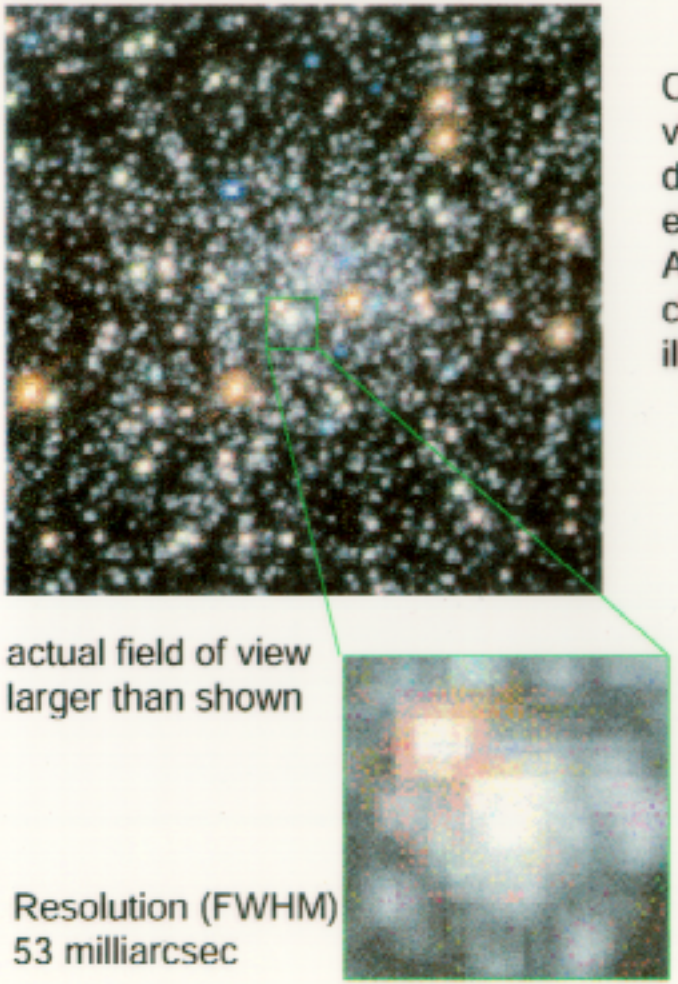


SOS



High Resolution Imaging

HST-WFPC2

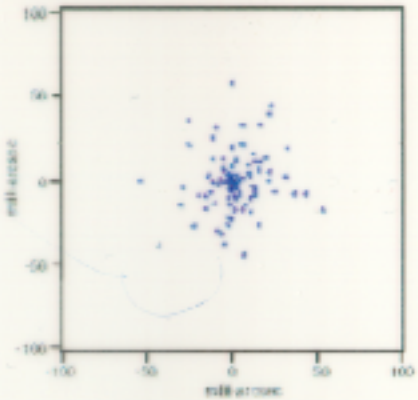


actual field of view
larger than shown

Resolution (FWHM)
53 milliarcsec

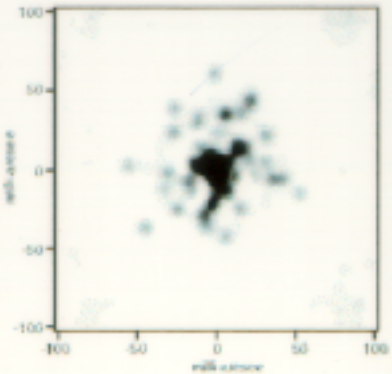
Over small fields of view SIM will show details that currently elude large telescopes. A simulated globular cluster core is used to illustrate this.

Cluster Core Model



"true star positions"

SIM



Resolution (FWHM)
10 milliarcsec

Field of View
0.3 arcsec