The Beauty and Limitations of Infrared Heterodyne Interferometry: (U.C. Berkeley Infrared Spatial Interferometer)

Dr. William C. Danchi[1]

Ringberg Workshop

September 2, 2003

[1]NASA Goddard Space Flight Center

Outline

- Introduction (some facts about ISI and its history)
- Heterodyne Detection
- Heterodyne vs. Direct Detection
- The Infrared Spatial Interferometer – Technical Details and Third Telescope Upgrade
- Examples of Scientific Results
- Future Improvements

The Infrared Spatial Interferometer (ISI) – A Heterodyne Interferometer for the Mid-Infrared

Science Team:

C.H. Townes (PI-Berkeley)

J. Weiner (Post-doc)

S. Tevosian (Ph.D. student)

D. Hale (on-site scientist/engineer)

Collaborators:

W.C. Danchi (former PI- now at NASA GSFC)

+ post-docs (D. Wallace, J. Rajagopal)

+ Ph.D. Student (R. Barry)

J.D. Monnier (U. Michigan)

System Description

•Three Pfund-design telescopes consisting of 2 m flat mirror and 1.65 m parabola

•Maximum baseline 75 m

•CO_2 laser local oscillators (discrete frequencies available from 9-12 μm, DSB detection 5 GHz total bandwidth

•Delay line in rf cable segments of ~1 cm minimum length

•Lobe rotation to fix fringe frequency

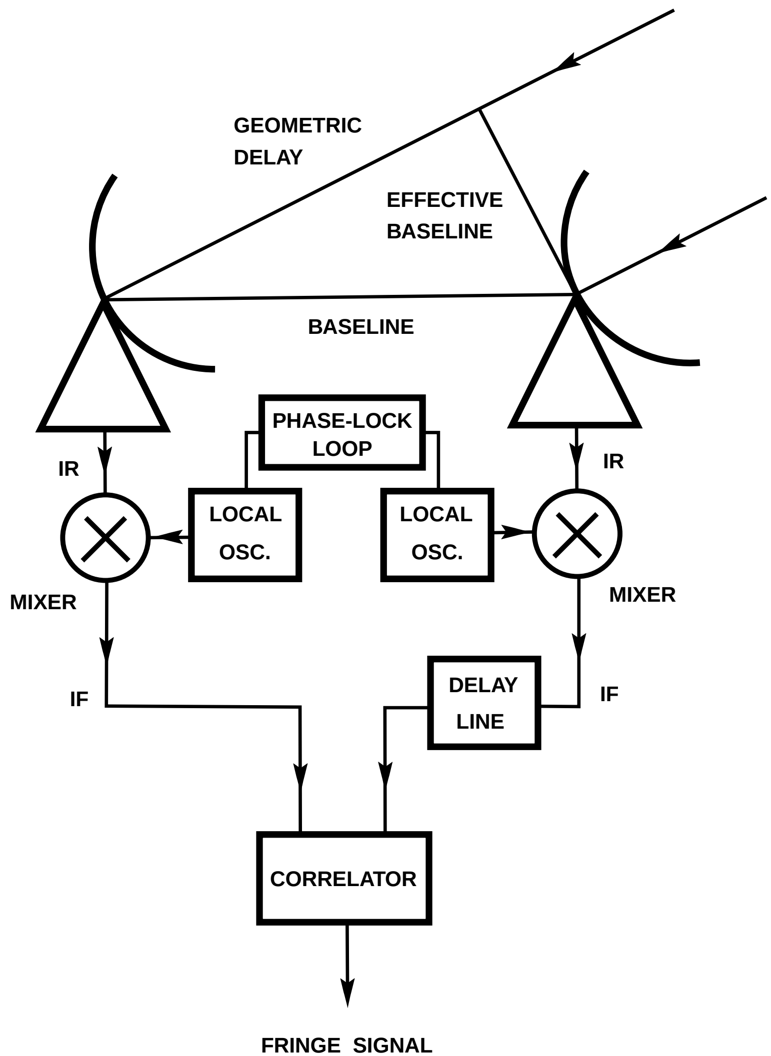
•Filter bank system to measure fringe visibility on and off spectral lines

•Near-infrared guide cameras (2.2 μm) since sources heavily obscured by dust emitting little visible energy

ISI Program History

- Funded by DARPA/ONR for two telescopes in FY83.
- Part of a program for long baseline interferometry, ISI was the IR part of the program and the Mark III was the optical part of the program.
- Construction phase – 1983-1988
- First fringes – June 1988
- First refereed paper – W.C. Danchi, M. Bester, C.G. Degiacomi, P.R. McCullough, and C.H. Townes, "Location and Phase of Dust Formation in IRC+10216 Indicated by 11 Micron Spatial Interferometry," *Astrophysical Journal*, **359**, L59-L63 (1990).
- Major optical and detection system upgrades in the early 1990's in ONR and NSF grants to Townes and Danchi.
- By mid-1990's it became clear that many dusty mid-infrared sources were asymmetrical. See Bloemhof et al., *ApJ* **333**, 300 (1988), and Lopez et al. in *ApJ* **48**, 807 (1997)
- This and the knowledge that closure phase imaging was successful at radio wavelengths prompted us to move forward with plans to expand the ISI. And we had been successfully operating the ISI for several years.

Simplified Block Diagram – Heterodyne Interferometer



- IR light mixed with Local Oscillator
- Signal down-converted to IF band
- Delay compensation at IF
- Simple multiplying correlator

Heterodyne Noise Power

$$N_{het} = h\nu\sqrt{\frac{2\,\Delta\nu}{t}}$$

- Heterodyne noise power
  - One quantum per second per unit bandwidth, for same polarization as LO
  - Result from uncertainty principle for phase and number of photons

•$h\,\nu$ is quantum energy

•$\Delta\nu$ is single sideband bw

•t is post-detection averaging time

Direct Detection Noise Power

$$N_{direct} = \sqrt{\frac{2\Delta\nu}{t} \frac{1-\varepsilon}{e^{h\nu/kT} - 1}}$$

- ε is transmission of optics
- T is temperature of optics
- $h\nu$ is quantum energy
- $\Delta\nu$ is bandwidth
- t averaging time

- For background limited case depends on temperature of optics and atmosphere
- And on transmission through system
- Noise due to fluctuations in number of quanta in received radiation

Heterodyne vs Direct SNR Comparison

$$\left(\frac{S}{N}\right)_{het} = \frac{P_\nu}{h\nu}\sqrt{2\,\Delta\nu\, t}$$

$$\left(\frac{S}{N}\right)_{direct} = \frac{P_\nu}{h\nu}\sqrt{\frac{2\,\Delta\nu\, t\ \ (e^{h\nu/kT}-1)}{1-\varepsilon}}$$

$$\left(\frac{S}{N}\right)_{direct} \Big/ \left(\frac{S}{N}\right)_{het} = \sqrt{\frac{e^{h\nu/kT}-1}{1-\varepsilon}}$$

- For equal bandwidths direct detection has a substantial advantage, particularly at short wavelengths, i.e., visible
- For T = 293 K and ε =0.9, the advantage is a factor of 37 at 10 μm
- However practical considerations reduce this advantage …

Real World Complications

1. The *transmission, ε, is generally very low for direct detection* systems, ~0.01-0.03, whereas *it is much higher for heterodyne systems*, ~0.3.
2. The *time scale for integration, t, in direct detection is often very small, due to necessity of rapid tracking of fringes*, ~0.01-0.1 sec, and it is typically an all or nothing situation. *This is not true for heterodyne detection since there is no active fringe tracking*.
3. There is *no loss in signal-to-noise to split the IF and pairwise combine the IFs for any number of telescopes*. *In direct detection you lose signal power as 1/(N-1), where N is the number of telescopes.*
4. Because the LO (which has a perfect wavefront) is mixed with the radiation from the source, only the parts of the source wavefront that is in phase with that from the LO is mixed. (Mixing Theorem). There is a *natural spatial filtering effect*. Also the total power in each telescope is easily measured without loss of SNR. So *it is easy to make a visibility measurement resistant to seeing and pointing errors*. *Fibers now allow this for direct detection, but with loss of SNR.*
5. *For heterodyne systems, delay compensation at IF, with ~ 1 cm increments, so it is done electronically.*
6. *Correlation is done electronically, with wide-bandwidth analogue electronics.*

Conclusion – The situation is more complicated than most people are aware of.

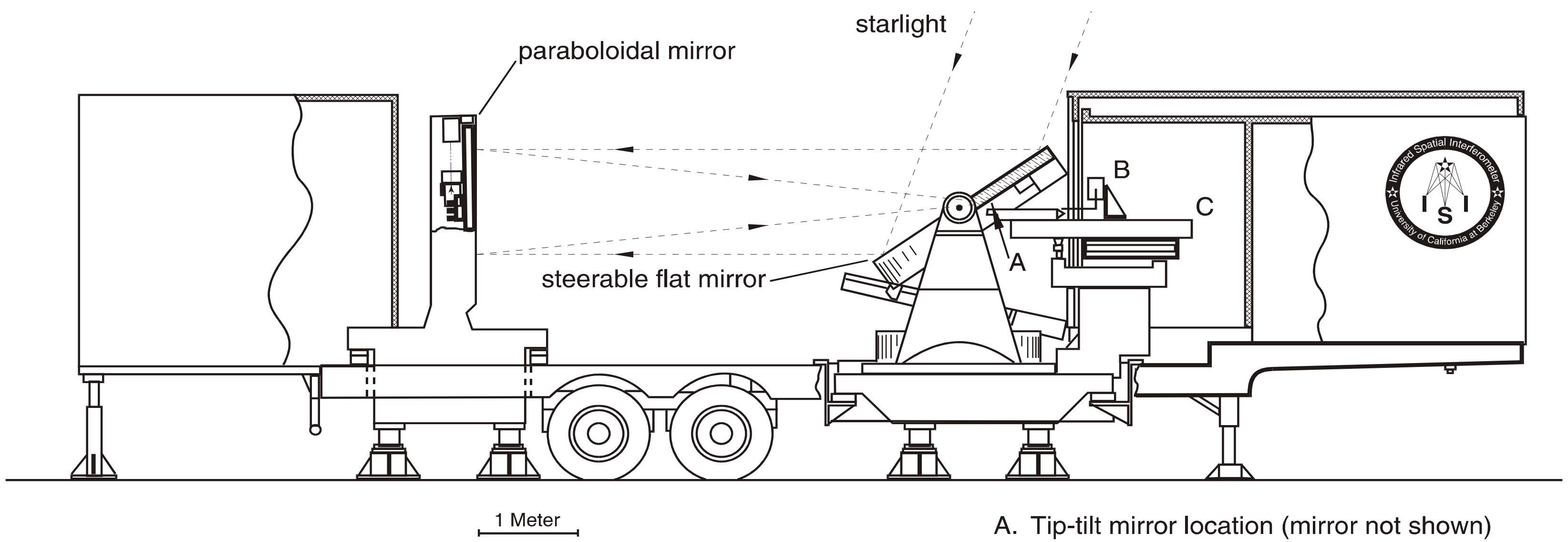
What does this mean?

- Direct detection systems often provide less of an advantage than generally thought.
  - Using $\varepsilon = 0.01$, and $t=0.01$, then theoretical advantage is: $(SNR)_{direct}/(SNR)_{het} \sim 1\text{-}2$.
  - The only real advantage left is bandwidth, which gives a factor of ~10, assuming 10% bandwidth at 10 μm for direct and 4 GHz IF (DSB) for heterodyne.
- Conclusion is break-even point is ~6-10 telescopes for current technologies.
- MIDI sensitivity of 100 mJy is reasonable, as it is about a factor of 4 better than ISI (50-100 Jy), scaling with telescope area (factor of 23) and bandwidth (factor of 10), but this factor is lost if one does beam combination with more than 3 telescopes!!!
- ***Heterodyne detection could be interesting for all four unit telescopes (VLT-HI) in mid-infrared!***

Another heterodyne advantage

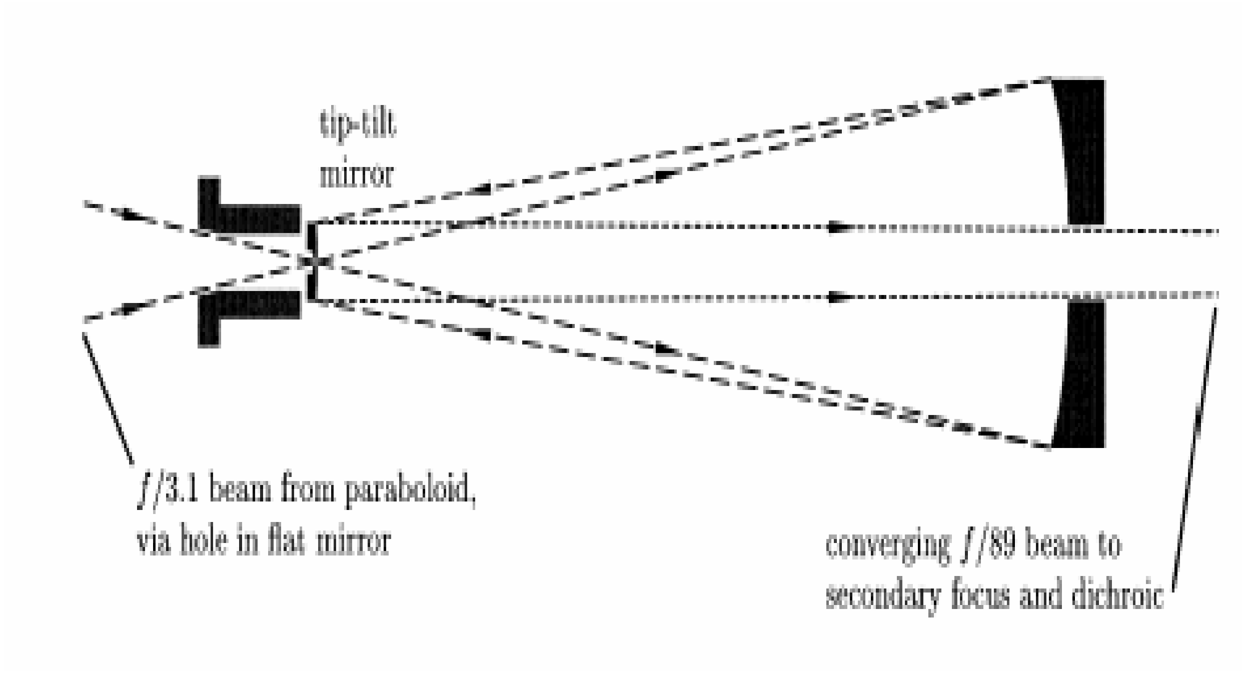
- Spectroscopy on narrow spectral lines, e.g., ammonia, silane, …, where R ~10^5-10^6.
- Measure visibilities on and off spectral lines to learn distribution of molecules relative to distribution of dust (Monnier's thesis).
- In this case heterodyne detection can have higher SNR than direct detection …

Schematic View of ISI Trailer

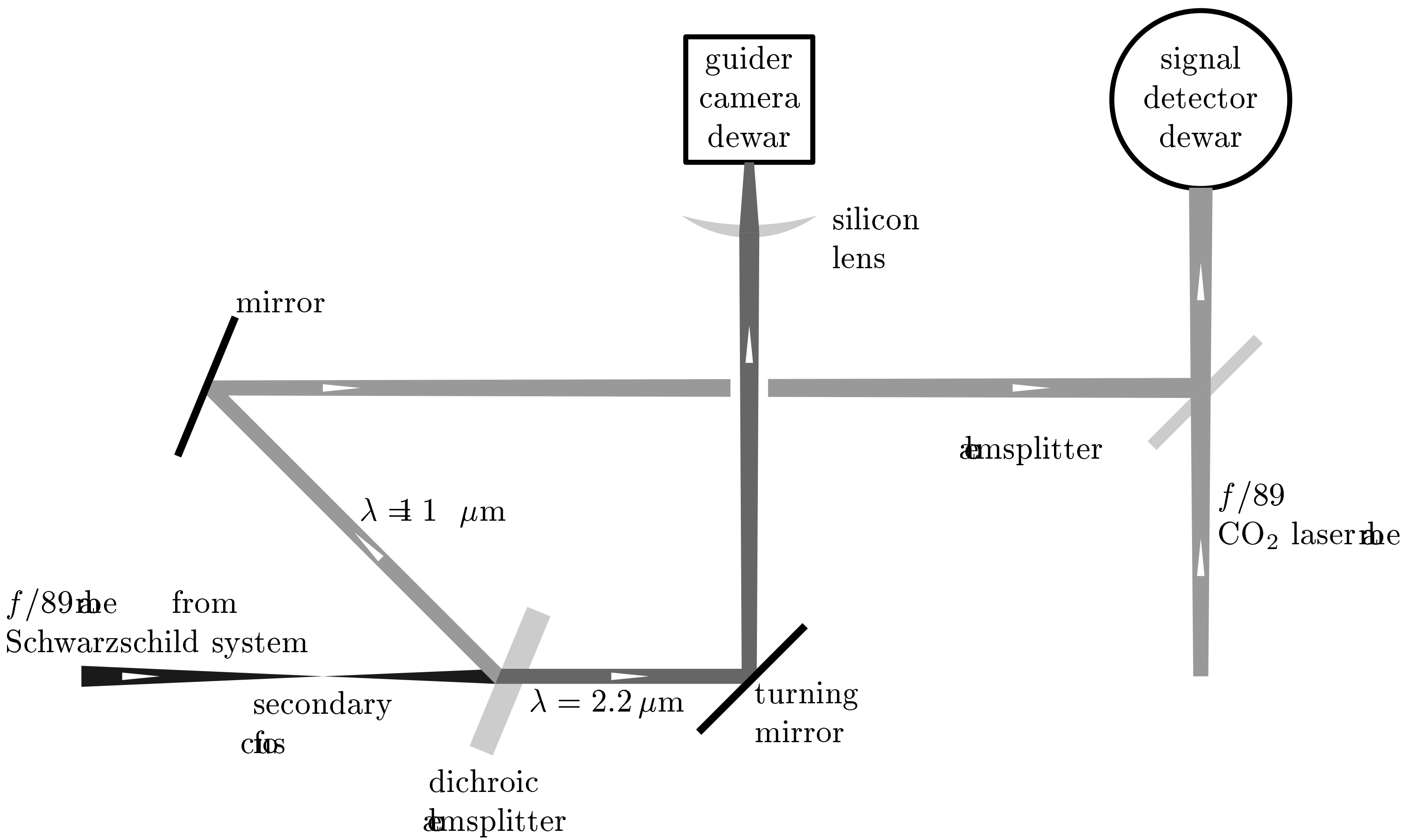


A. Tip-tilt mirror location (mirror not shown)
B. Large Schwarzschild mirror mount
C. Optics table

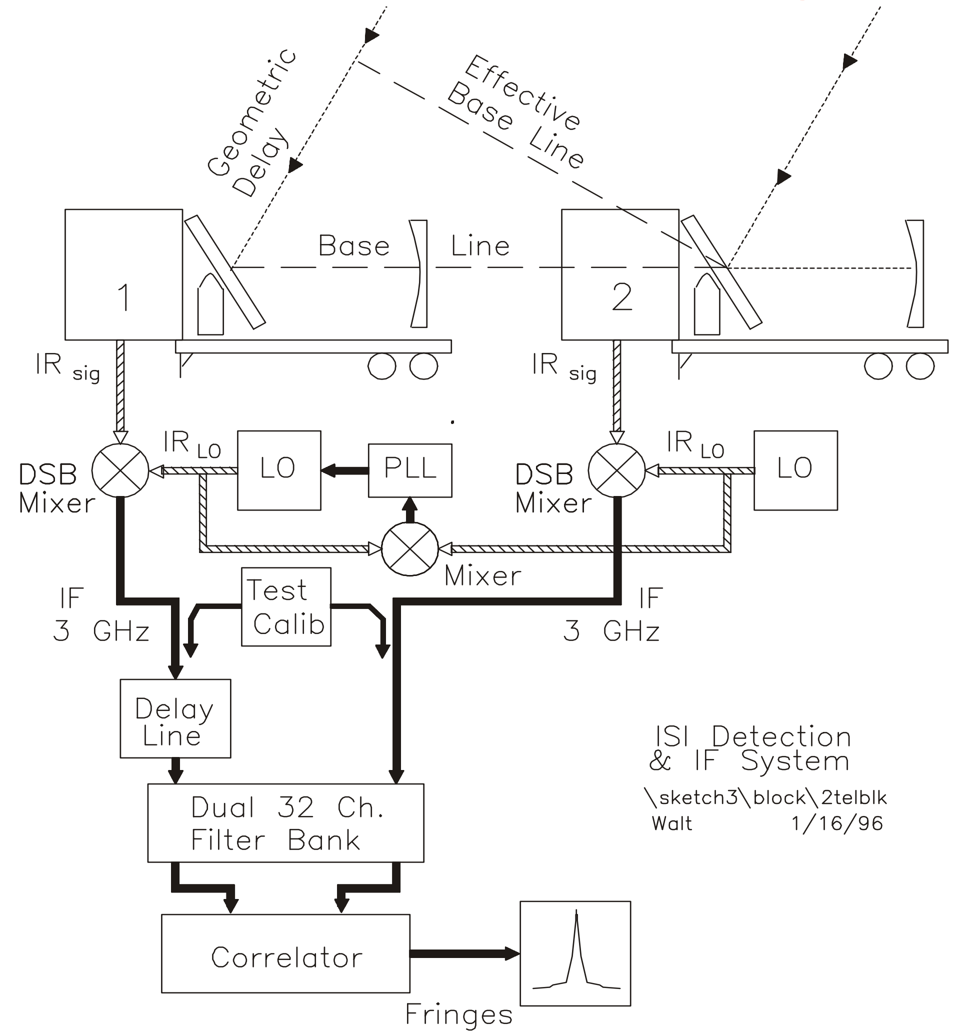
Schwarzschild Optical System



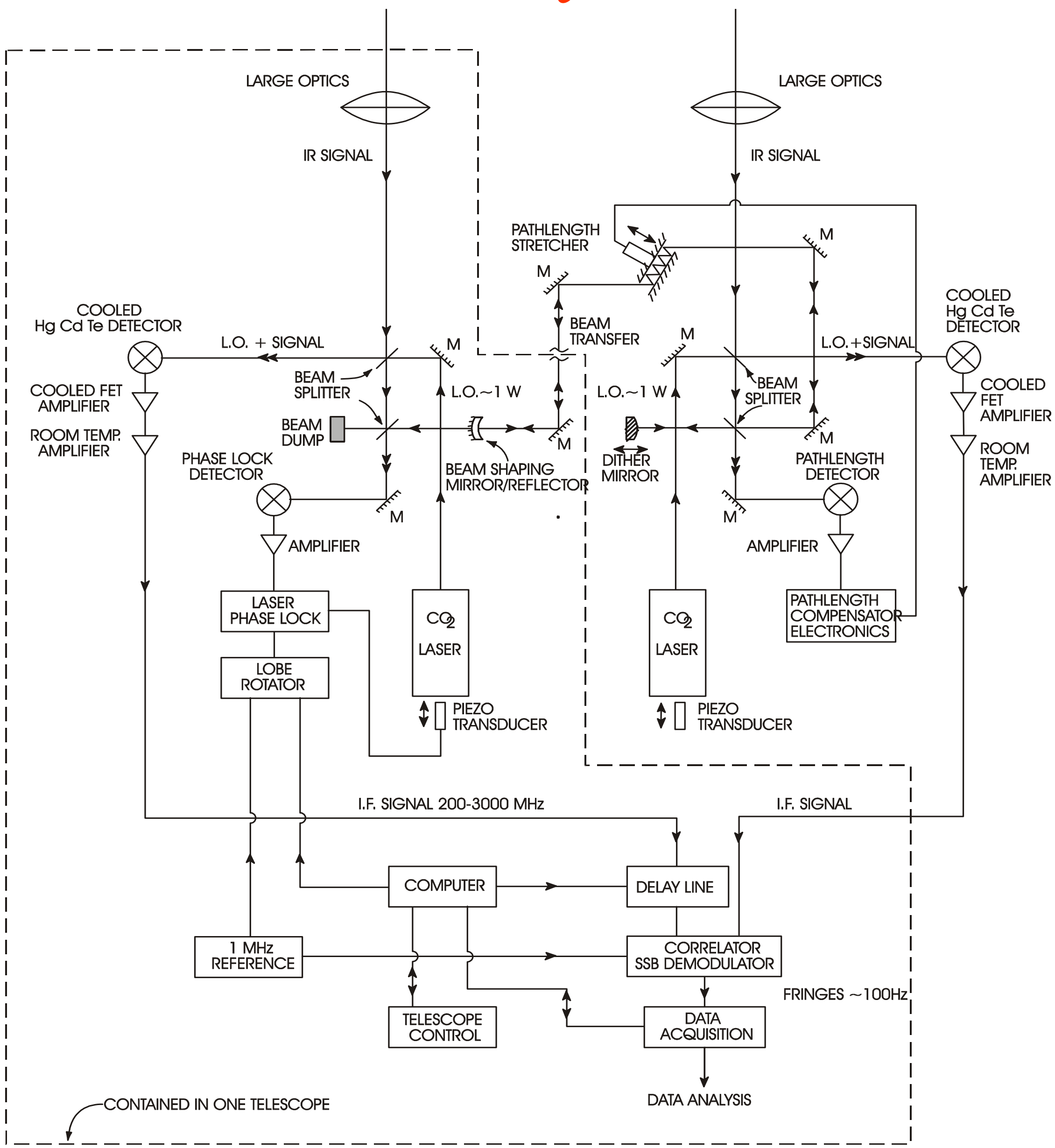
ISI Guiding Camera Optics



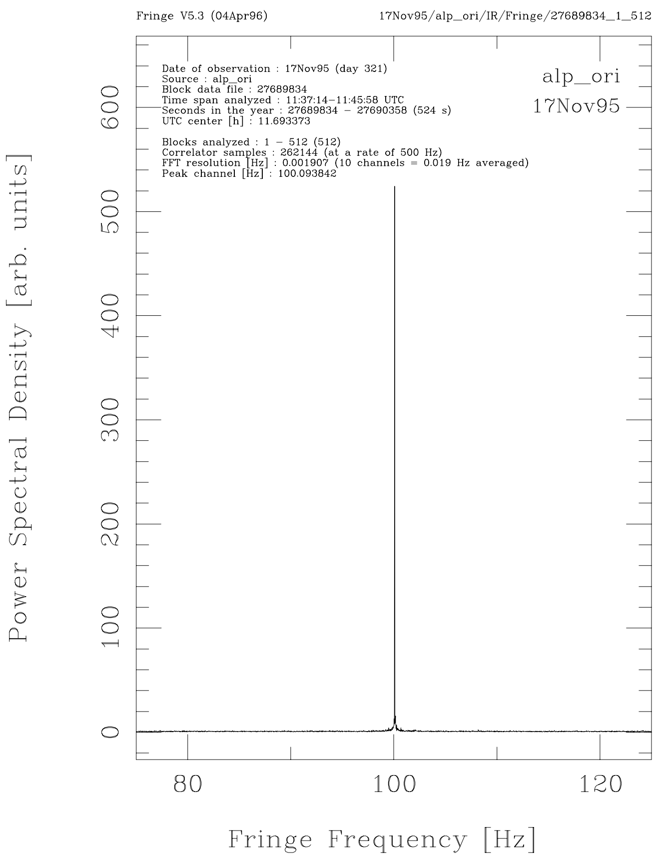
ISI Detection System
Simplified Block Diagram

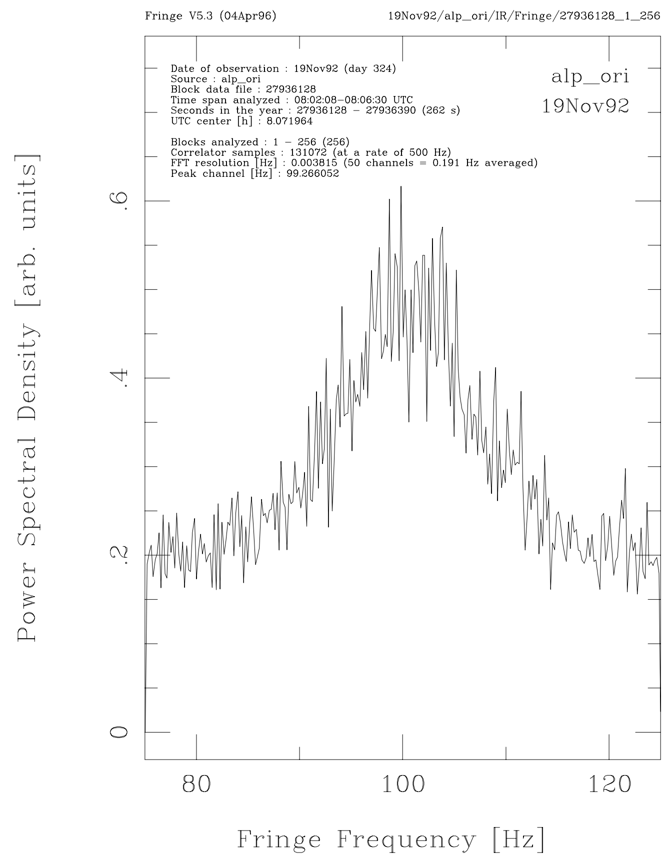


Detailed Detection System Block Diagram

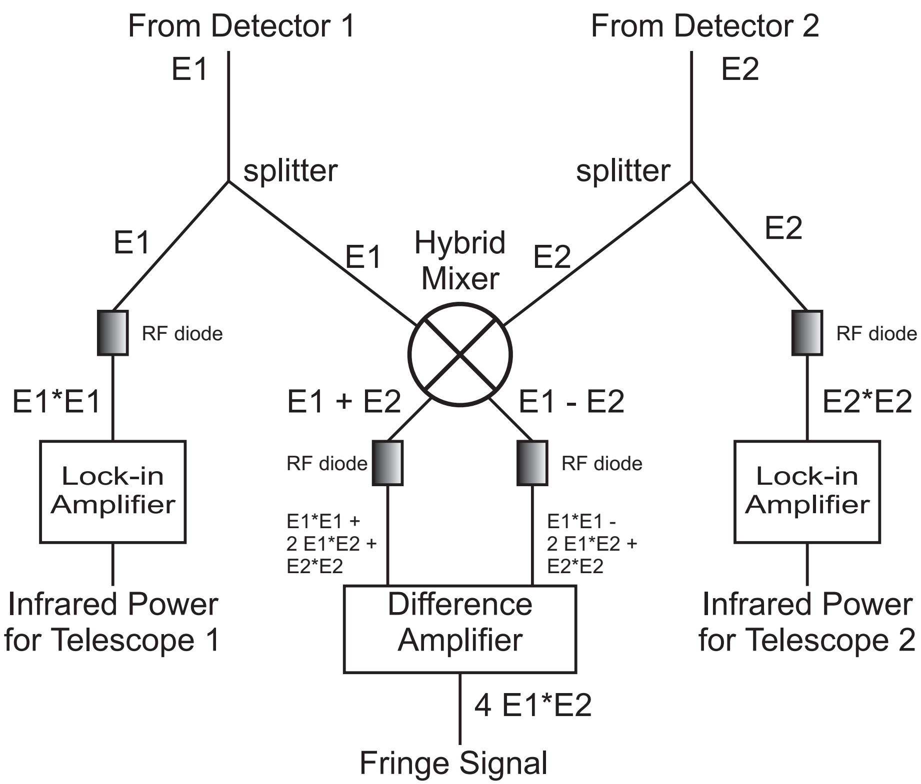


Example of ISI Fringe Detection





Visibility Measurement



$$Vis = \sqrt{\frac{P_{fringe}}{IR_1 \times IR_2}}$$

- This measurement of visibility relatively insensitive to intensity fluctuations due to pointing errors, etc.
- Visibilities calibrated by observations of point sources

Third Telescope Program History

Funded primarily through the NSF ATI program.

A. Initial grant 1996-1999 (May) for $2.1 million – Danchi (PI), Townes, Bester (co-PIs)

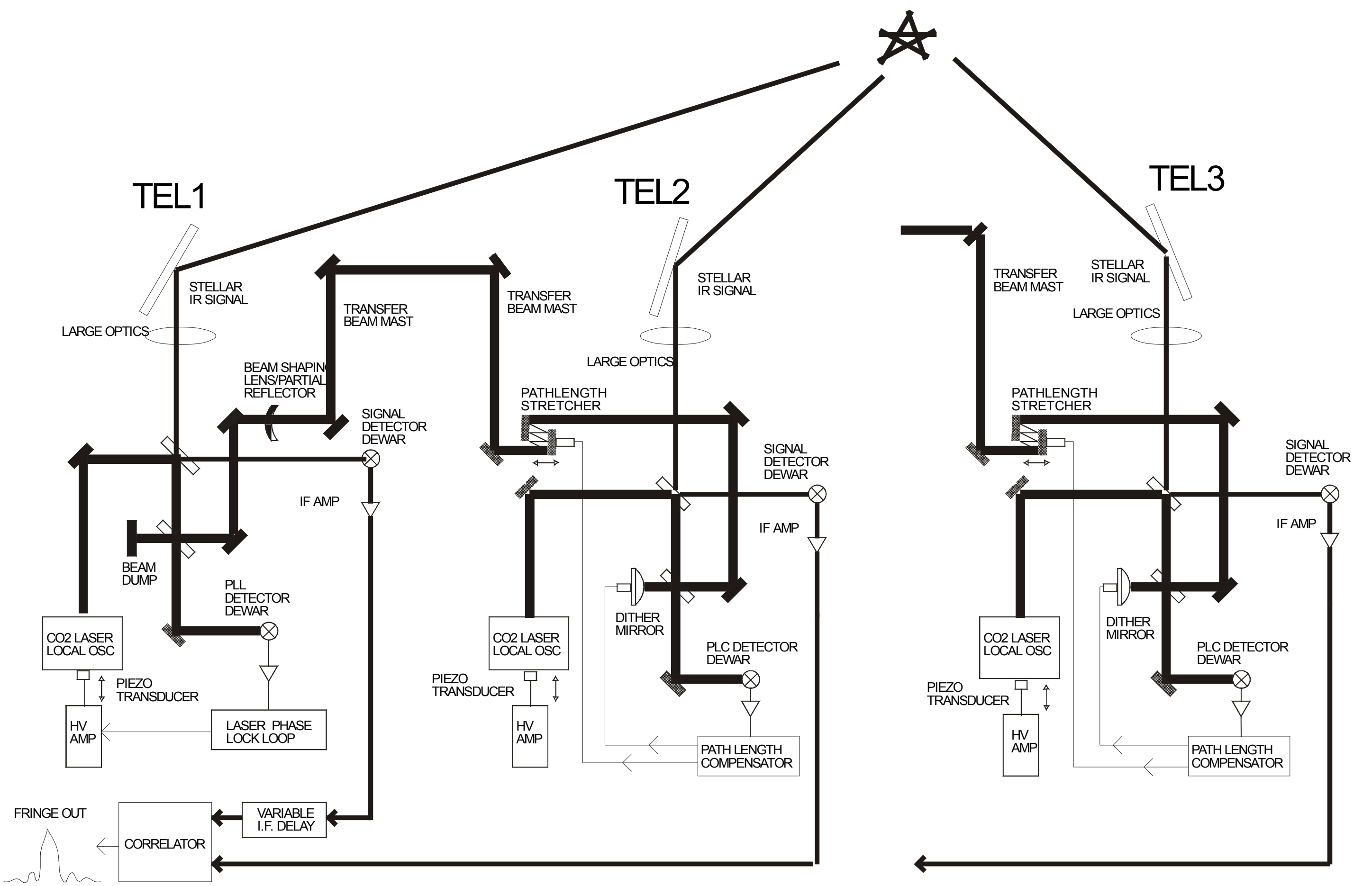
- For construction of third telescope only.

B. Second grant 1999 (Jun) - 2001 (Nov) for $1.3 million – Danchi (PI), Townes (co-PI)

- Completion of third telescope.
- Includes laser master oscillator facility, control trailer facility.
- Funds to obtain first closure phases.

C. Additional funds from Packard Foundation, NASA, and Gordon & Betty Moore Foundation

ISI Expansion Phase I

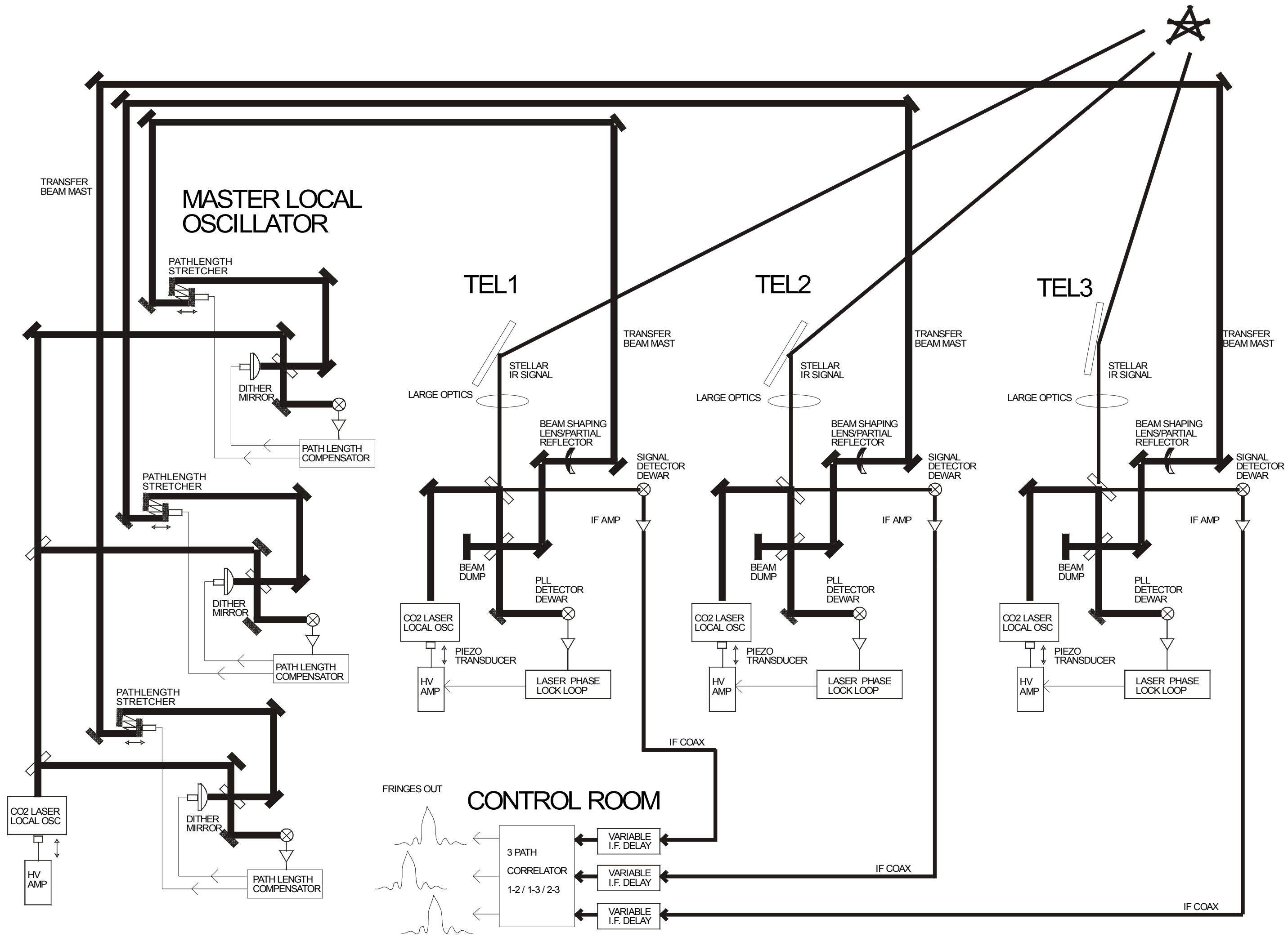


Note: Telescope 2 is shown operational; telescope 3 is on standby.

Infrared Spatial Interferometer Third Telescope Phase: Optics

sketch\3\3t\2t_optic.skd Walt F. 8/19/98

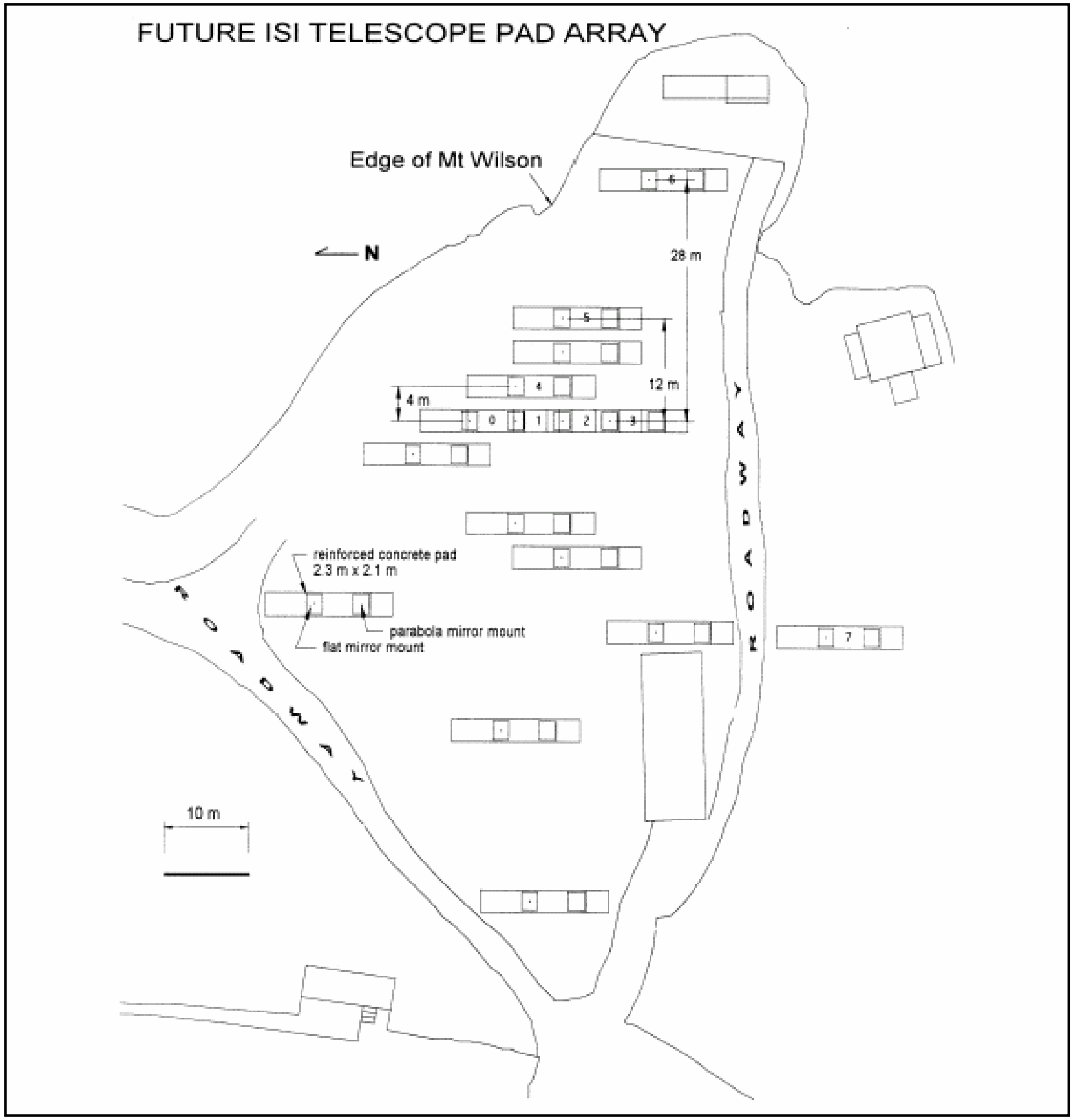
ISI Expansion Phase II



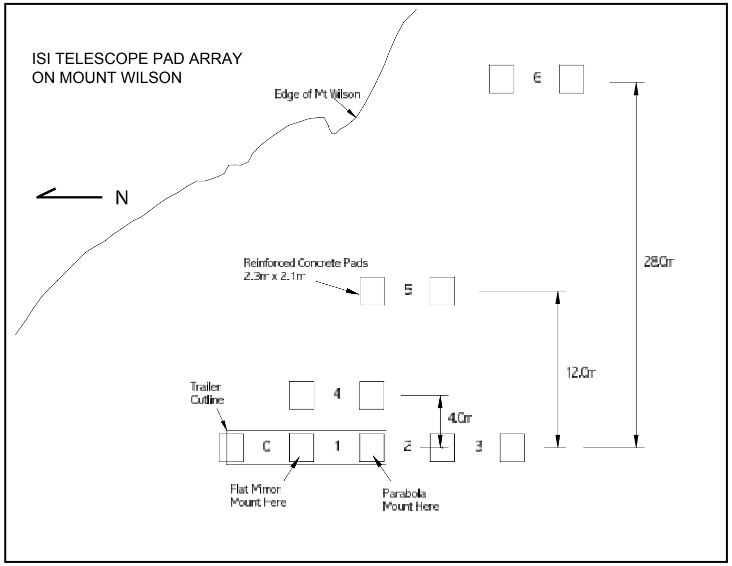
Infrared Spatial Interferometer 3 Integrated Telescope: Optics

sketch3\3t\in_optic.skd Walt F. 8/19/98

ISI Expansion Upgraded Site



Original Site



Original Observing Program Goals

Measure:

- •Sizes
- •Shapes
- •Optical Depths
- •Dynamics
- •Wavelength Dependence
- •Time Evolution
- •Spectral lines

Measurements will help us to:

1. Test theories of dust production and mass loss mechanisms
2. Constrain optical properties of dust
3. Better understand stellar evolution on the AGB
4. Spectral lines probe astrochemistry
    - •i.e., importance of grains
    - •Temperature and density structure of gas/dust envelopes

SOME KEY ISI RESULTS

•Dust is very close to photospheres for oxygen-rich Mira variables and Carbon stars, typically < 5 R_* or so. Implies dust forms within a pulsation cycle or every few cycles, time scale within a few years (<10).

•Dust is far from the photosphere on average for Supergiants like α Ori, α Sco. Implies dust formation is infrequent, time scale ~50-100 yrs.

•Multi-epoch study of o Ceti, provided evidence for dust formation and destruction in clumps. Motivated imaging program (third telescope).

•Location of SiO masers + inner radius of dust shell allowed approximate determination of atmospheric scale height for VX Sgr.

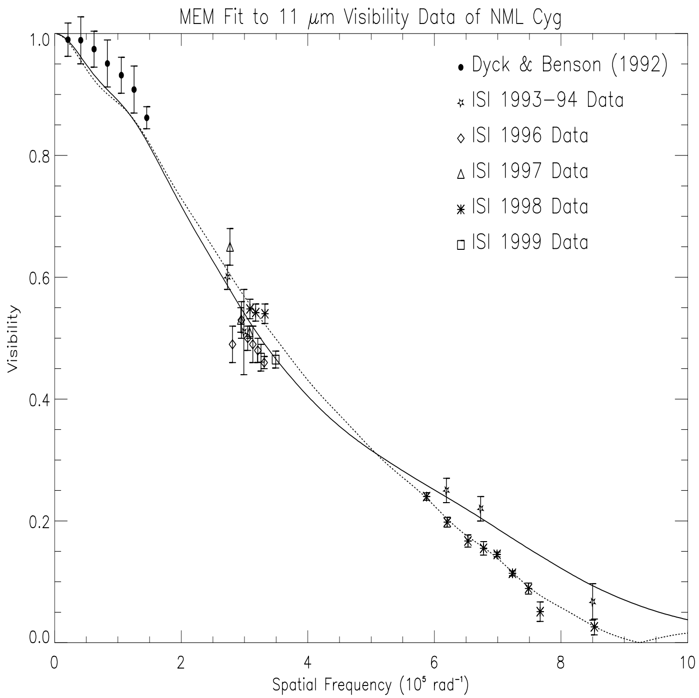
•Evidence for episodic dust formation for NML Tau and NML Cyg.

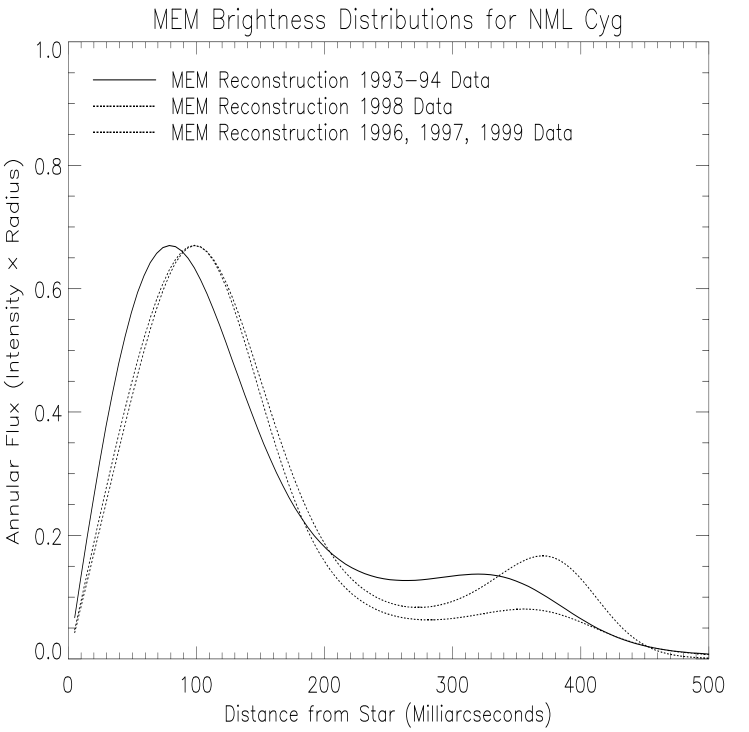
•Addition of filter bank system allowed for determination of location of molecular shells of Silane and Ammonia relative to dust inner radius. Found R_{silane} and $R_{ammonia}$ >> R_{dust} for IRC +10216.

•Most recently, precise determination of stellar diameters, (1%), with absence of contamination from molecular blanketing and hot spots.

•A LARGE NUMBER OF PUBLICATIONS HAVE RESULTED FROM THESE UNIQUE STUDIES

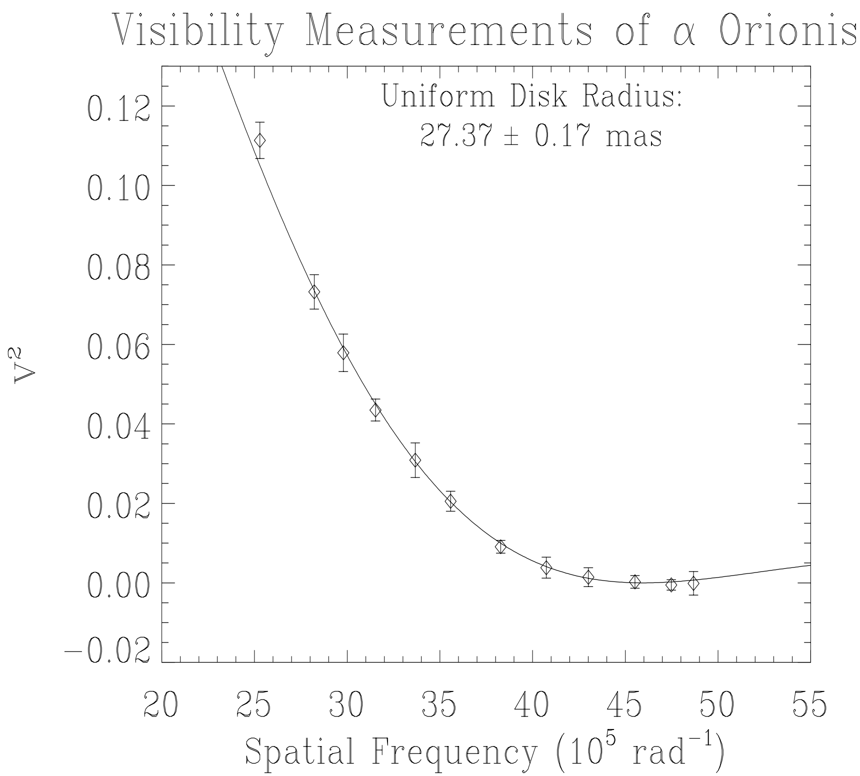
Proper Motion of Dust Shells Surrounding NML Cyg

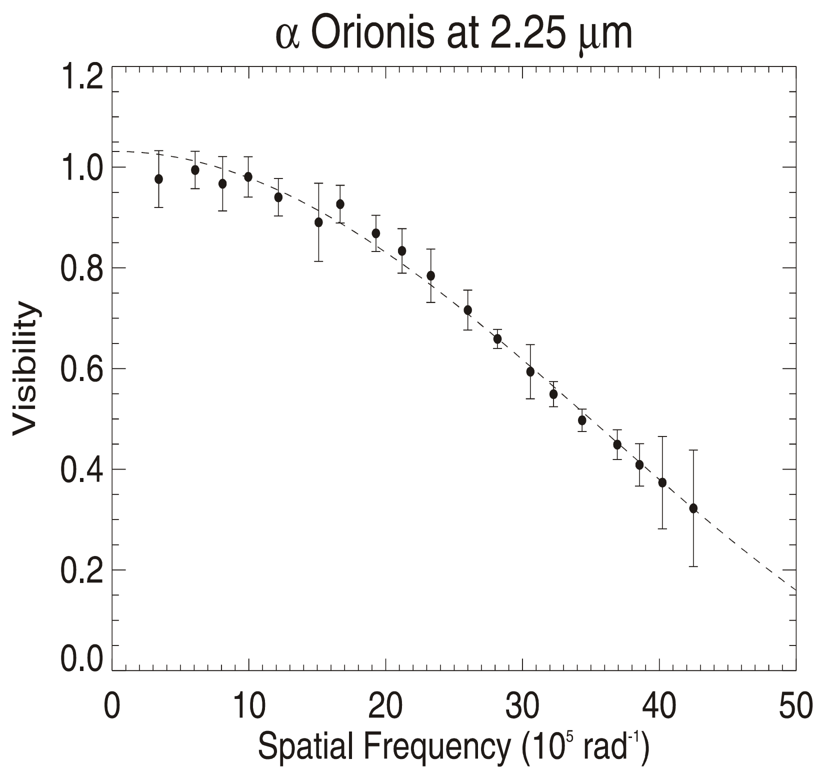




- Observed change in visibility data between 1993 and 1999
- Evidence for two discrete dust shells moving away from the star
- Time between emission of shells 65+/-14 years
- If dust velocity same as masers distance is 1220+/-300 pc
- REFERENCE: W.C. Danchi, W. Green, D.D.S. Hale, K. McElroy, J.D. Monnier, P.G. Tuthill, and C.H. Townes, *Astrophysical Journal*, 555, 405 (2001). .

Diameter of α Ori and o Ceti at 11 μm





UDD = 54.7+/-0.3

UDD = 42.6+/-1.9 mas

•Diameters are very different at 11 μm than at 2.25 μm

•Limb darkening is only 0.5% effect at 11 μm

•REFERENCE: J. Weiner, W.C. Danchi, D.D.S. Hale, J. McMahon, C.H. Townes, J.D. Monnier, and P.G. Tuthill, *Astrophysical Journal Letters*, 544, 1097, (2000).

Work in Progress

• Closure Phase has been achieved recently with 3 telescopes, with reasonable statistics, ~ 1 degree or less, rms (SEE C. H. Townes talk, next)

•Beginning observations with upgraded system

•Could use better near-ir guider cameras

•More funding support from NSF/NASA/ …

Wish List for Heterodyne and Direct Detection Interferometers

- Good, low loss 10 micron fibers, for heterodyne detection, for transmission of LO between telescopes, for direct detection, for beam clean-up and total power measurement (like FLUOR)
- Much larger bandwidth heterodyne detectors
- Solid state tunable LO sources
- Better throughput for direct detection systems
- Vacuum delay paths for direct detection systems
- Cold delay paths for direct detection systems

CONCLUSION – There is room for improvement for both types of systems!