Infrared spatial interferometer (ISI)

High Spectral resolution, high angular resolution and new techniques

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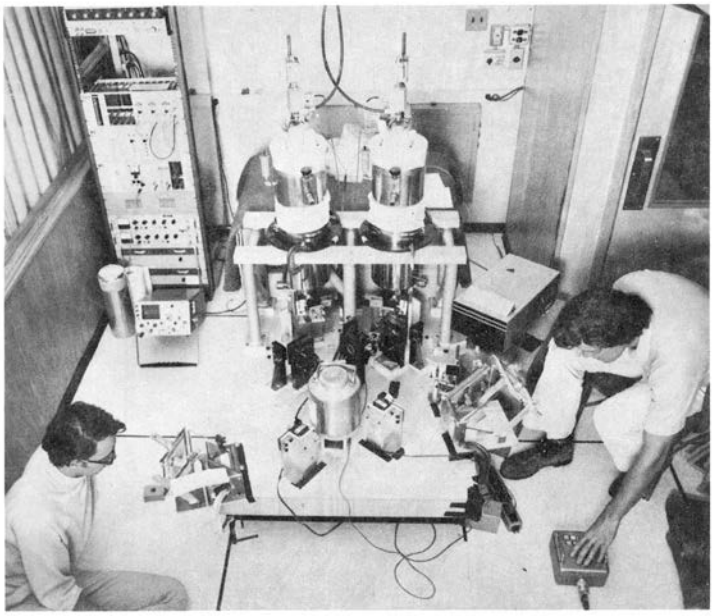
E.H. Wishnow

and many more…

Grad students get a *

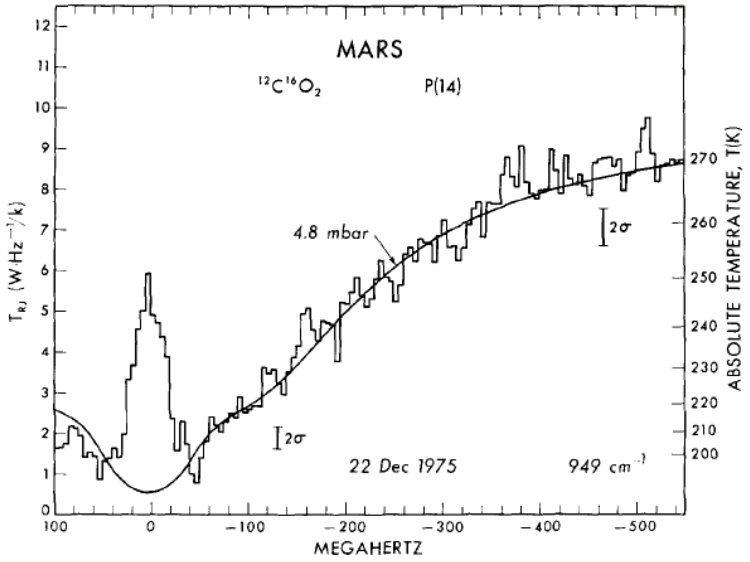
Heterodyne det. demonstration at McMath-Pierce tele. Kitt Peak

New techniques, High spectral resolution



10 μm interferometry using heterodyne detection.
5.5 m baseline between auxiliary siderostats
Johnson, Betz, Townes 1974
Atmosphere shown to be stable enough for interference fringes from Mercury to be detected.

Also high resolution spectroscopy of Venus, Mars, and stellar environs.
Right: Very sharp CO2 line in Martian atm.
later called “natural lasers on Mars”



Kostiuk et al. at GSFC, het. spect. on Subaru
Ethane & winds on Titan using 14CO2 LO lines

Infrared Spatial Interferometer

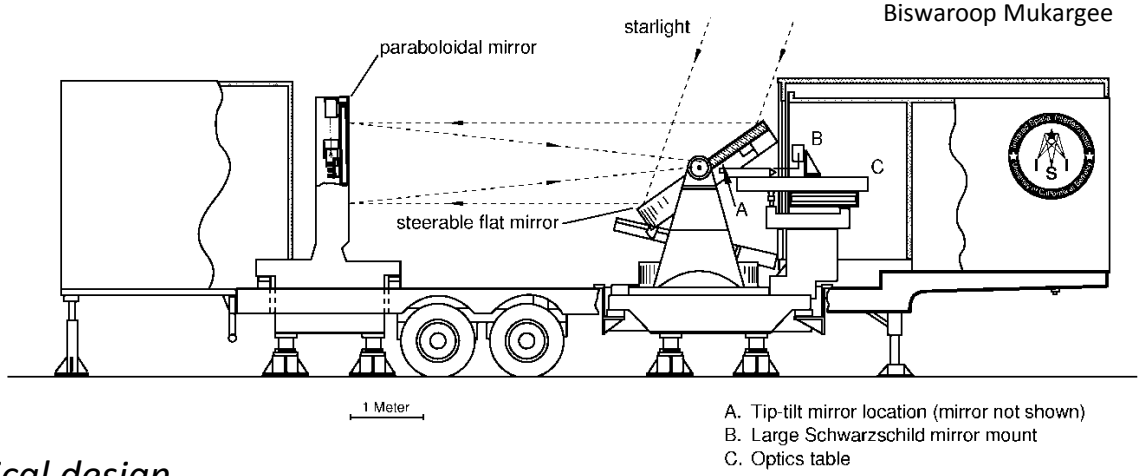
World's highest frequency radio telescope interferometer, operates at 27 THz (11 μm). Heterodyne detection using $^{13}C^{16}O_2$ lasers as local oscillators. Geometric delays removed using RF delay lines.

Currently located at Mt. Wilson Observatory, a site noted for very stable seeing.

Two telescopes in operation 1988
First fringes 1988
Third telescope 2003
Closure phase measured 2004

Telescopes designed for transport as a standard semi-trailer

Biswaroop Mukargee



Pfund optical design,
65" f/3.14 parabolic primary, 80" flat mirror

Interferometry principle of operation: Definition of "Visibility"

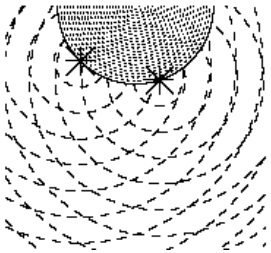
Mathematical description: Visibility is the complex 2D FFT of the 2D source intensity distribution (Van Cittert-Zernike theorem)

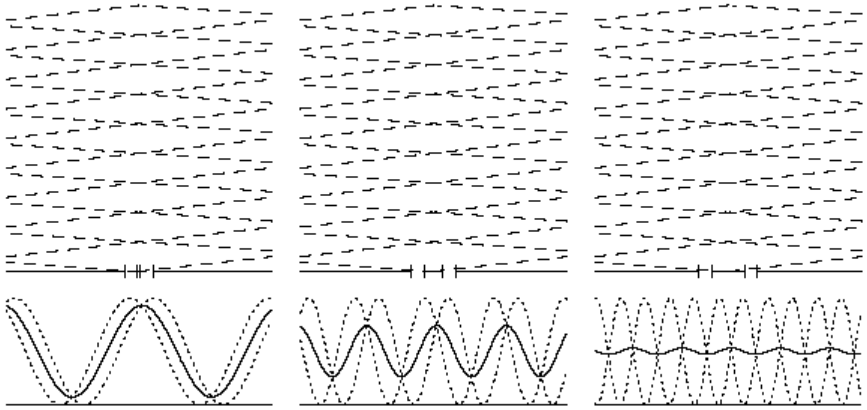
Phenomenological description: The envelope of fringes in a Young's double slit experiment gives information on the source size

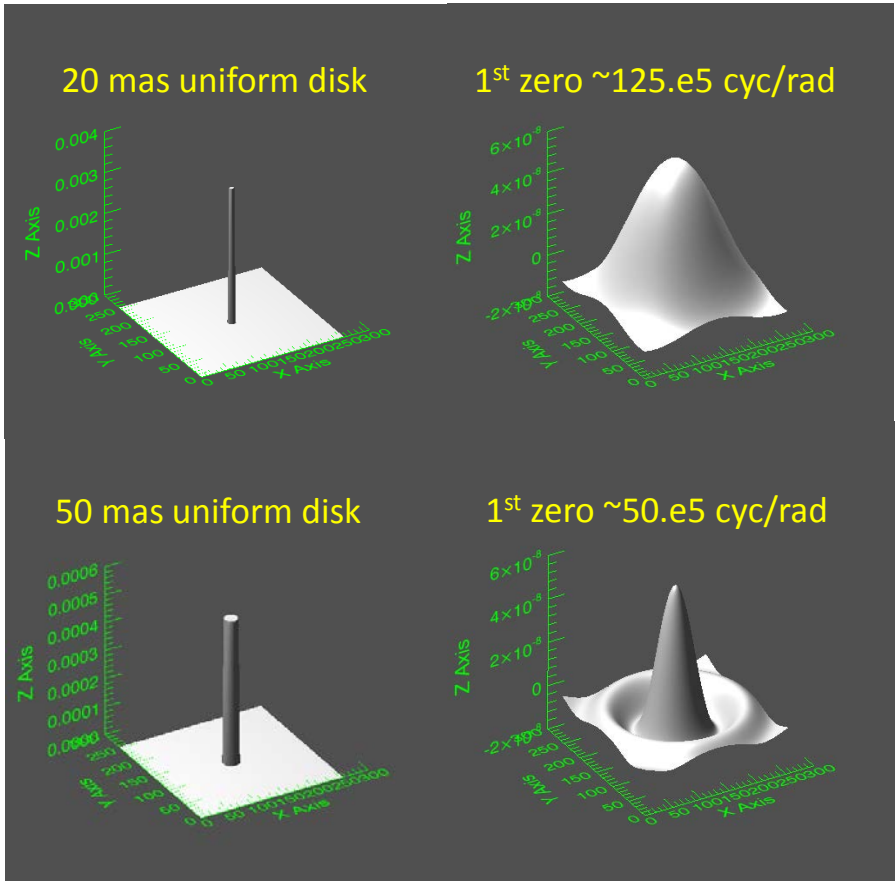
Michelson Visibility

$$V_{ij} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}},$$

$$V_{ij}^2 = \frac{|F_{ij}|^2}{P_i P_j}.$$

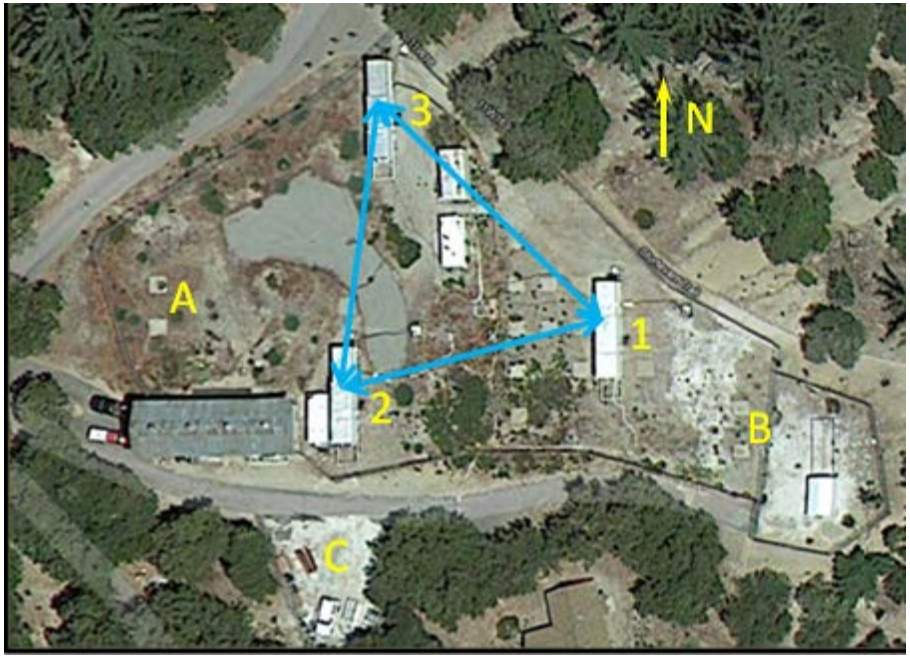






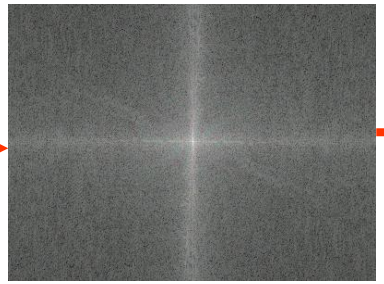
Weiner, 2002

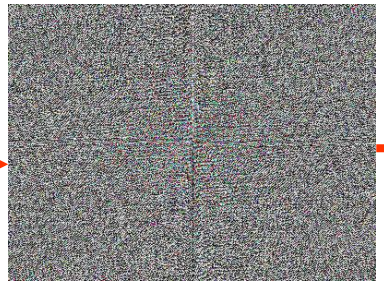
ISI array configurations and moving telescopes

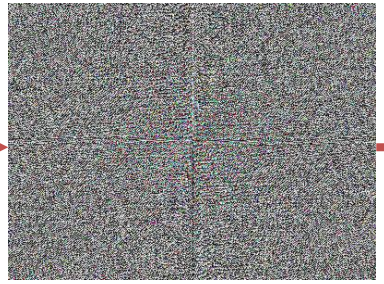


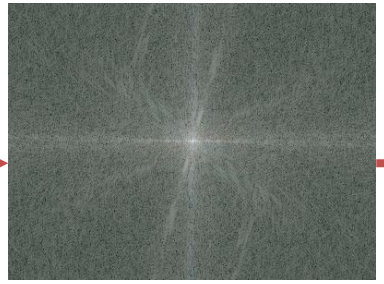
ISI site. Teles. 1,2,3 are shown. Cement pads for longest baselines EW are A,B 85m. Longest NS baseline 3,C ~60m

How Important Is Phase?









K. Tatebe

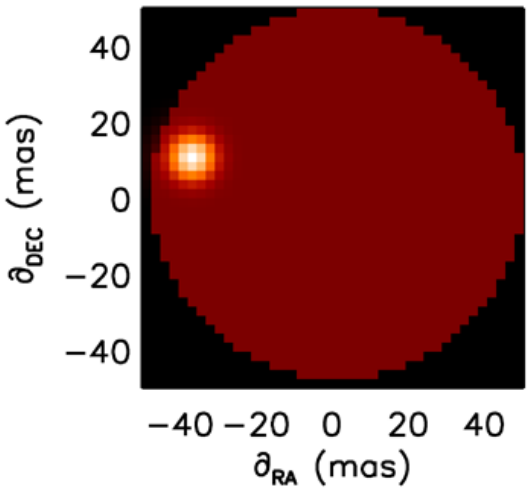
Closure phase as a measure of asymmetry

The visibility curve is the power spectrum of the image as function of spatial freq.

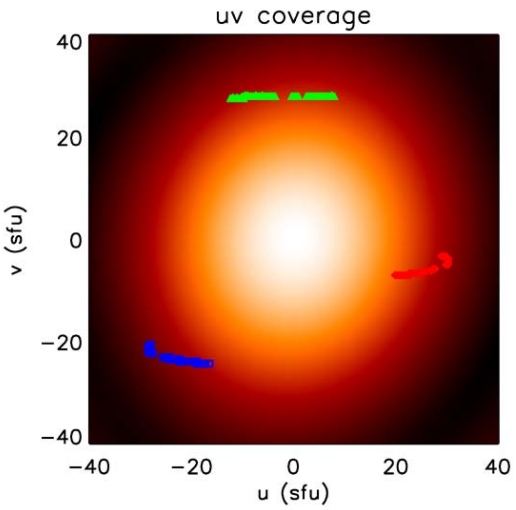
The image phase gives the positions of features in the image.
Atmospheric turbulence prevents an accurate phase measurement, but the ISI can record the *closure phase*:

$$\Phi_{CP} = \phi_{12} + \phi_{23} + \phi_{31}$$

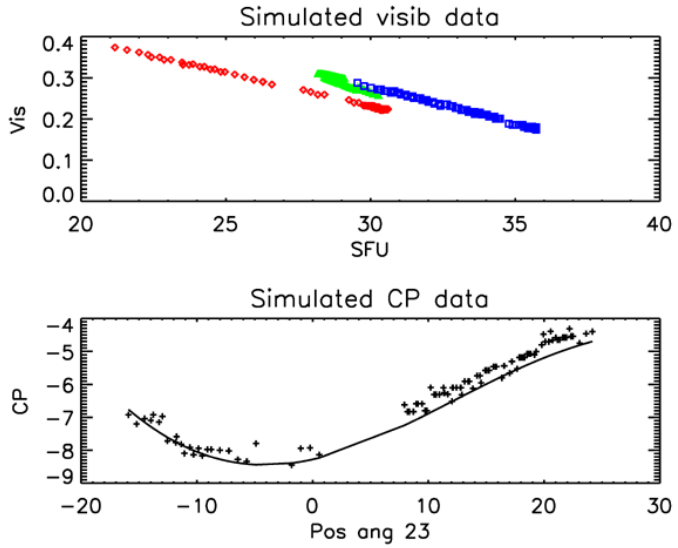
The closure phase provides vital information about stellar asymmetries.
For example, the closure phase is zero for sources which are centro-symmetric.



Central part of 2D image

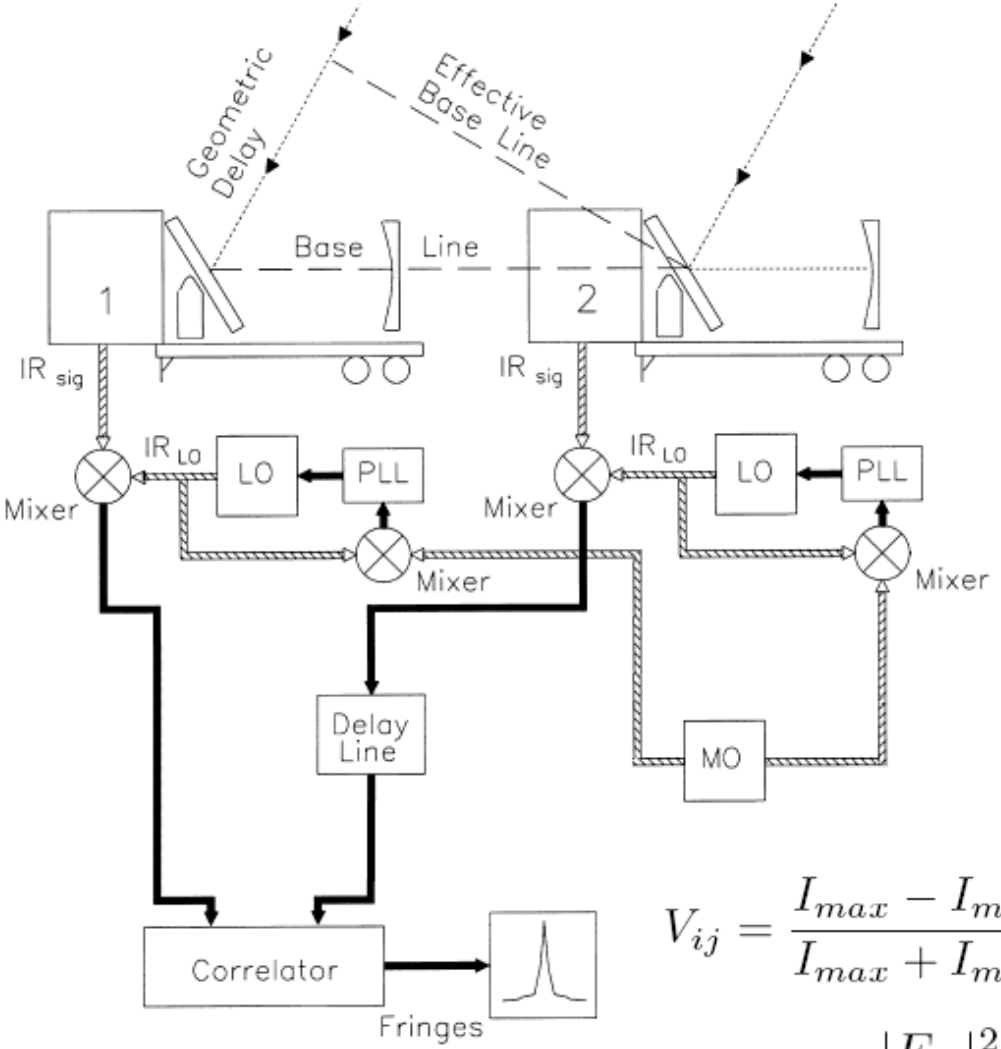


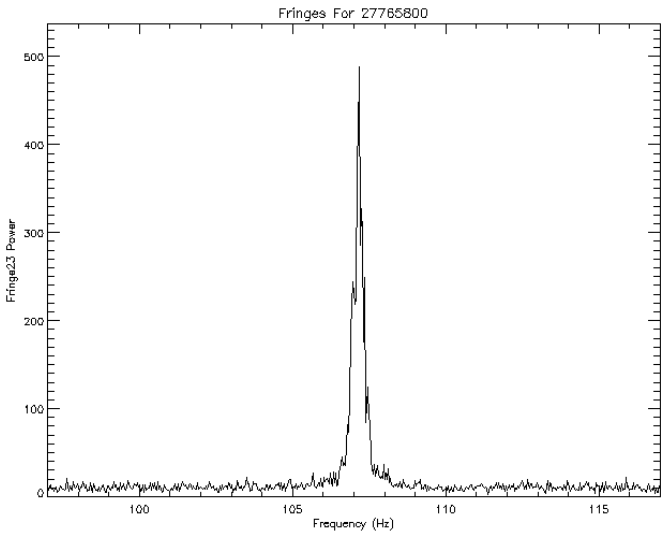
2D FFT of image
abs(visibility)

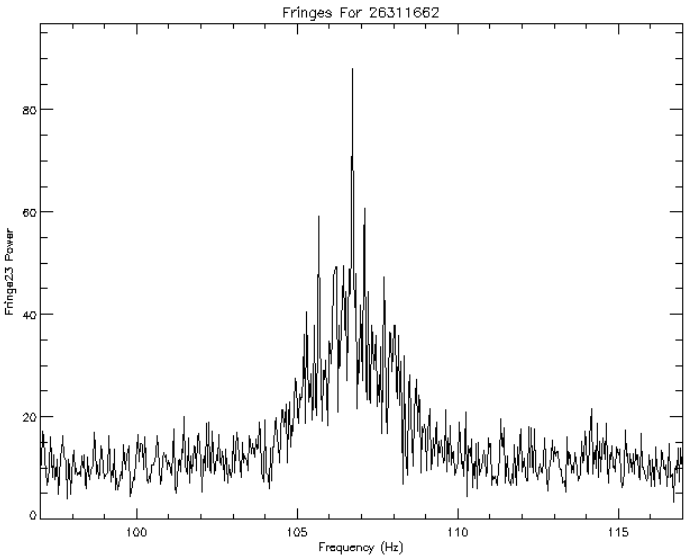


For samples in uv plane,
Visibility & closure phase

Interferometer scheme, examples of fringes





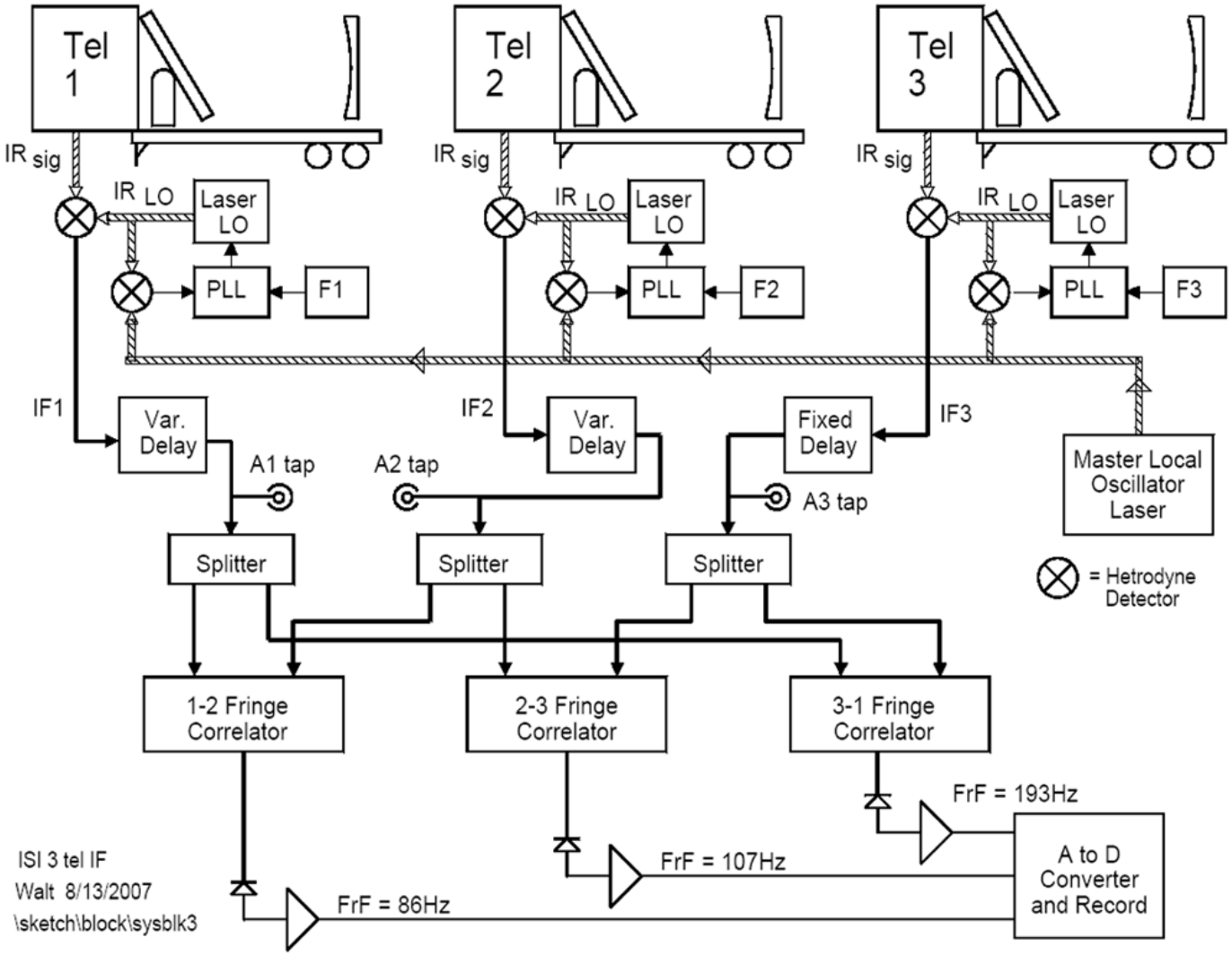


$$V_{ij} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}},$$

$$V_{ij}^2 = \frac{|F_{ij}|^2}{P_i P_j}.$$

Heterodyne detection using CO_2 lasers as local oscillators

Current system, spectrometer taps A1,A2,A3



Heterodyne signal to noise

At detector, $E = E_{LO}\cos(w_{LO}t) + E_S\cos(w_s t) + E_0\cos(w_0 t + \delta)$

E0 is zero-point energy fluctuations,
one photon per root bandwidth per time

Johnson & Townes 2000
Optics Comm, 179, 183

Power law detector forms product terms; including beat frequency difference (and sum)
where $w_0 = w_s$ is the pertinent noise term

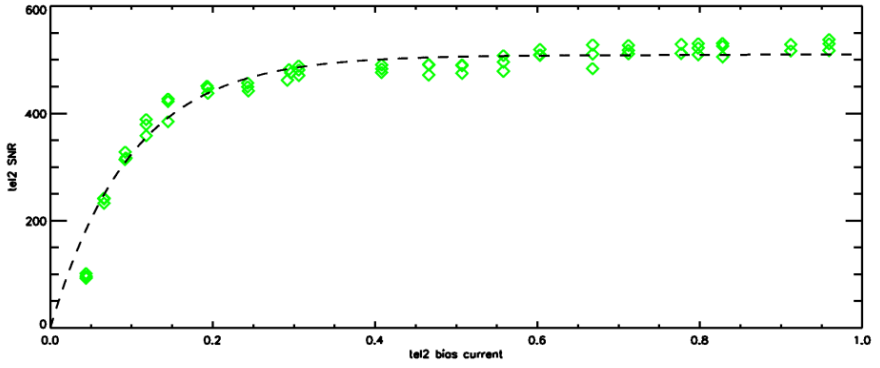
S/N heterodyne α sqrt($\Delta\nu$) just like direct detection
however heterodyne detectors have limited b.w.

System noise temp at 11 μm ~ $h\nu/k$ = 1300 K
for wavelengths > 1 cm, amplifier noise will dominate
for 1 μm, $h\nu/k$ = 14000 K

Multiple LO's falling on a single detector
Have increased signal and noise in same proportion

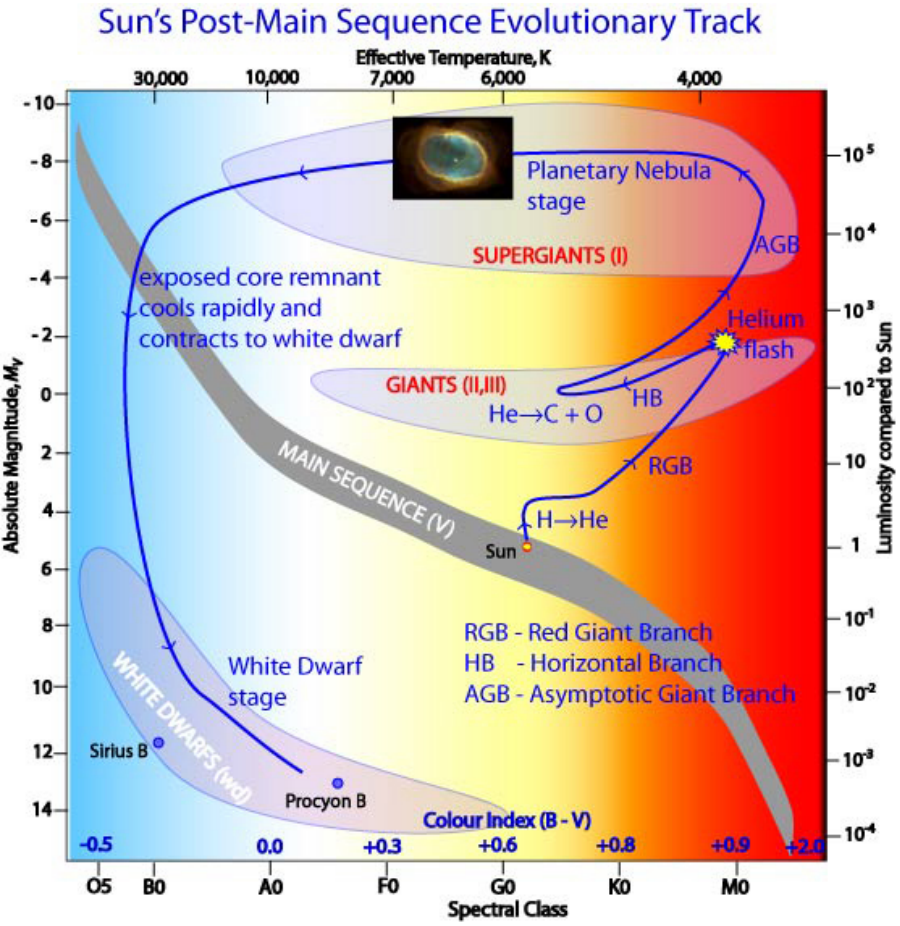
Note that in mid-IR, at very high resolution: R ~ 1e6 where photon number/res element is near read noise, Het can be superior to direct det.

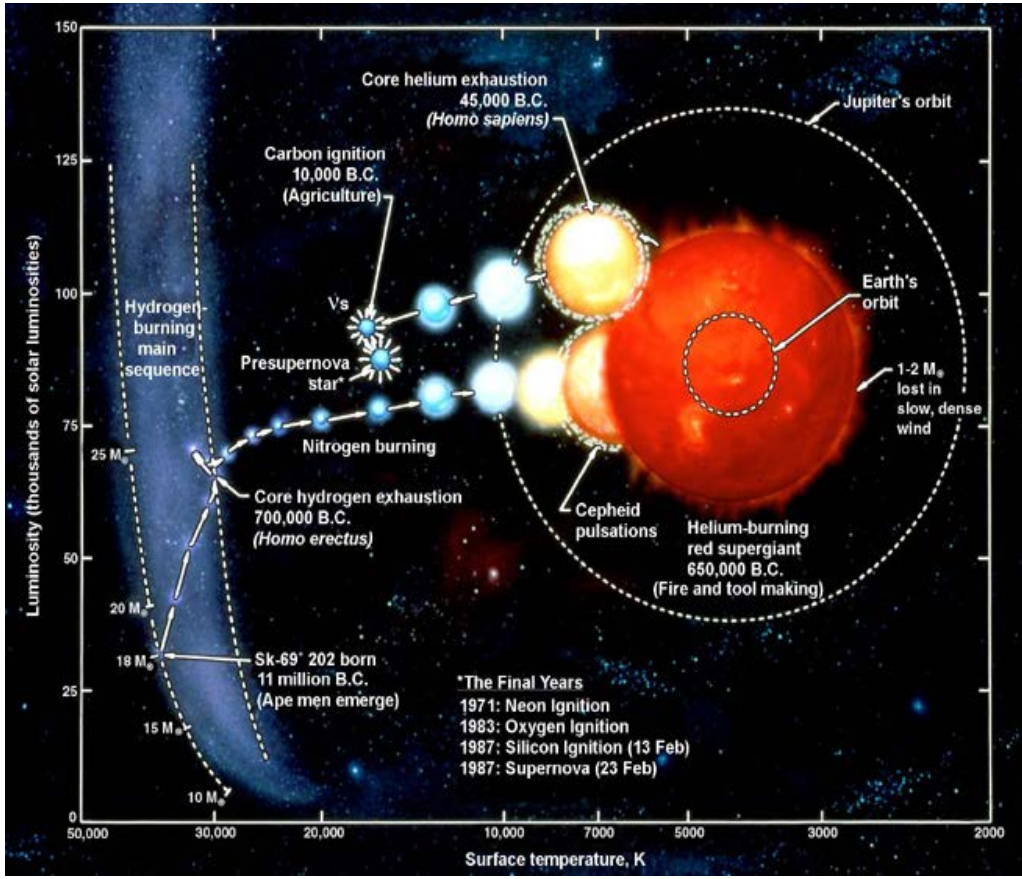
Detector test measurement showing bandwidth limit of S/N



SNR vs. det. current α LO power

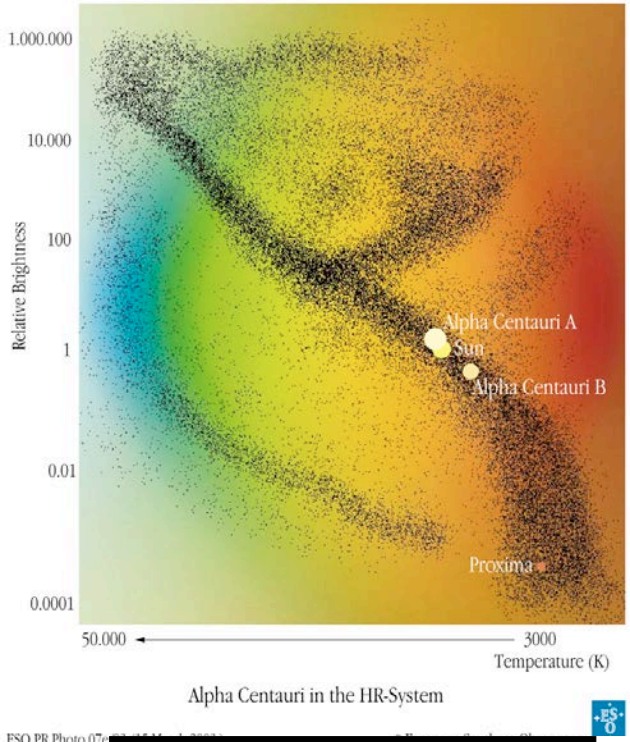
Hertzsprung-Russell Diagram & Evolutionary path of a Mira star & red giant

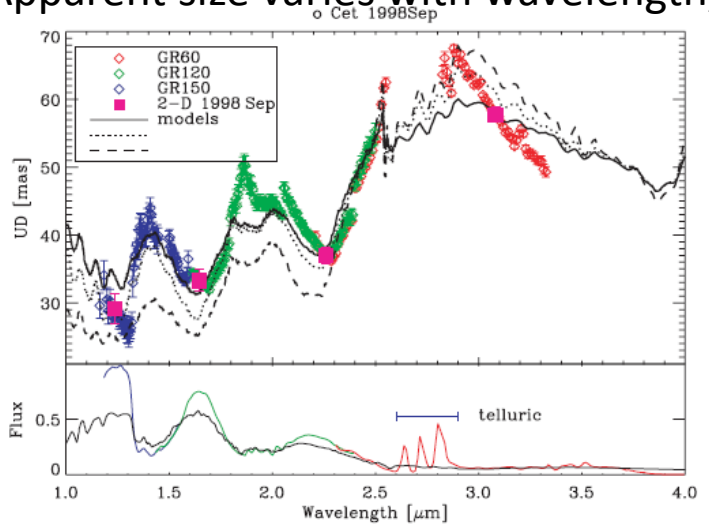




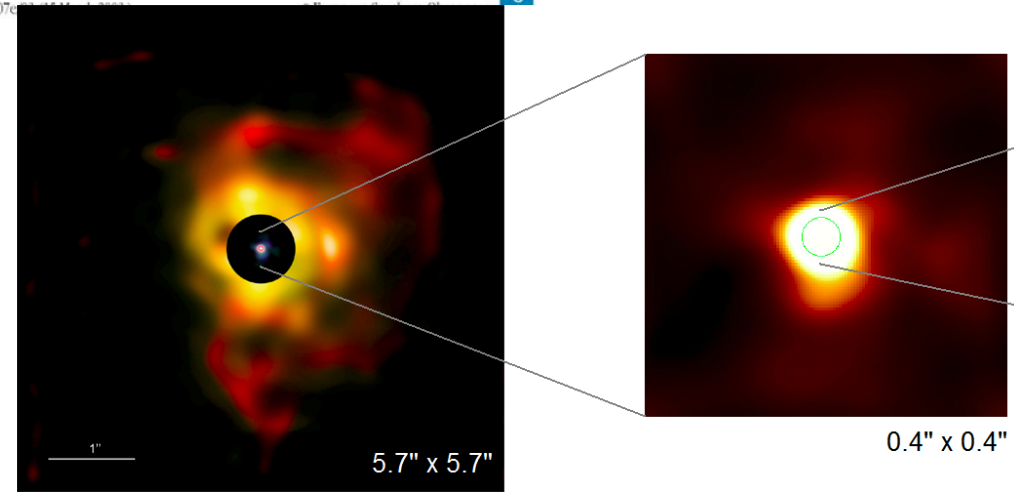
Aspects of Red Giant & Mira stars

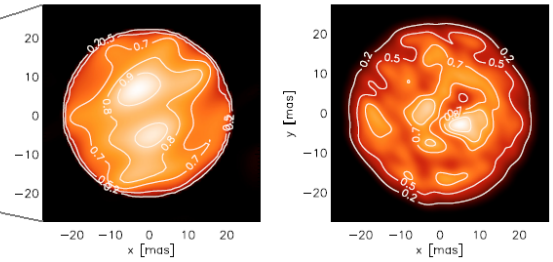
Apparent size varies with wavelength, Keck aper. mask





Woodruff et al.,
ApJ 691, 1328, 2009





mid-IR deconvolution image complex dust shells (Kervella et al. 2011)

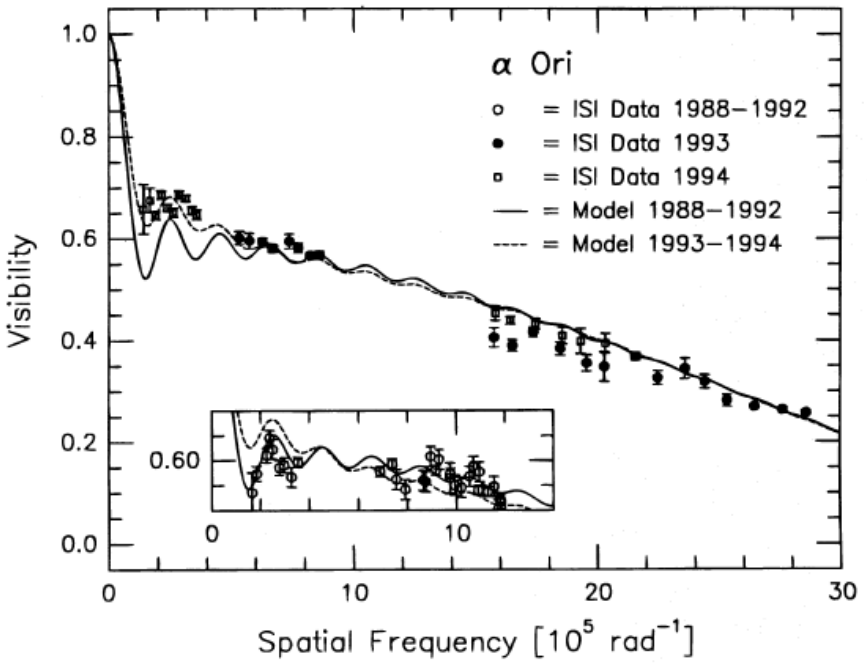
K band deconvolution image extended atmosphere, photosphere diam 43.7 mas (Kervella et al. 2009

H band interferometry with bright surface features (Haubois et al. 2009)

numerical model image comparison to C (Chiavassa et al. 2010).

ISI two telescope results: Stellar variations over time

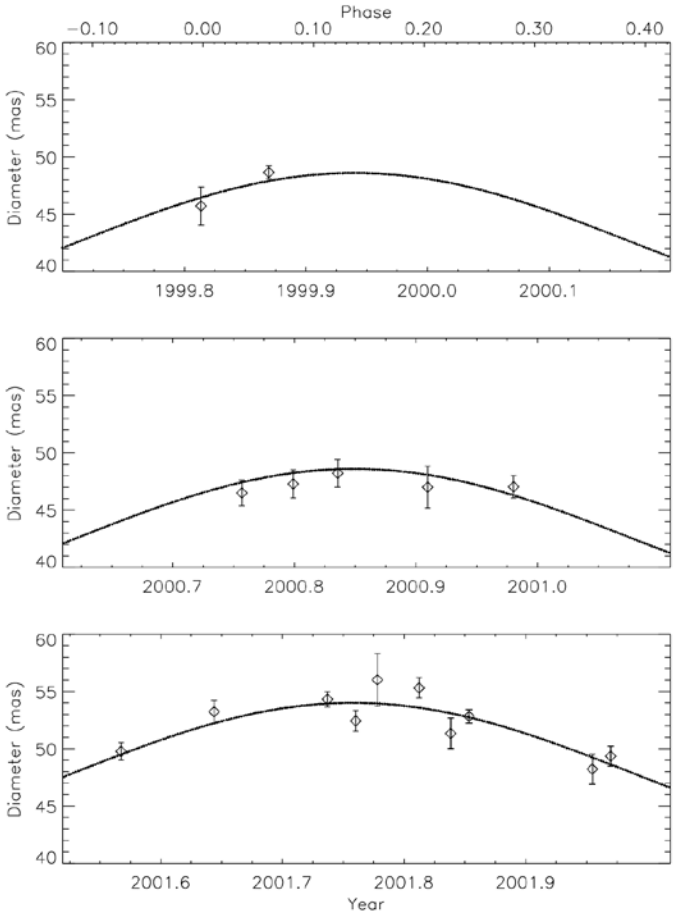
Betelgeuse visibility variations



Fringe visibility measured over various baseline distances.
Spatial frequency in units of 10^5 cycles/radian
1 SFU = 0.5 cyc/arcsec
Two main components to the visibility curve: stellar and dust.

Bester et al. 1996

Variations in angular size of Mira over a stellar luminosity period

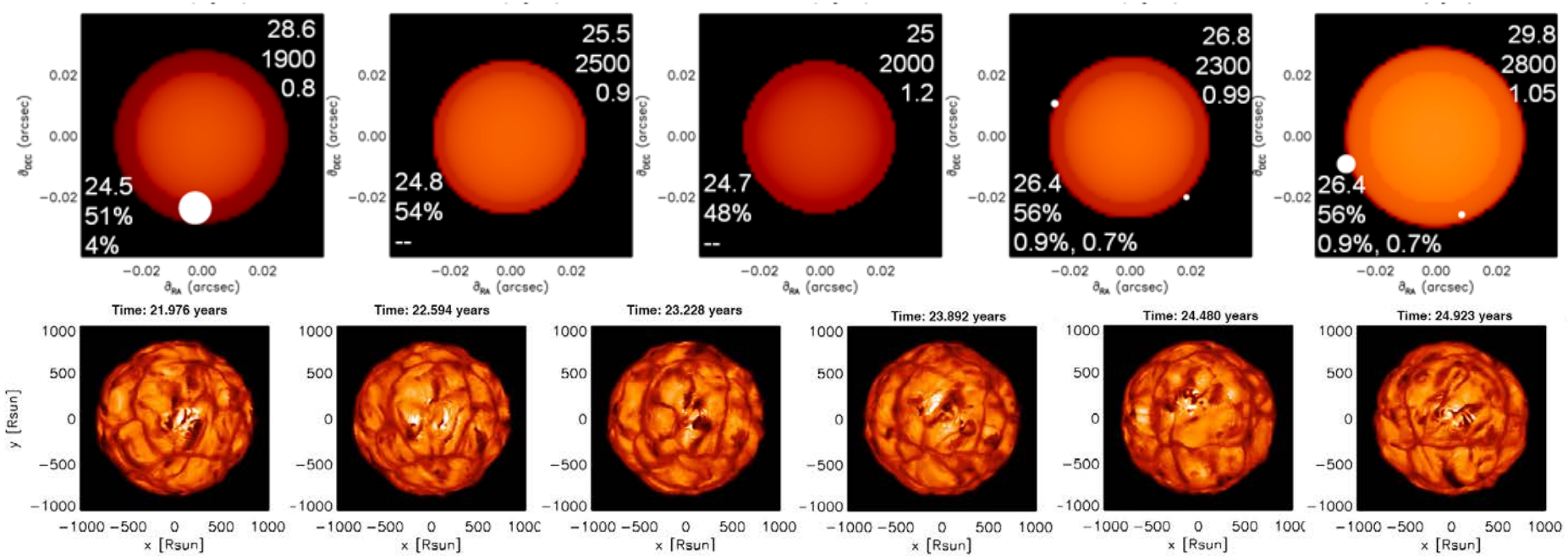


Weiner et al. 2003

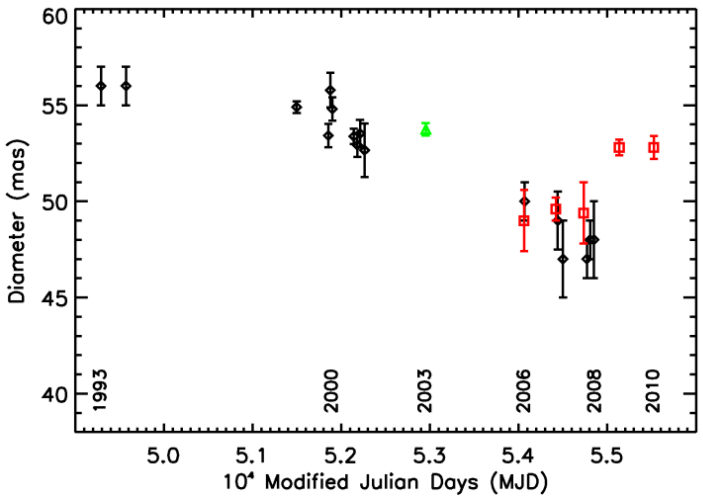
The perils of daytime observing?

Dec 1990
Madfred Bester

Comparison of 11 μm fitted "images" to 1.8 μm theory

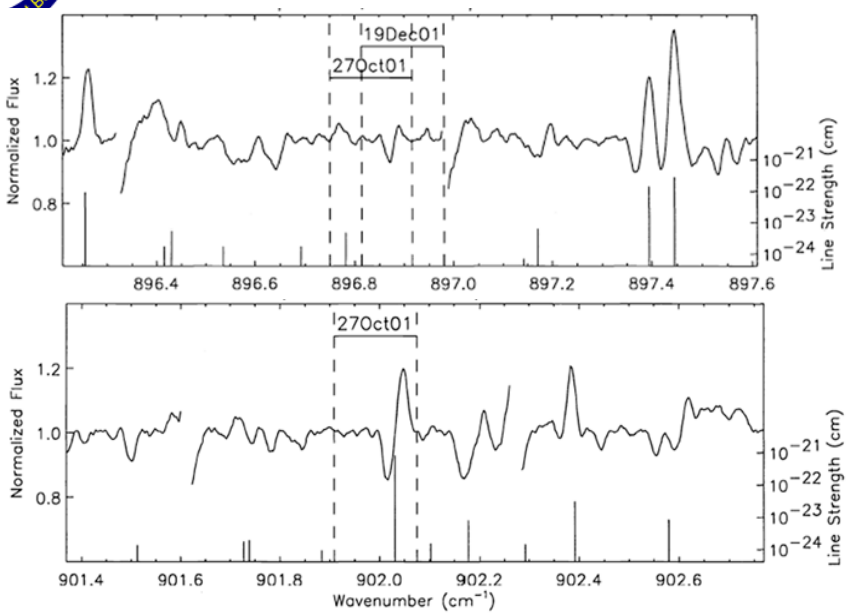


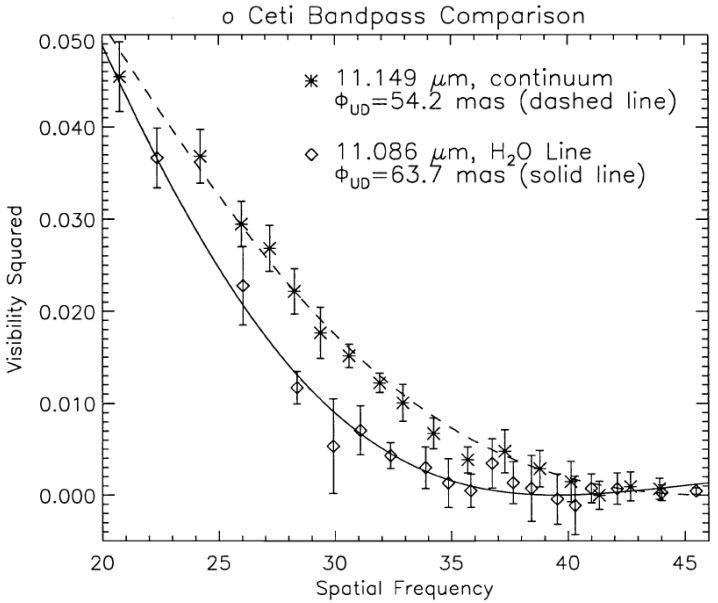
Series of theoretical images H band covering 3 years
Chiavassa et al., A&A, 506, 1351, 2009



Betelgeuse "images" and long-term monitoring of the angular size of Betelgeuse, Ravi et al. 2011

O Ceti, uniform disk fits to visibilities on-off spectral line





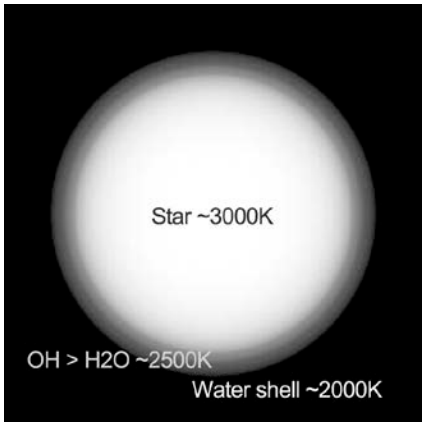
Weiner et al. 2003, SPIE, 4838, 172

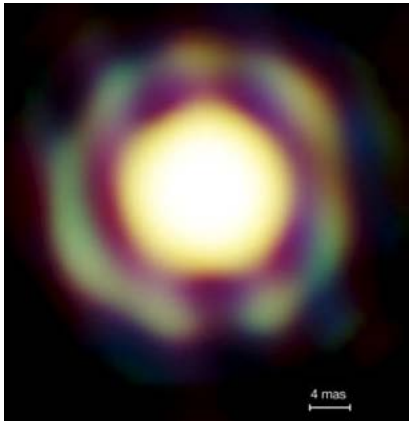
Previous ISI
Spectroscopic-interferometry
RF analog system

VY Cma
NH3 forms at ~40R*

IRC +10206
NH3 forms at ~20 R*
SiH3 forming at ~80R*

Monnier et al. 2000
ApJ, 453, 868

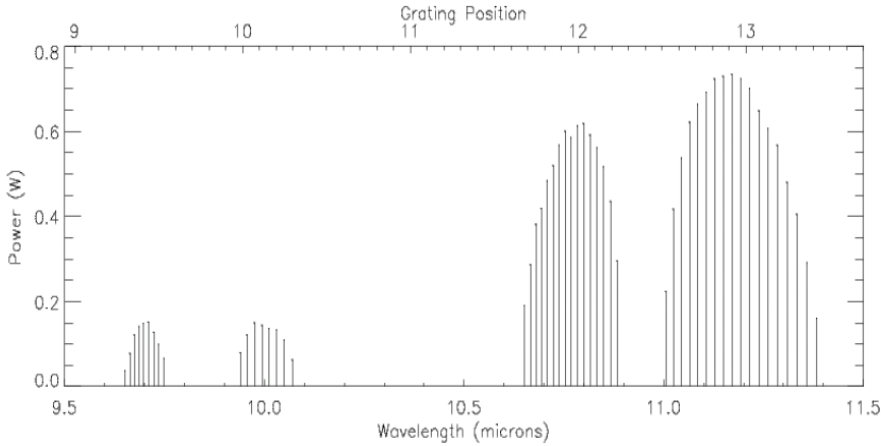




T Lep, VLTI, 1.4-1.9 μm,
Le Bouquin et al. 2009 A&A L

Spectral range covered, OH & H2O lines of interest

ISI $^{13}CO_2$ laser lines



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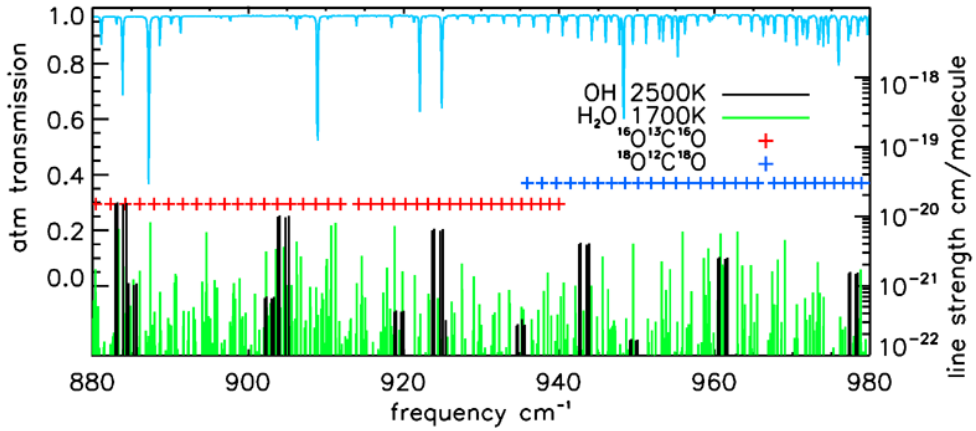
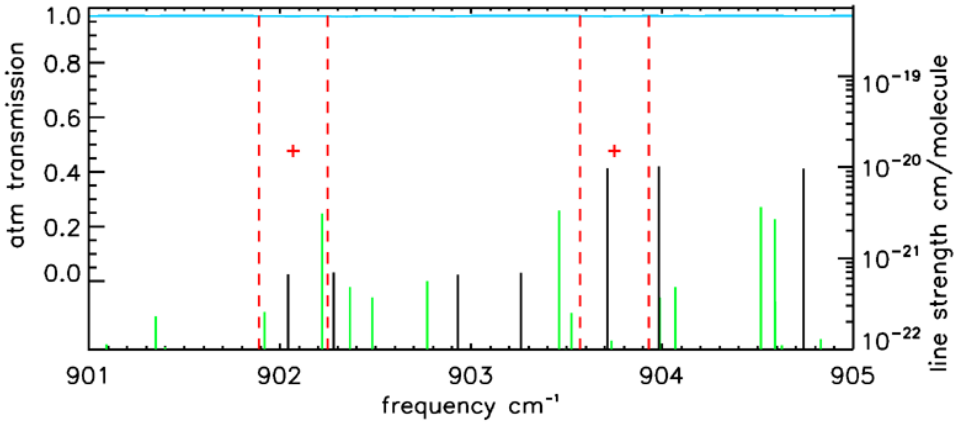
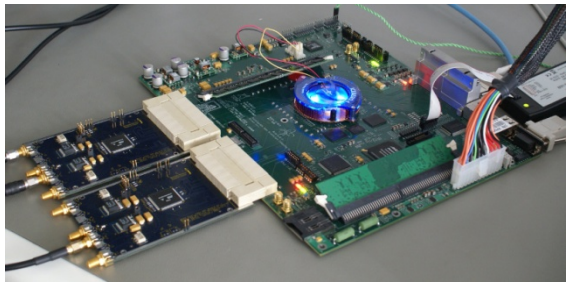


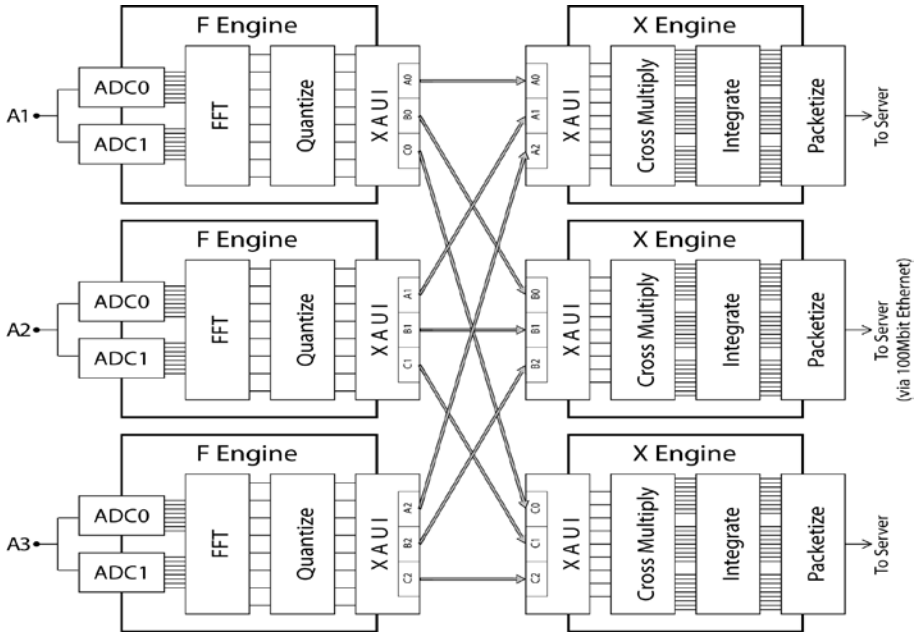


Simulation of αOri
OH black
H2O green
Band covered red

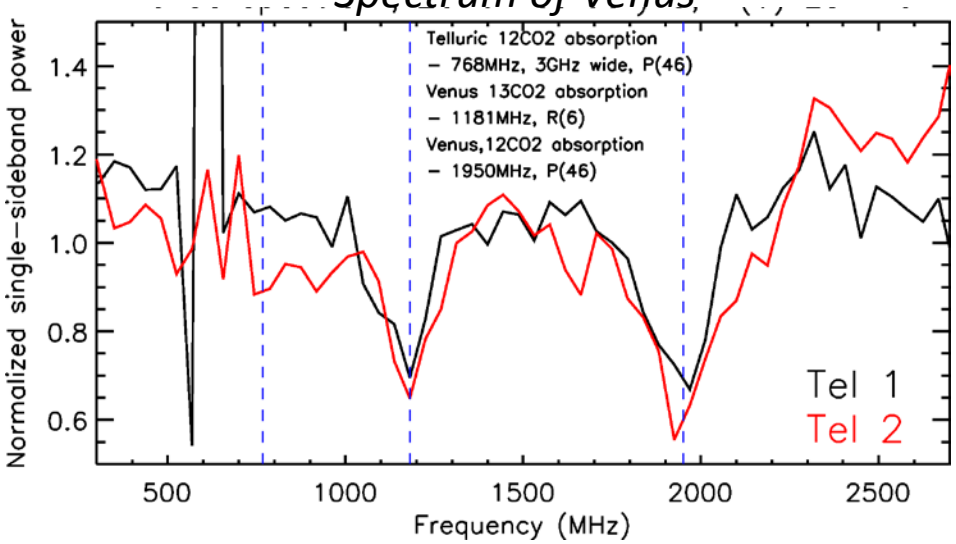
FPGA digital spectrometer-correlator

3 GHz BW, 64 channel
Spectral resolution of 600,000





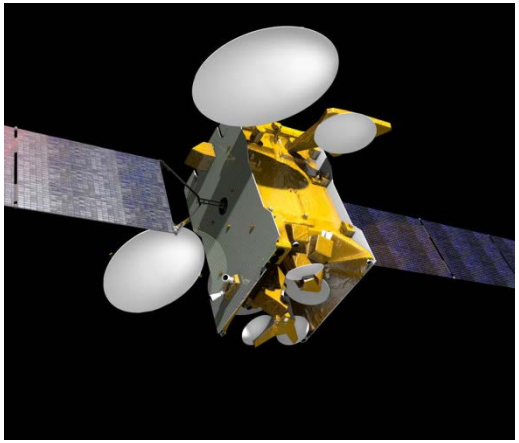
Spectrum of Venus



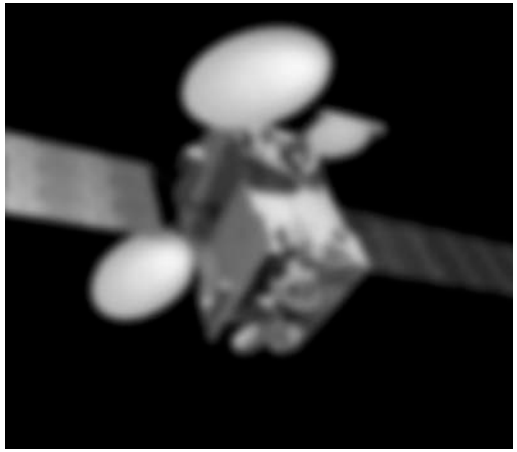
6 Gsamp/sec using interleaved ADCs
128 pt FFTs every 22 ns.
Data swapped between boards for cross-correlation and accumulation.
45000 spectra, every ms.
Collaboration with Mallard, Werthimer, CASPER

DARPA program to image geo-synchronous satellites

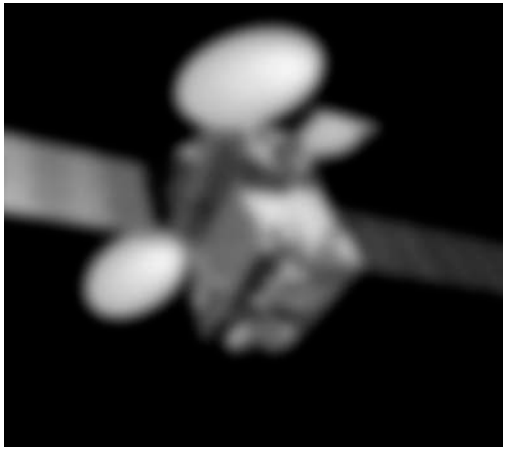
Interferometry of geo satellites
10 cm resolution @ 36000 km
~3 nrad ~ 0.6 mas, V band magnitude = 11
Many samples in UV plane to form images
Telescopes w/ /AO
linked with optical fibers
Move baselines in 5 min
Conduct meas. at Starfire in NM



Sat image



~10 cm resolution
1 um wavelength
360 m baselines

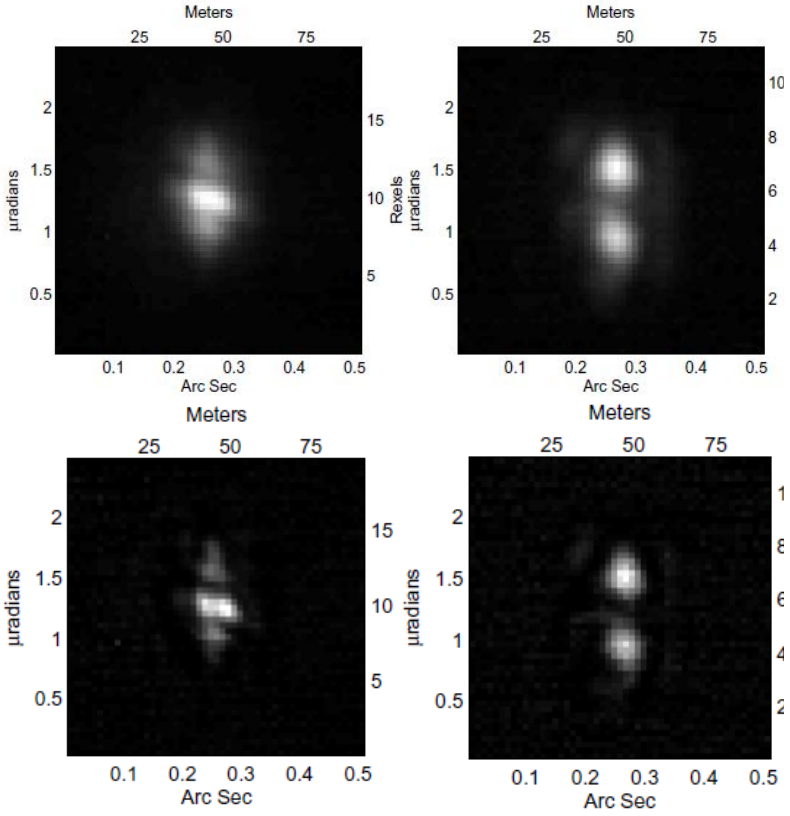


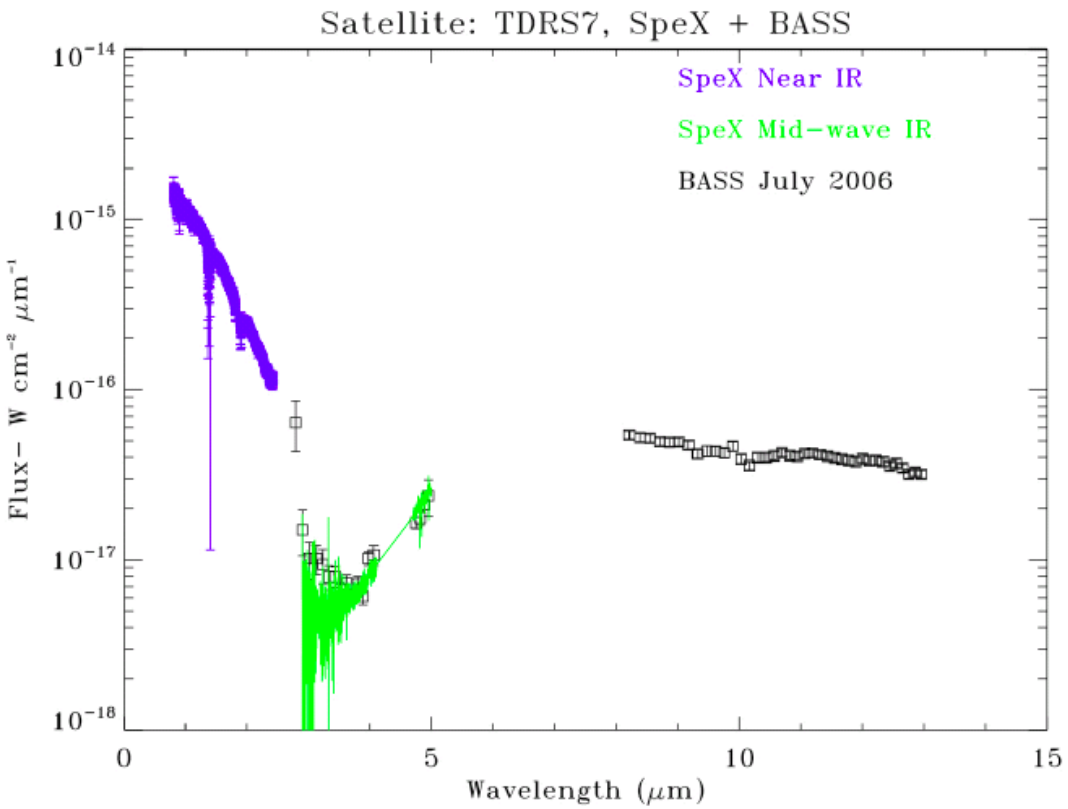
~40 cm resolution
1 um / 100 m baselines
10 um / 1km

Status of Program?
Similar to Planet Formation Imager?

10 um / 7 km

Data from geo-satellites, 10 um is a poor region





Data from Keck AO.
Drummond, Rast 2010
Left: 1.25 um, Right: 2.17 um
Below deconvolved images

dtic.mil/get-tr-doc/pdf?AD=ADA531722

Data from IRTF

Skinner, et al., IR spectro-photometric observations of Geosynchronous satellites, in: Proceedings of the AMOS Technical Conference, September 2007, Maui, HI, 2007.

Other optical-IR interferometers

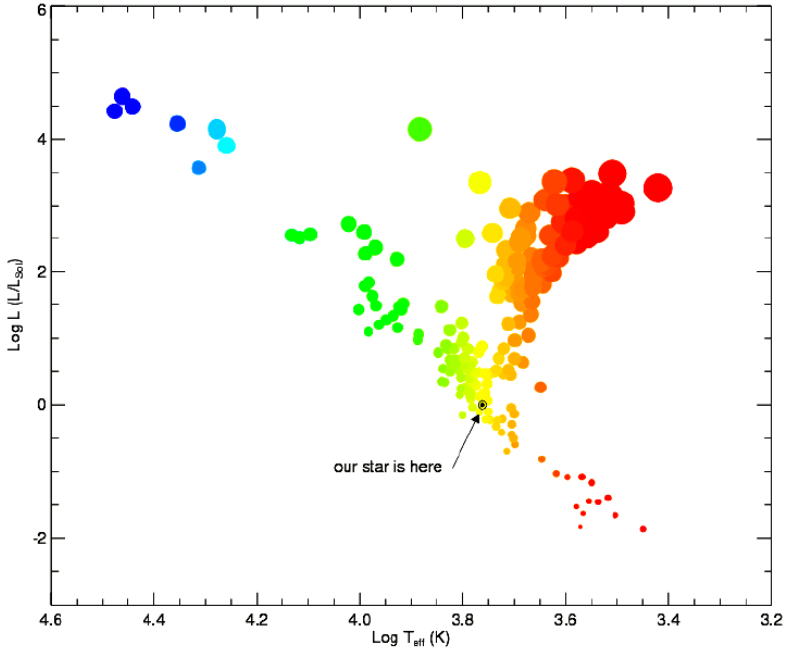
NPOI
6x12 cm
Augment w/
Keck outrig

CHARA
6x1m

Keck
2x10m

Also LBT, VLT--Gravity

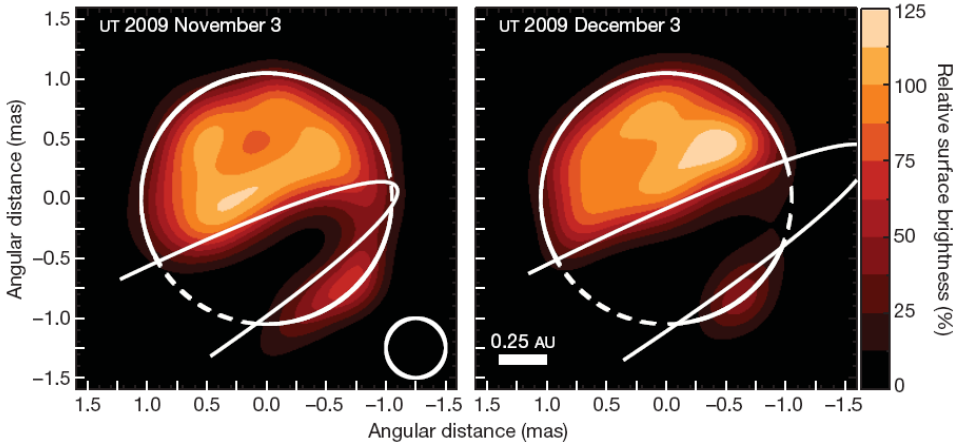
Magdalena Ridge
under const.



HR diagram of 250 measured stellar diameters

Physics Today, June 09

Boyajian, CHARA



Kloppenborg et al. Nature, 464, 870, 2010

Epsilon Aurigae and eclipsing binary (25 yr. period)
F star, with orbiting B star enshrouded by a disk

Three telescope array, ~36 m baselines

Sean Lockwood/Walt Fitelson

Biswaroop Mukerjee

Group photo, illuminated by moonlight

Dave Hale

Three telescope linear array, 4,8,12 m baselines

Backup slides

SETI Studies

No. 4772 April 15, 1961 NATURE 205

INTERSTELLAR AND INTERPLANETARY COMMUNICATION BY OPTICAL MASERS

By Dr. R. N. SCHWARTZ and Prof. C. H. TOWNES*
Institute for Defense Analyses, Washington, D.C.

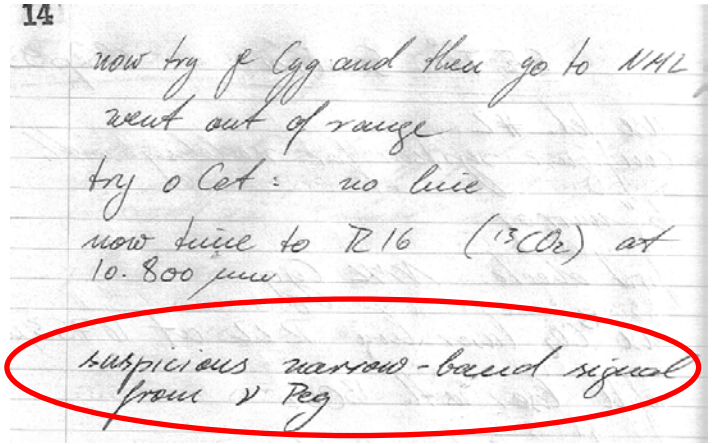
Thus, it appears that if one postulates the existence of an optical maser system beamed towards us of the characteristics of system (*a*) at a distance of the order of 10 light-years, it is within the state-of-the-art for us to detect it.

Theoretical and experimental work continued by Betz

???

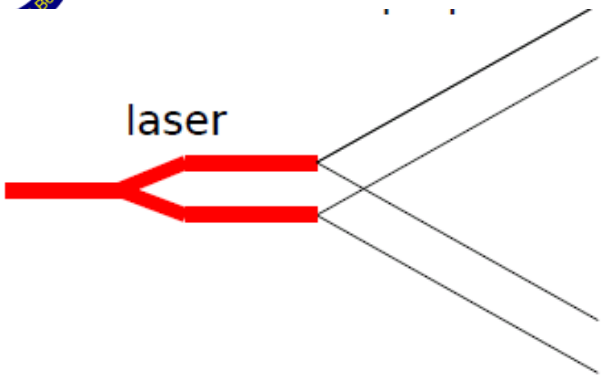
BERKELEY SETI RESEARCH CENTER

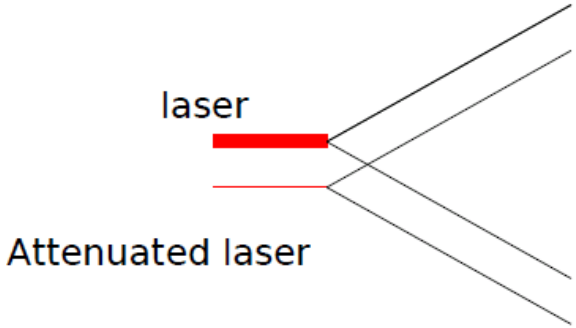
Participating in ongoing Panchromatic search, support from Templeton Foundation.

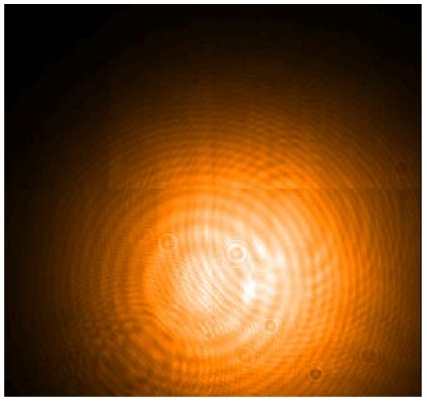


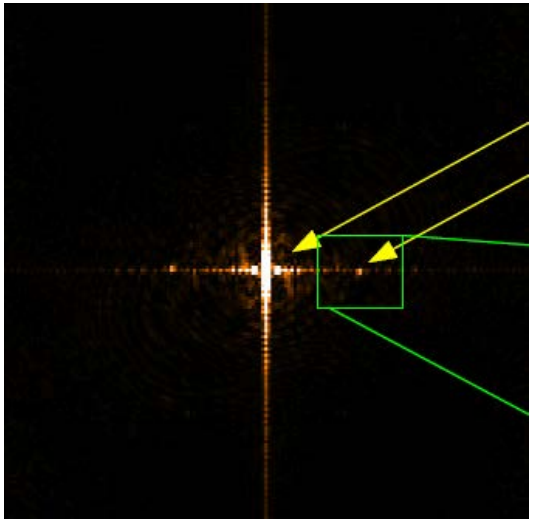
Bester notebook sep 1993

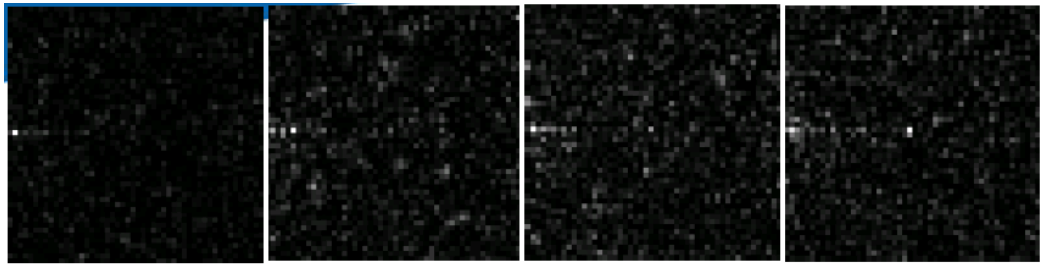
Photonic Heterodyne?







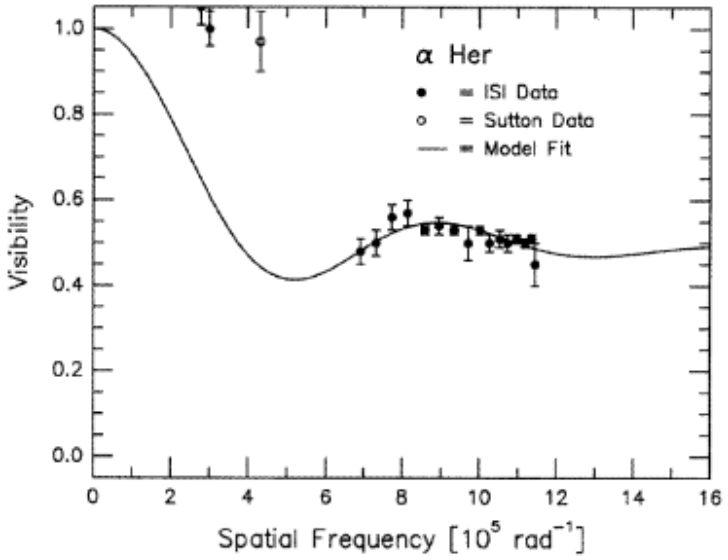


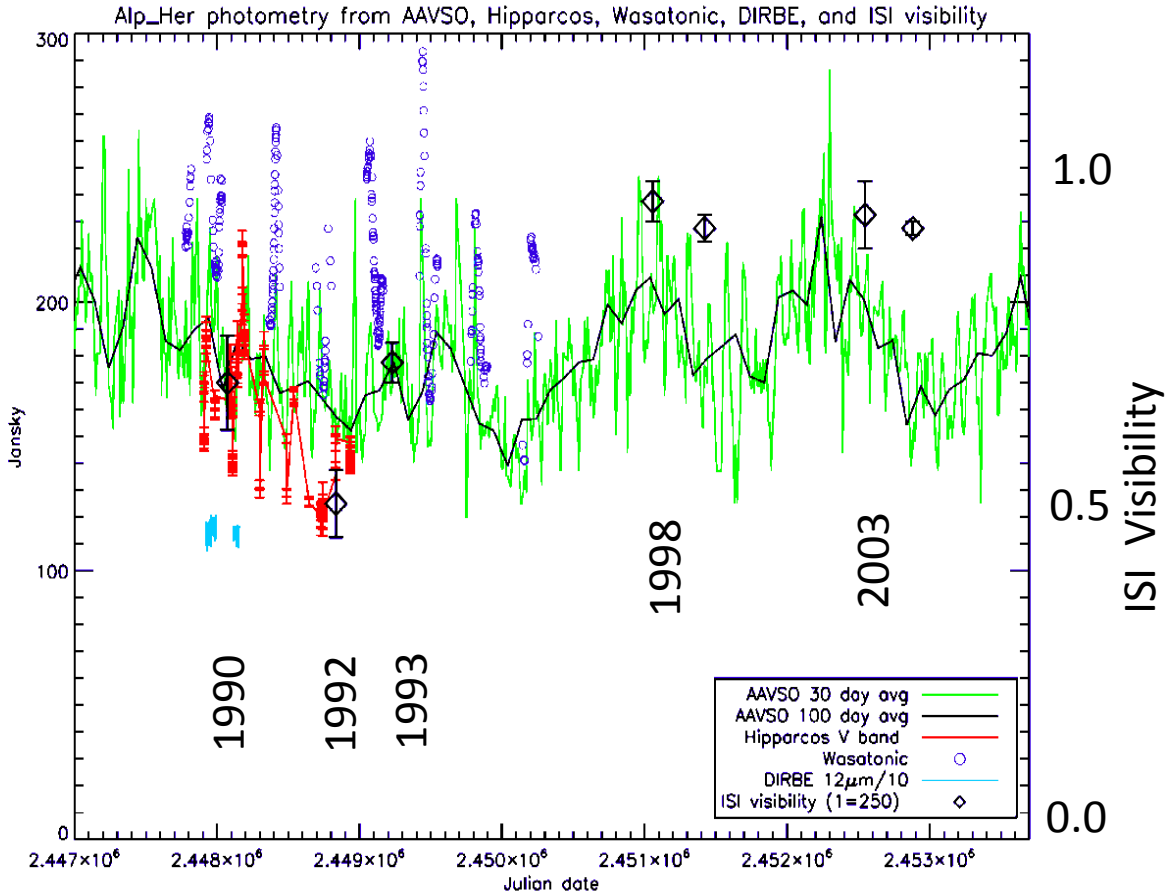


Laser & fast camera

Ettiene Le Coarer, Renewing Heterodyne, OHP 2013

Long term studies: variations of α Her

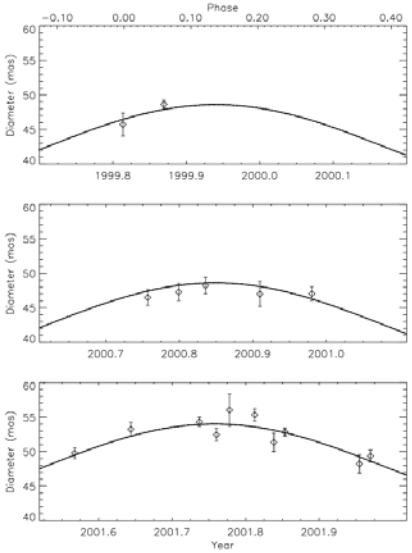




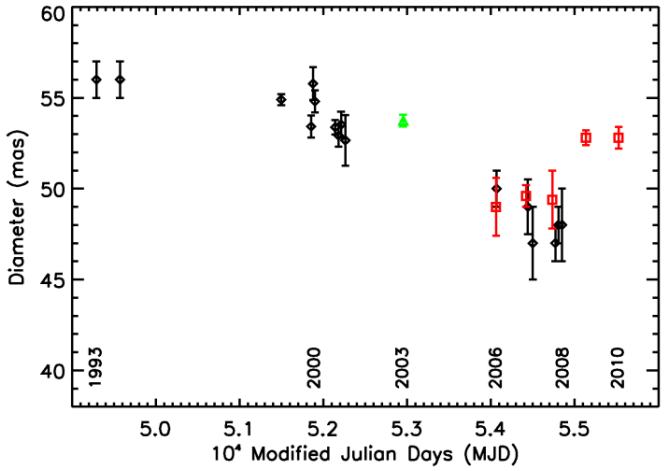
Tatebe et al. "Observation of a Burst of High-Velocity Dust from α Herculis,"
2007, ApJ, 658, 103. From 92 to 93, about 75 km/sec

Infrared spatial interferometer (ISI)

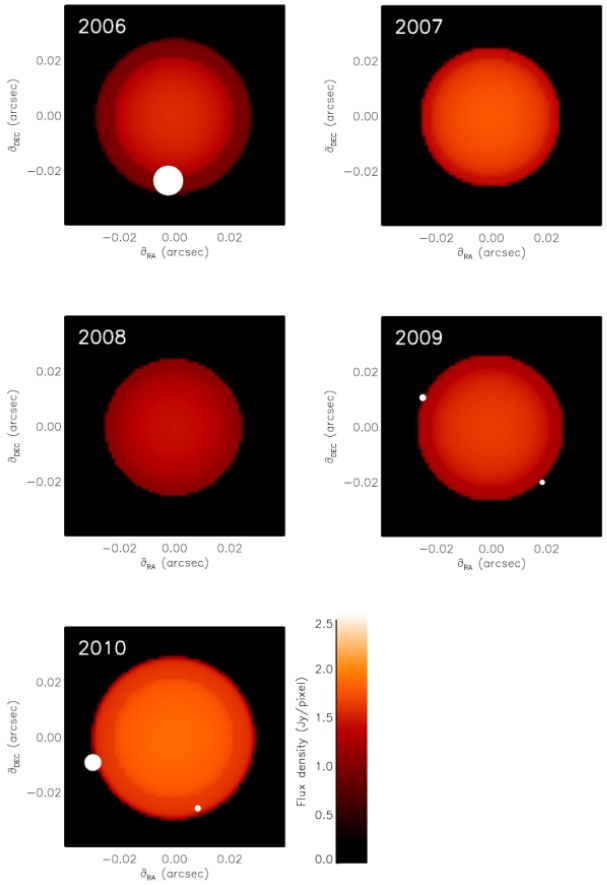
Combines High Spectral resolution, high angular resolution and new techniques



Variations in angular size of Mira compared to luminosity phase
Weiner 2000



Long-term monitoring of the angular size of Betelgeuse
Ravi 2011



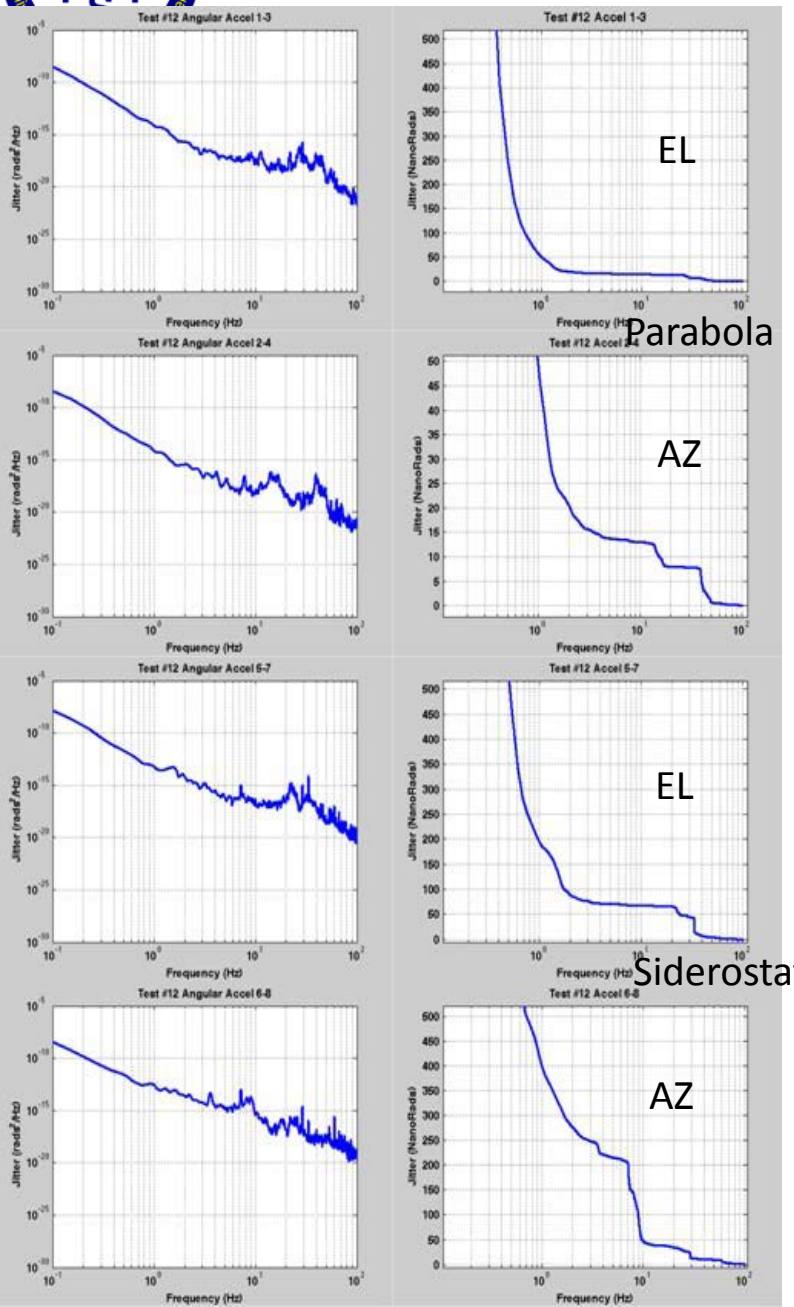
Variations in stellar shape and "hot-spots" of Betelgeuse
Ravi 2011

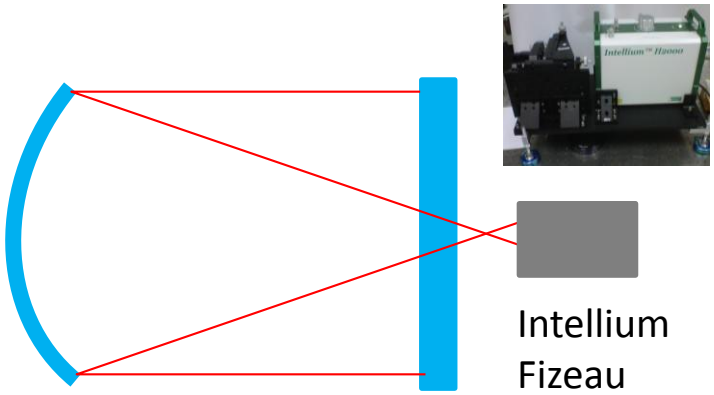
Measurements of dust shells surrounding red giant stars and their surprisingly rapid changes with time. Danchi 1994, Bester 1996, Tatebe 2007

Measurements that NH3 and SiH4 form at 20-40 and 80 stellar radii from stars, respectively. Monnier 2003

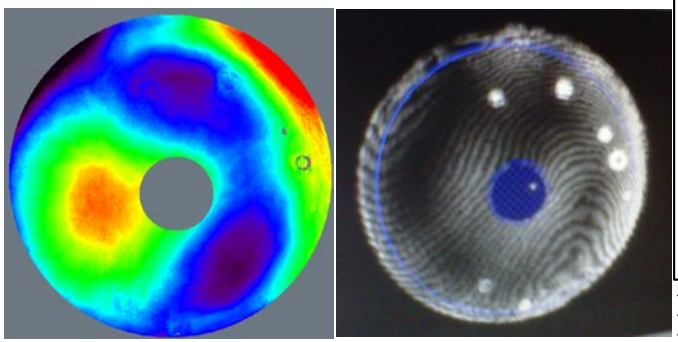
Measurements of dust shell asymmetries using 3 telescopes and phase closure. Tatebe 2006, Chandler 2007

ISI Vibration tests/Optical wavefront tests

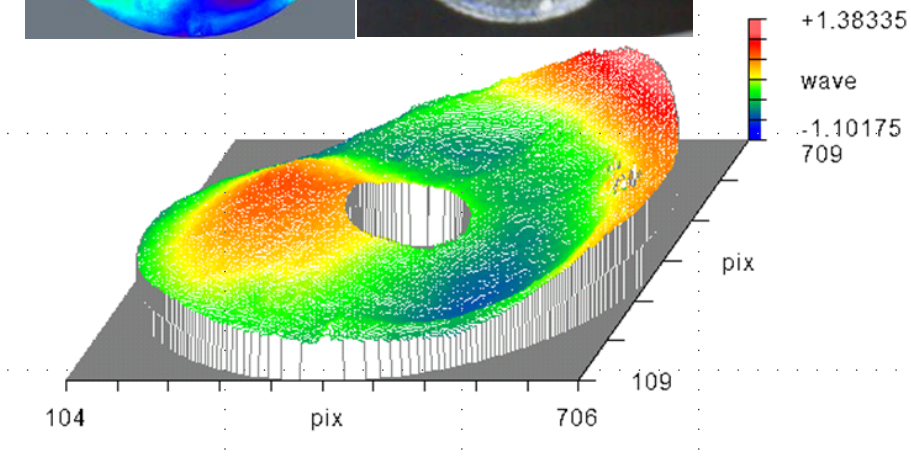




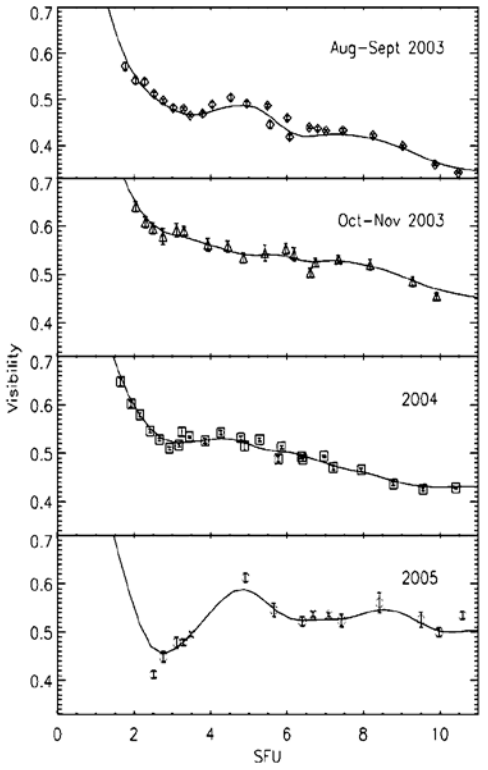
Double pass meas of ISI mirrors

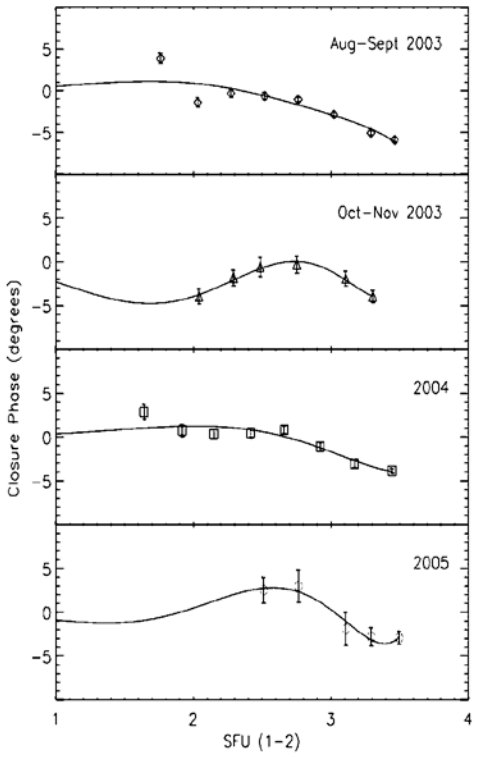


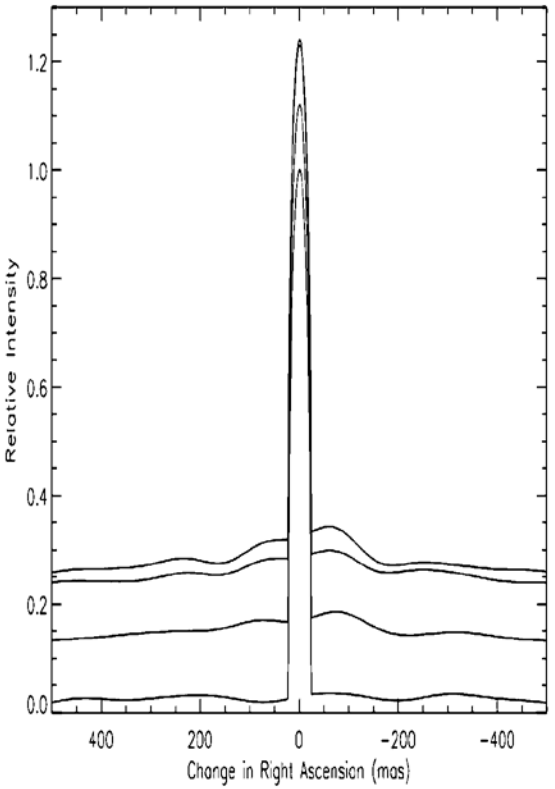
PV	2.485	wave
Rms	0.382	wave
Power	0.023	wave
Aberration	wave	angle
Tilt	1.537	-162
Focus	-0.794	
Astigmatism	1.147	35
Coma	2.315	18
Spherical	0.756	

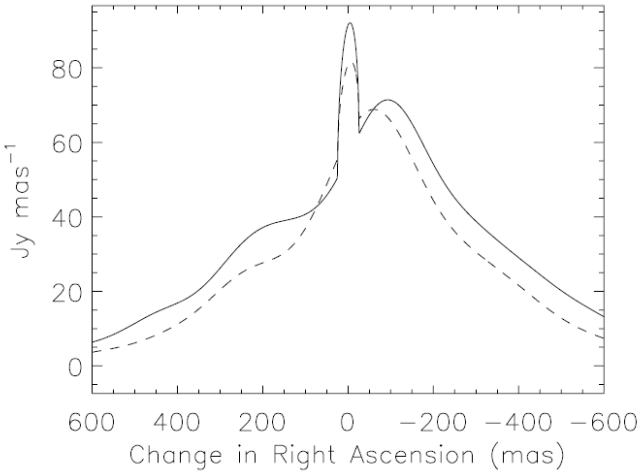


Using Phase Closure: Evolution of dust surrounding stars









Asymmetry of dust
IRC+10216
2004 (solid)
2006 (dashed)

Chandler et al., ApJ 657, 1042, 2007

In descending order:
Aug-Sep 2003
Oct-Nov 2003
2004
2005

Chandler et al., ApJ, 670,1347, 2007