Observations of late-type stars with the Infrared Spatial Interferometer (ISI)

Stellar Interferometry and the ISI

Mid-IR studies of red giant stars and surrounding dust changes over short and long time periods

High spectral resolution studies
new digital spectrometer-correlator

OHP2013
Ed Wishnow wishnow@ssl.berkeley.edu

Infrared spatial interferometer (ISI) scientists, technicians, students

C.H. Townes   W. Fitelson

K.S. Abdeli
M. Bester
A. Betz*
K. Blanchard
A.A. Chandler
J. Cobb
J. Chu
W.C. Danchi
C.G. Degiacomi
R. Fulton
L.J. Greenhill
R.L. Griffith
D.D.S. Hale*
S. Hoss

M. Johnson*
K. Konevsky
E.A. Lipman*
S. Lockwood
B. Lopez
W. Mallard
T. MacDonald
J. McMahon
H. Mistry
D. Michaud
J.D. Monnier*
B. Saduolet
J. Storey
K. Tatebe*

S. Tevousian
P.G. Tuthill
K. Reichl
V. Ravi
J. Remy
C.S. Ryan
J. Shapiro
E.C. Sutton*
V. Toy
B. Walp
J. Weiner*
R.H. Weitzman
E.H. Wishnow

and many more…

Grad students get a *

Infrared Spatial Interferometer

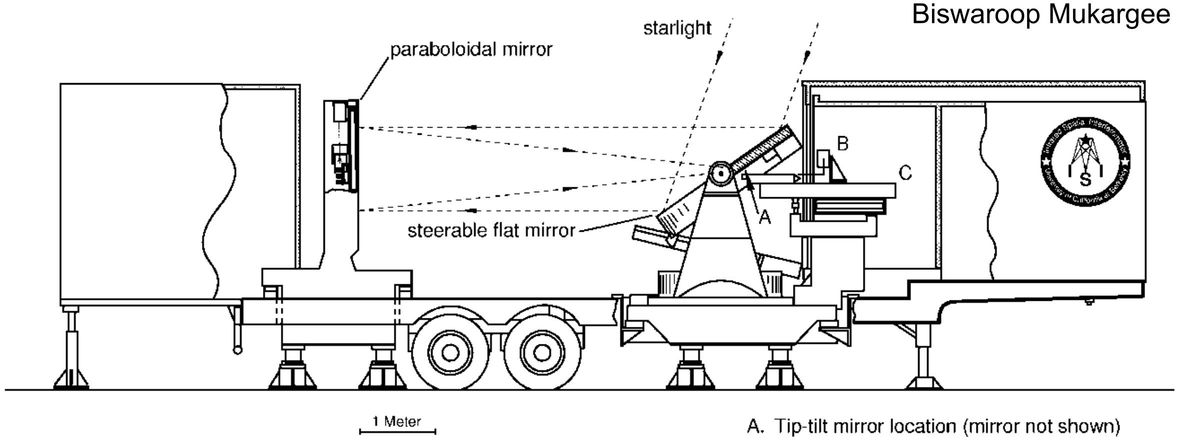
World's highest frequency radio telescope interferometer, operates at 27 THz (11 μm). Heterodyne detection using $^{13}C^{16}O_2$ lasers as local oscillators. Geometric delays removed using RF delay lines.

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

Two telescopes in operation 1988
First fringes 1989
Third telescope 2003
Closure phase measured 2004

Telescopes designed for transport as a standard semi-trailer

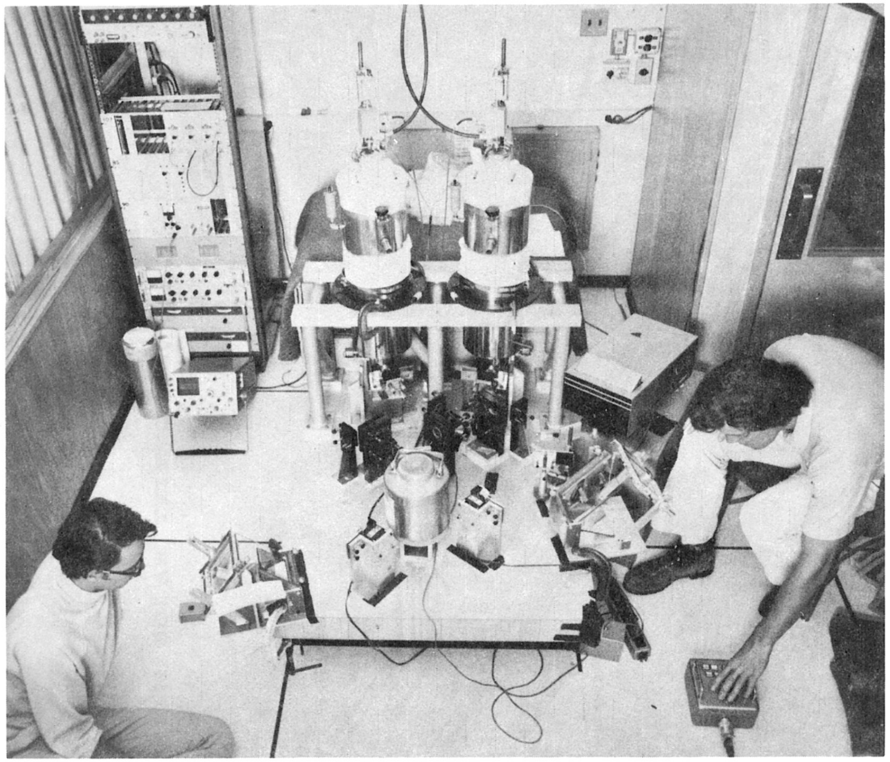
Biswaroop Mukargee



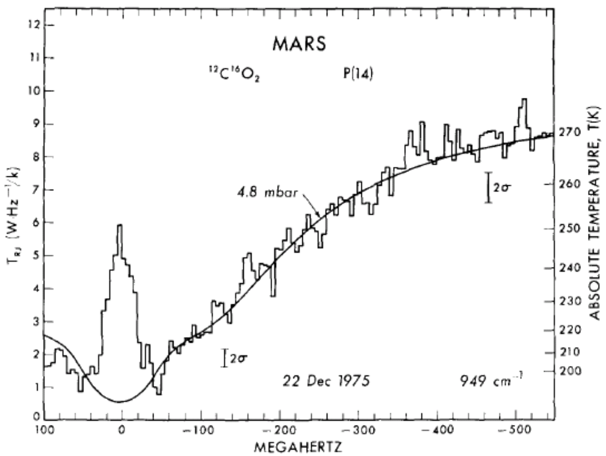
A. Tip-tilt mirror location (mirror not shown)
B. Large Schwarzschild mirror mount
C. Optics table

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

Demonstration at McMath-Pierce tele. Kitt Peak

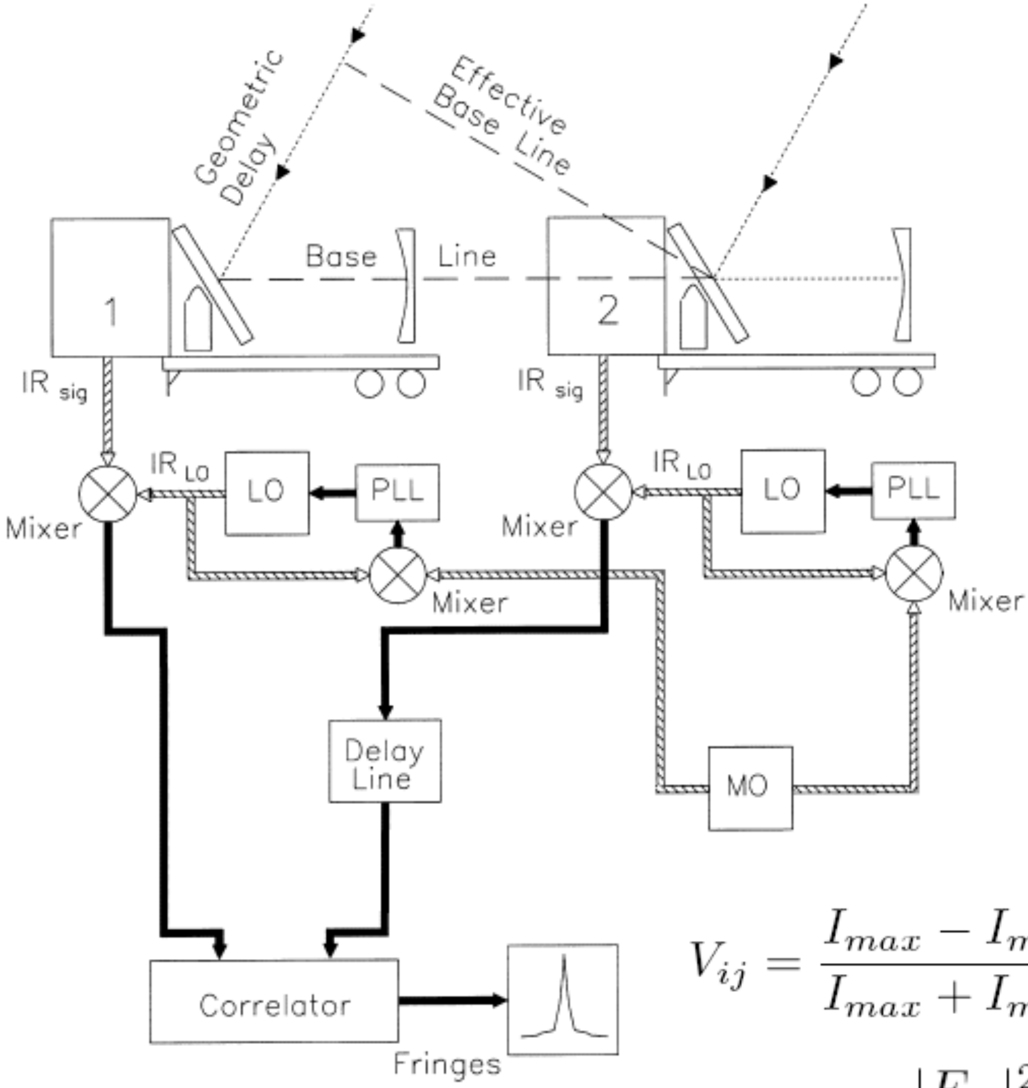


Mid-IR (10 μm) interferometry using heterodyne detection. 5.5 m baseline separation between auxiliary siderostats
Mike Johnson, Al Betz, Charles Townes
Phys. Rev. Lett, 33, 1617, 1974
Atmosphere shown to be stable enough for interference fringes from Mercury.



Heterodyne spectroscopy of CO2 on Venus and Mars.
Non-thermal emission at line center in Martian spectrum
Betz et al. Icarus 1977

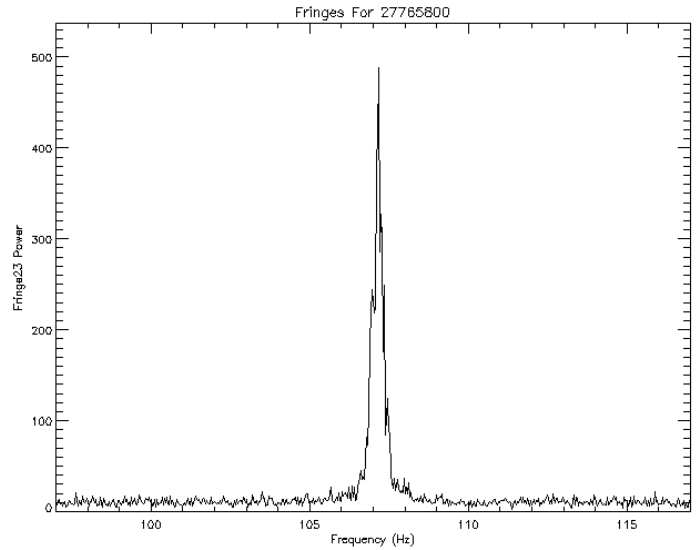
Interferometer scheme, examples of fringes

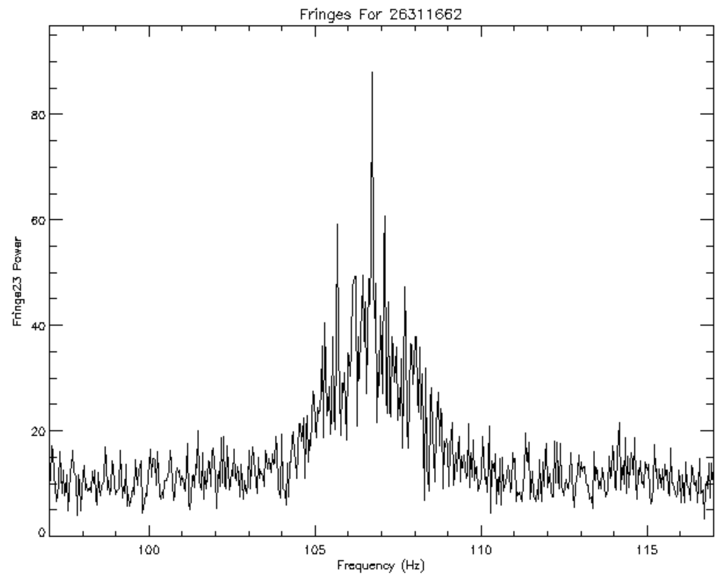


$$V_{ij} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}},$$

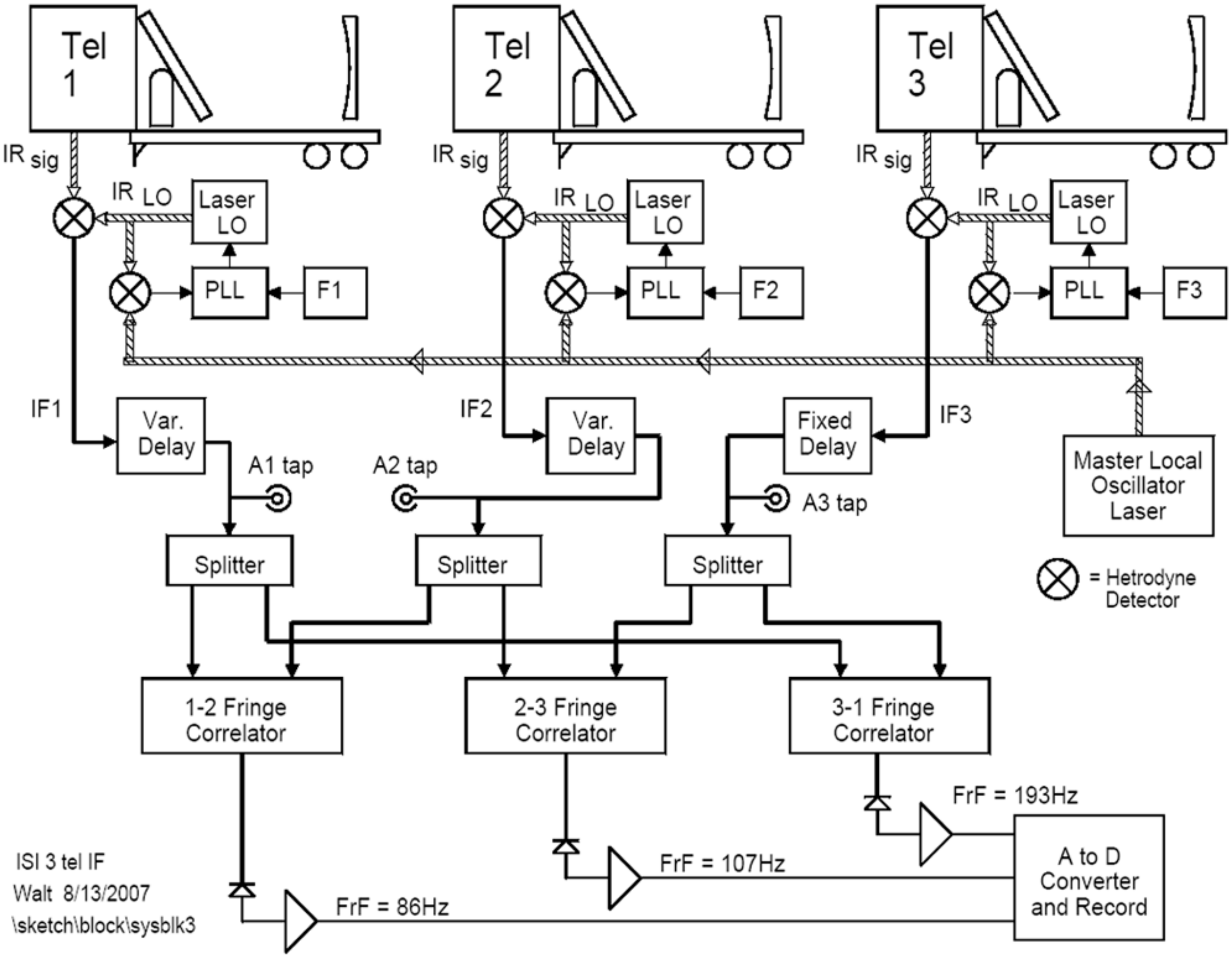
$$V_{ij}^2 = \frac{|F_{ij}|^2}{P_i P_j}.$$

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

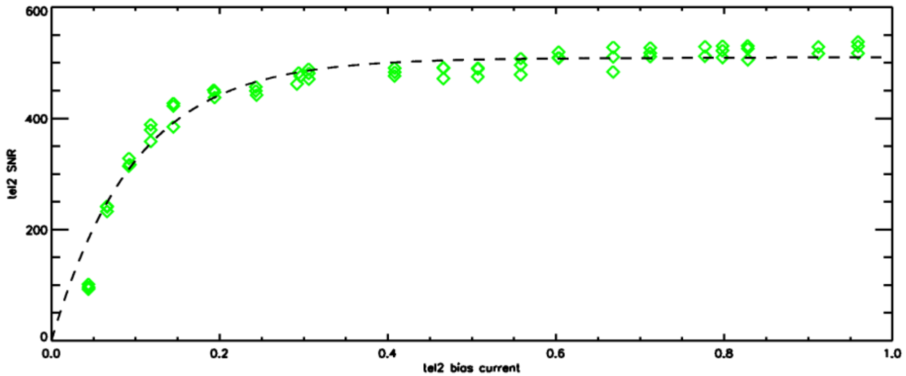
Power law detector forms product terms; including beat frequency difference (and sum)
where $w_0 = w_s$ is the pertinent noise term

Johnson & Townes 2000
Optics Comm, 179, 183

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

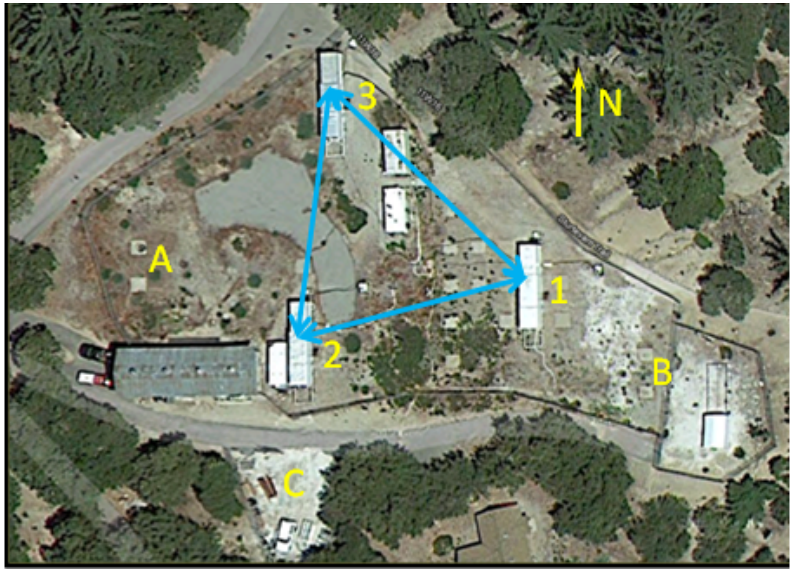
System noise temp at 11 μm ~ $h\nu/k$ = 1300 K
for wavelengths > 1 cm, amplifier noise will dominate
for 1 μm, $h\nu/k$ = 14000 K

Detector test measurement showing bandwidth limit of S/N

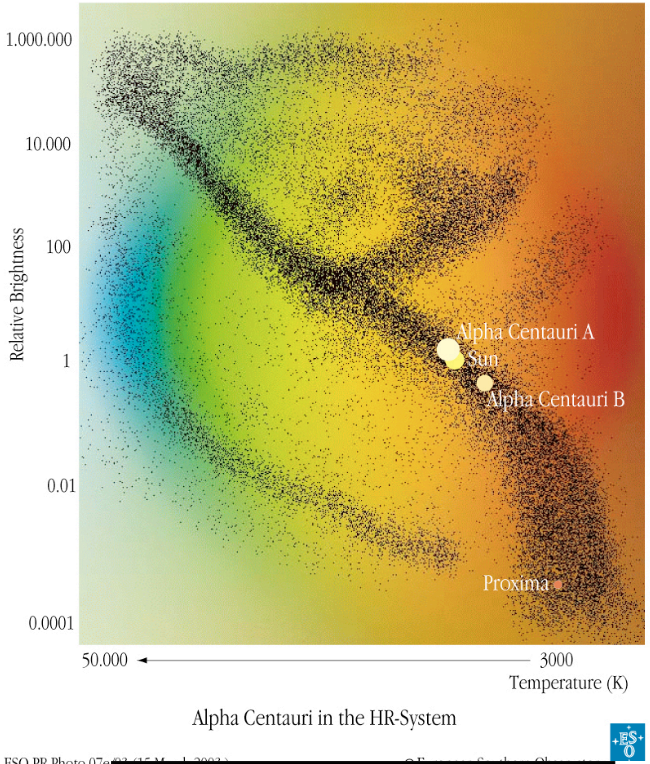


SNR vs. det. current α LO power

ISI array configurations and moving telescopes

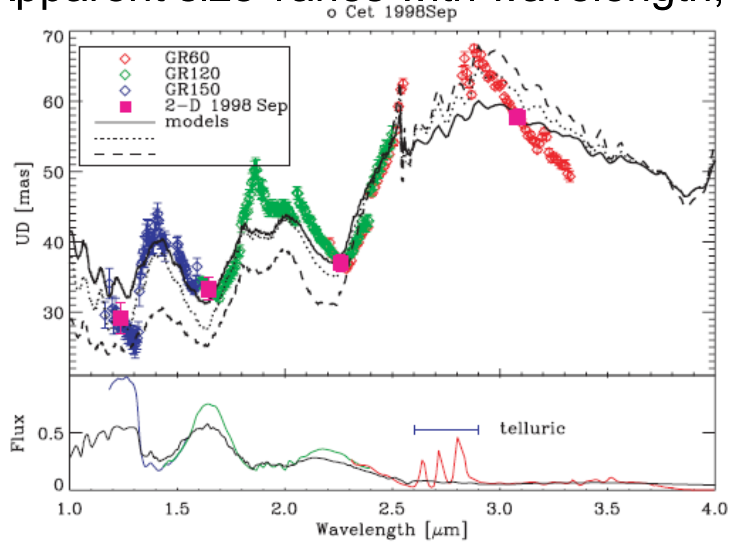


ISI site. Teles. 1,2,3 are shown.
Cement pads for longest baselines EW are A,B 85m. Longest NS baseline 3,C ~60m

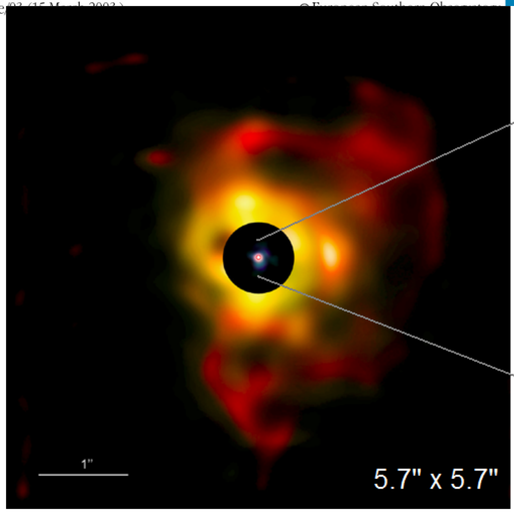


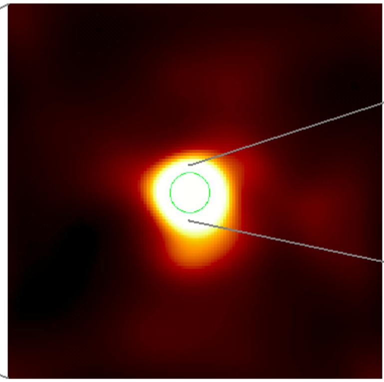
Aspects of Red Giant & Mira stars

Apparent size varies with wavelength, Keck aper. mask

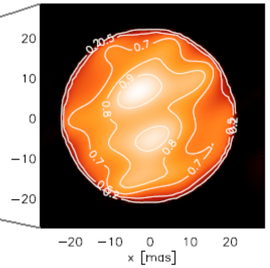


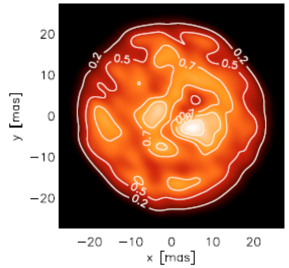
Woodruff et al.,
ApJ 691, 1328, 2009





0.4" x 0.4"





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

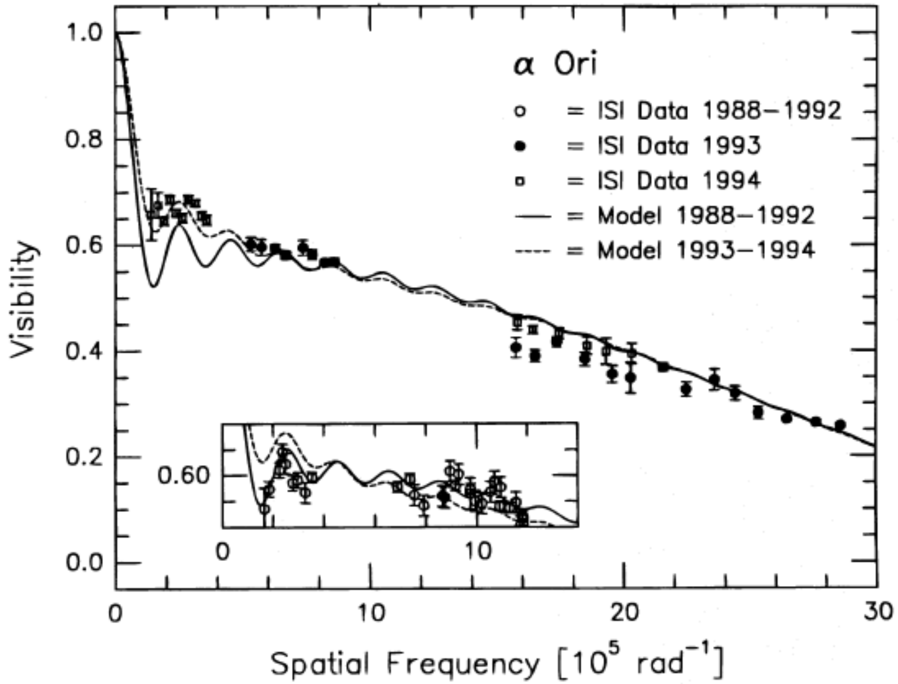
K band deconvolution image
extended atmosphere,
photosphere diam 43.7 mas
(Kervella et al. 2009

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

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

Stellar variations over time

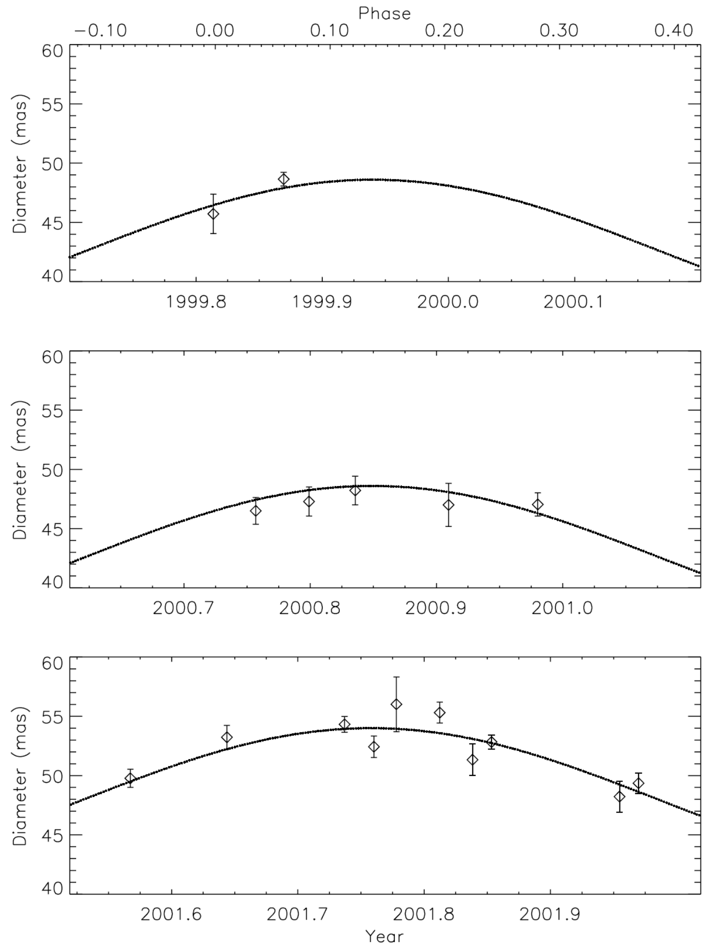
Betelgeuse visibility variations



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.

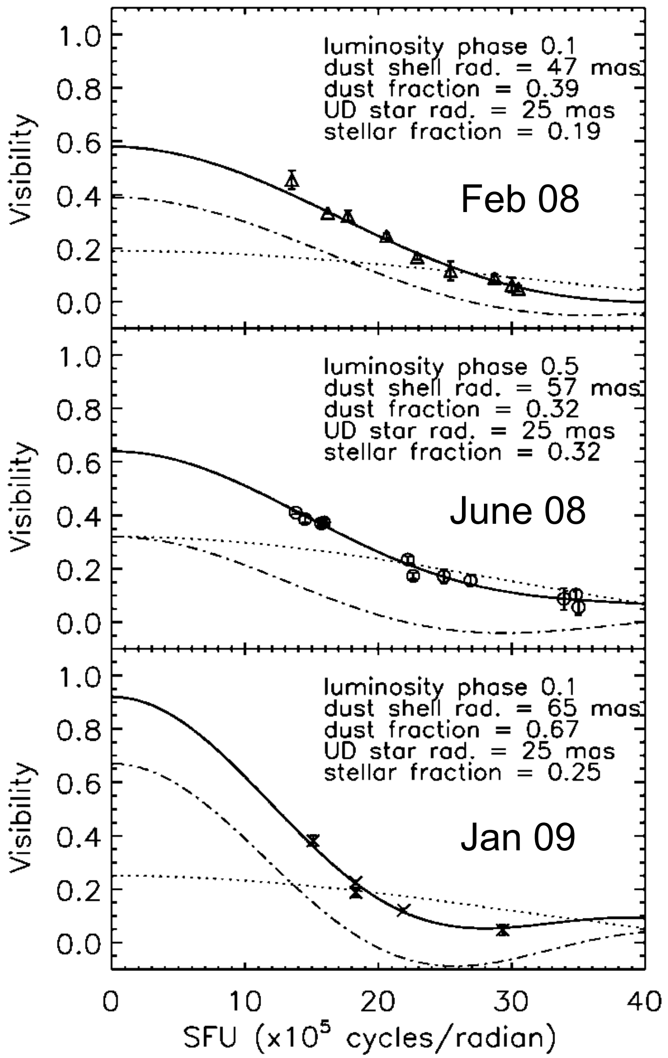
Bester et al. 1996

Mira diameter changes over a stellar luminosity period



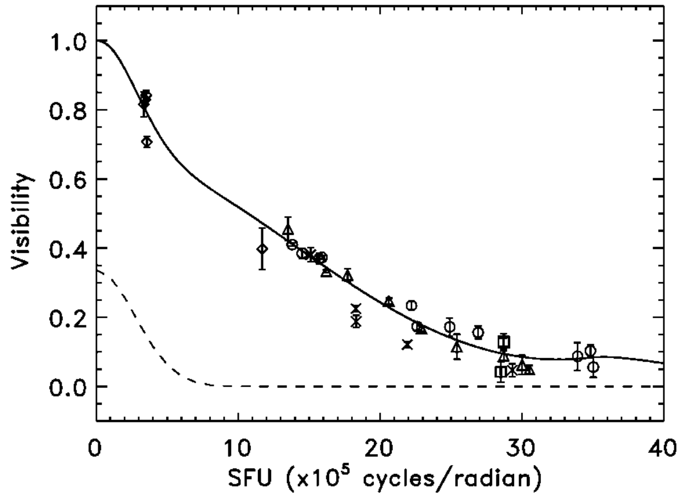
Weiner et al. 2003

W Hydrae change in visibility and intensity dist.

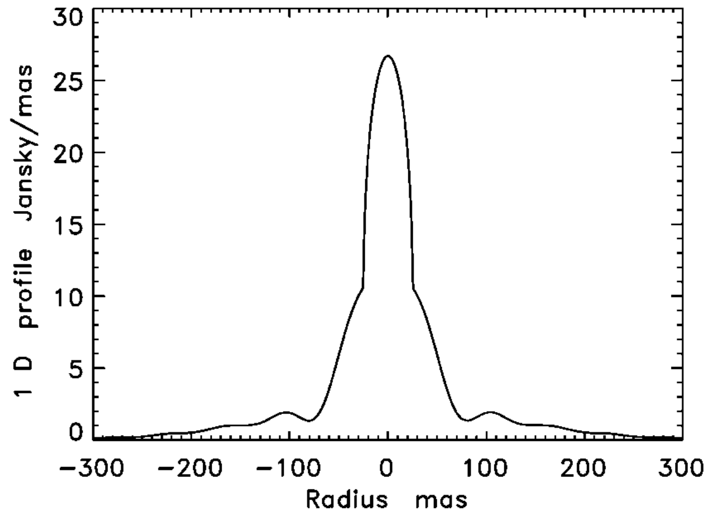


At 104 pc, a 47--65 mas change in radius over a year gives a velocity of 9 km/s

All data including June 1994 & June 1999 fitted with a smooth curve

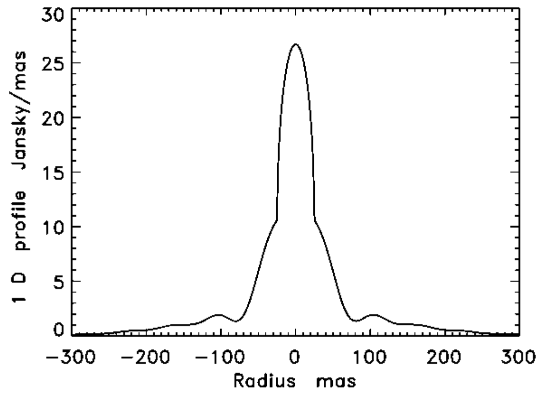


Fourier transform of above curve giving 1-dim. intensity distribution

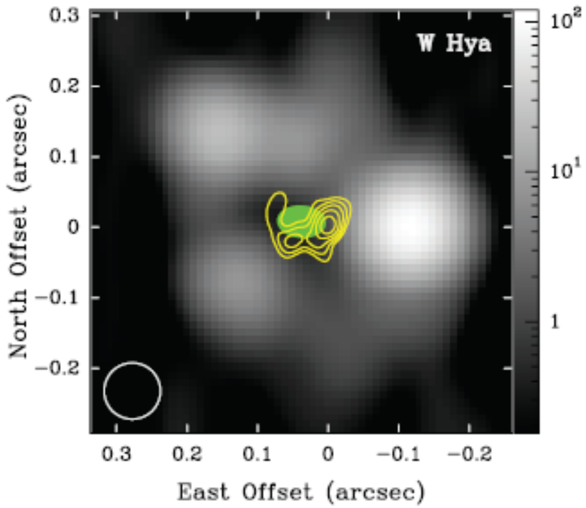


Zhao-Geisler et al., 2011, 11 um, measure FDD radius=45 mas. Approx. match to this dust shell.

Comparison of mid-IR to radio observations



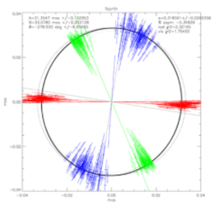
W Hya ISI
1D integrated profile



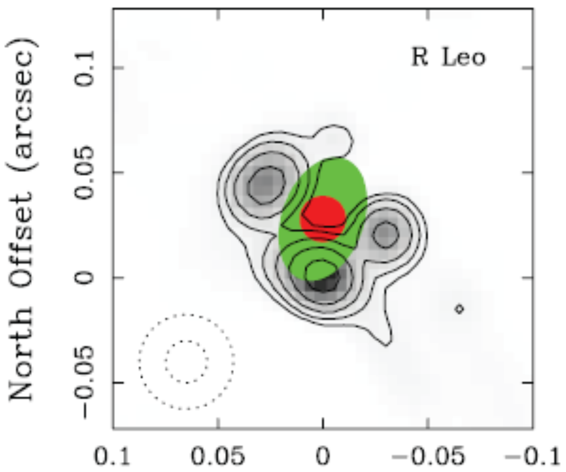
VLA A config
43 GHz, 7 mm
Opacity due to H- free-free
Radio continuum in green
Contours are SiO maser

Grey scale is H2O Maser
Emission, 22 GHz

R Leo ISI
Uniform ellipse fits to visibility



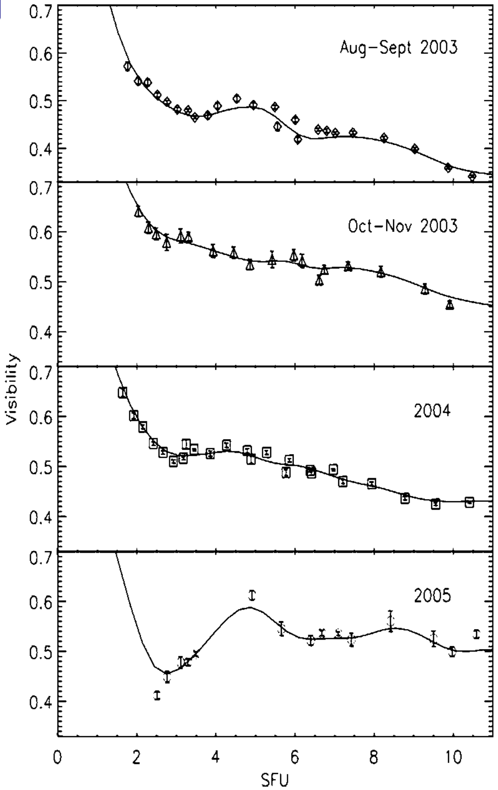
Ellipse 64x62 mas

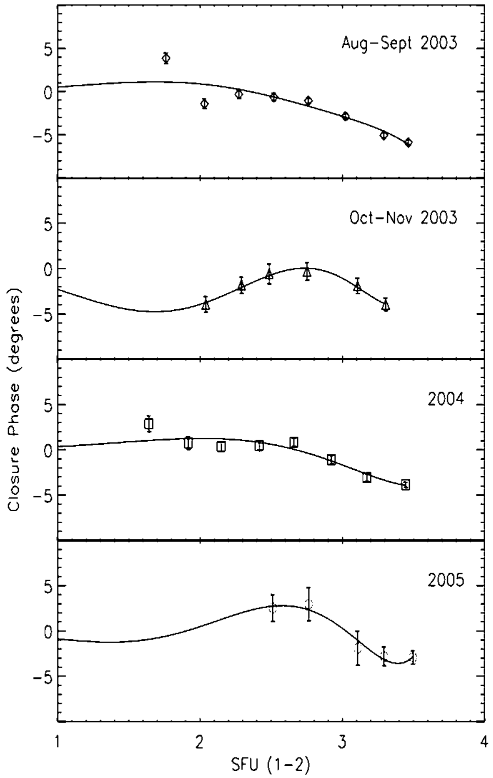


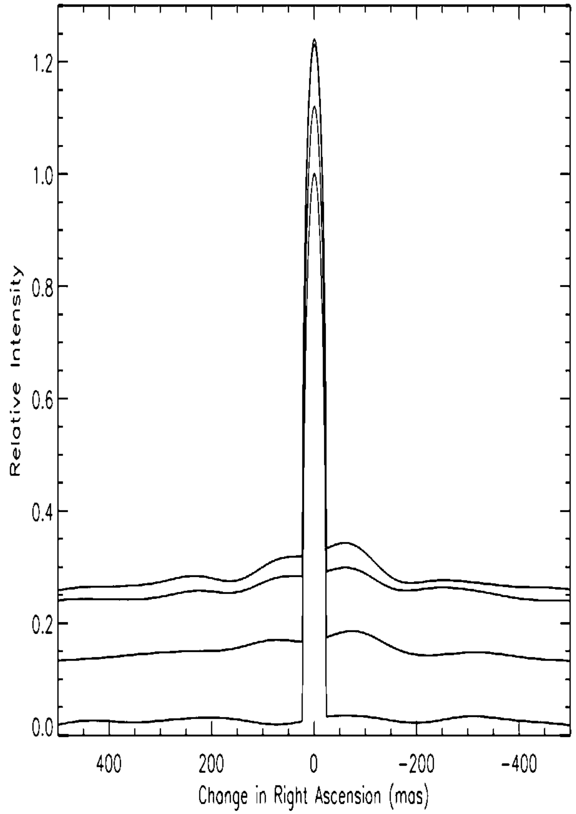
Radio continuum in green
Contours are SiO maser
Ellipse 61x39 mas

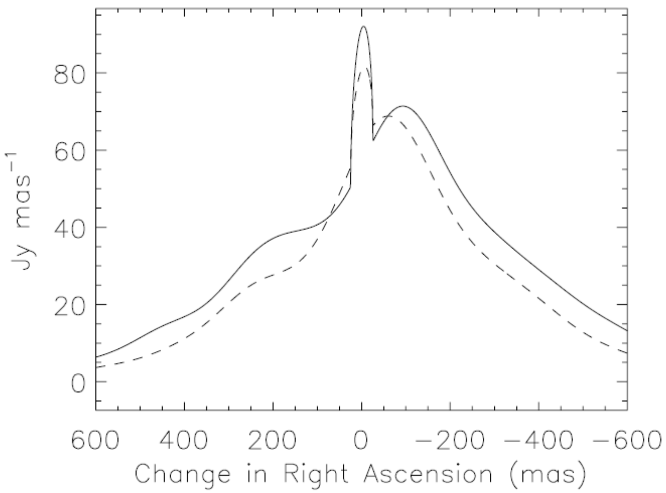
Reid & Menten, 2007, ApJ, 671, 2068

Using Phase Closure: Evolution of dust surrounding stars









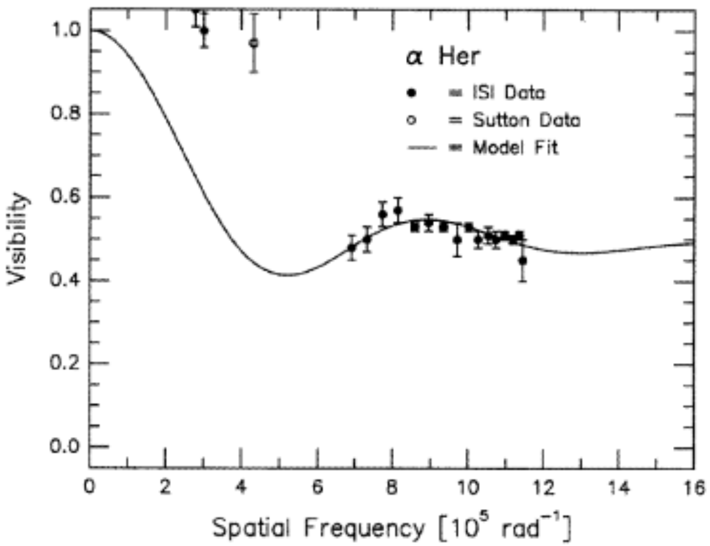
Asymmetry of dust
IRC+10216
2004 (solid)
2006 (dashed)

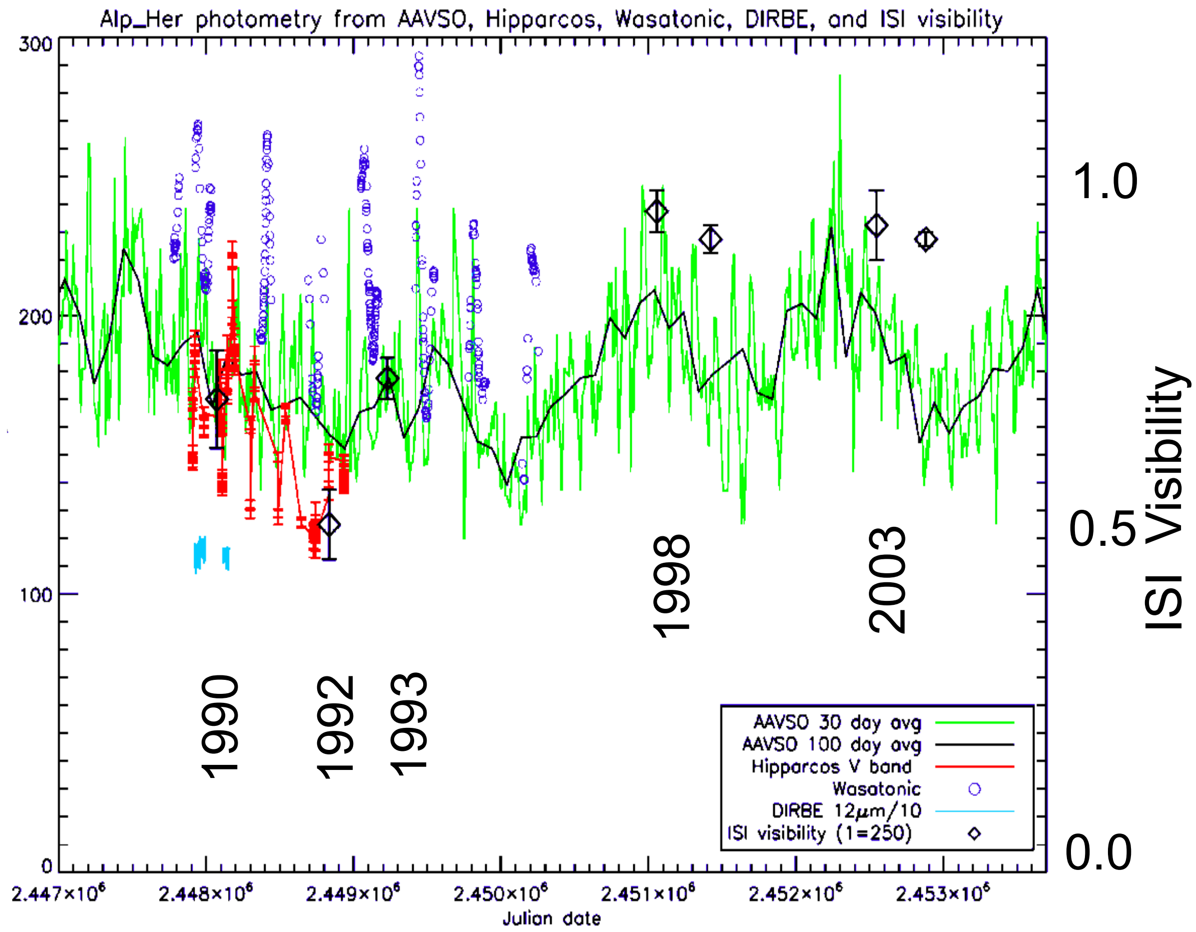
Chandler et al., ApJ
657, 1042, 2007

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

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

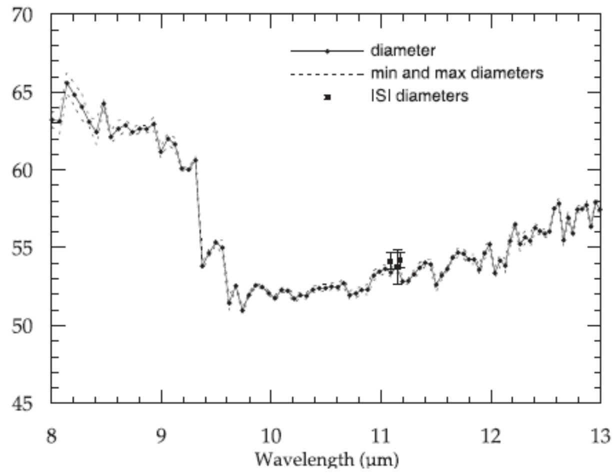
Long term studies: variations of α Her



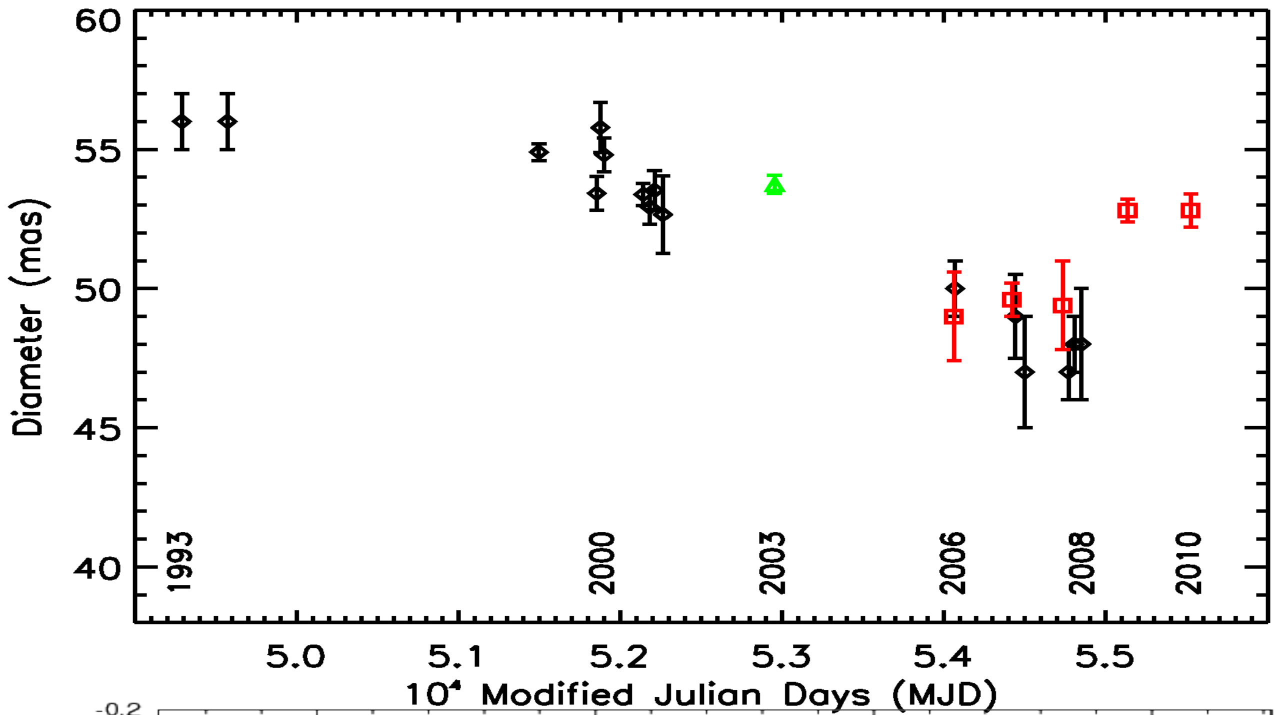


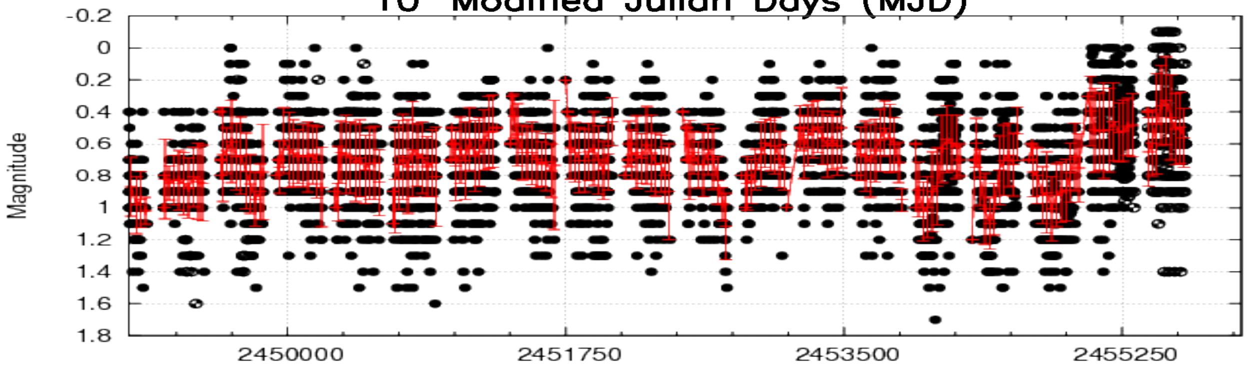
Tatebe et al. “Observation of a Burst of High-Velocity Dust from α Herculis,”
2007, ApJ, 658, 103. From 92 to 93, about 75 km/sec

Betelgeuse 11 um UD size over 17 years



Perrin 2007, A&A, 474, 599

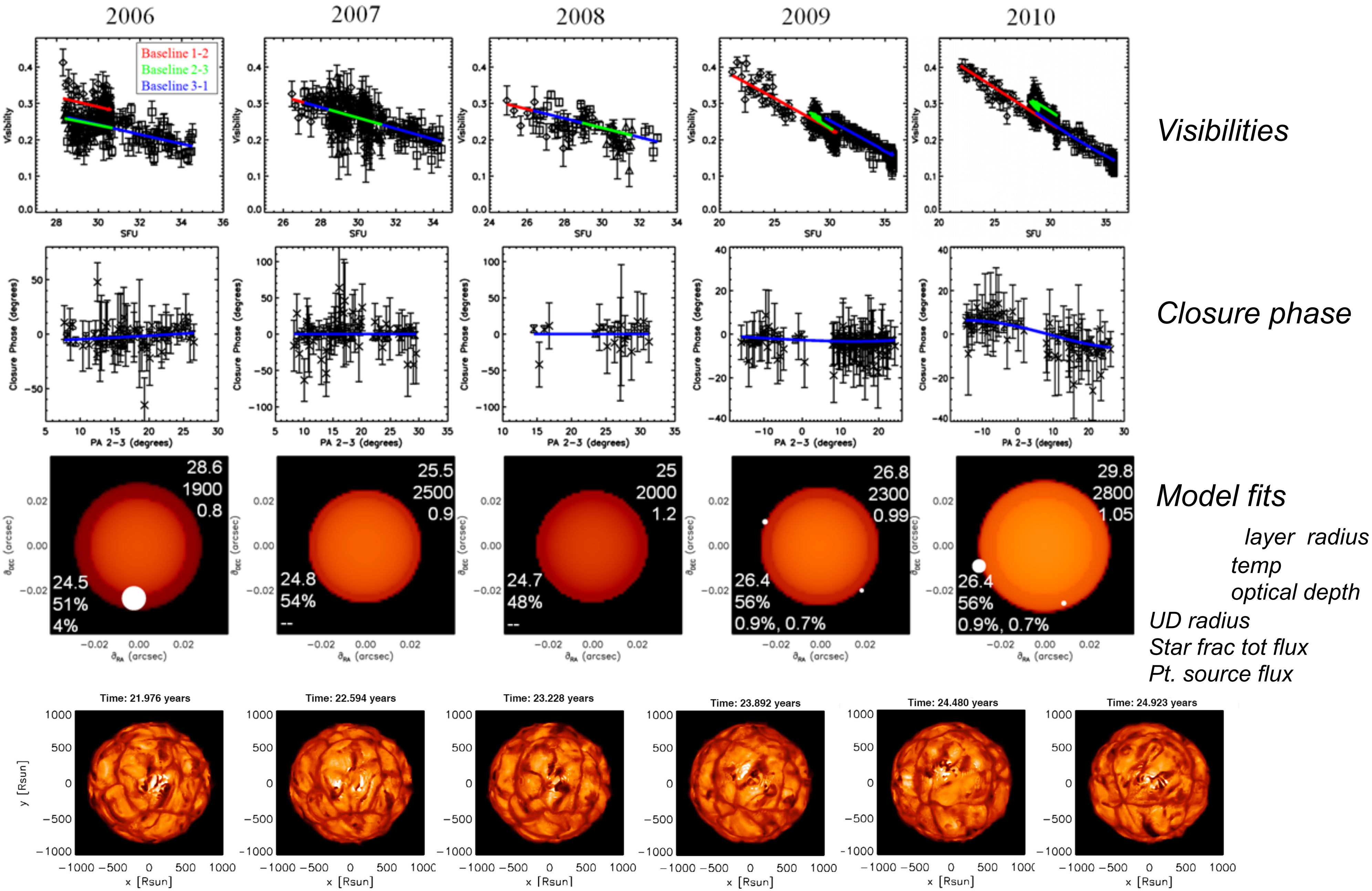




Black pts. Townes, Wishnow, Hale & Walp, 2009, ApJ, 697, L127
Green pts. 10.03, 11.04, 11.15 μm from Perrin et al., 2007, A&A, 474, 599
Red pts. Ravi et al. 2011, ApJ, 740

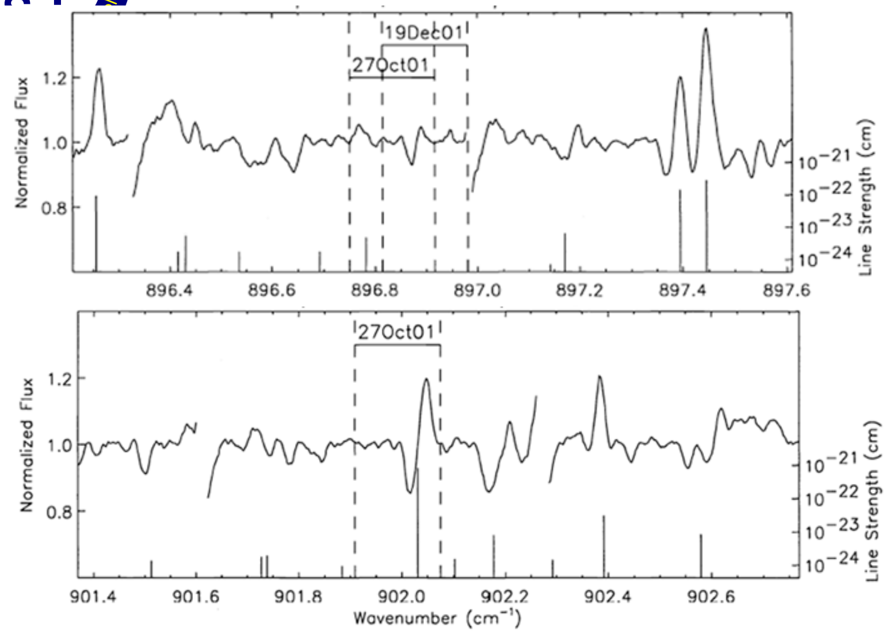
Ohnaka plots K band meas over same period w/ 43 mas diameter
2011, A&A, 529

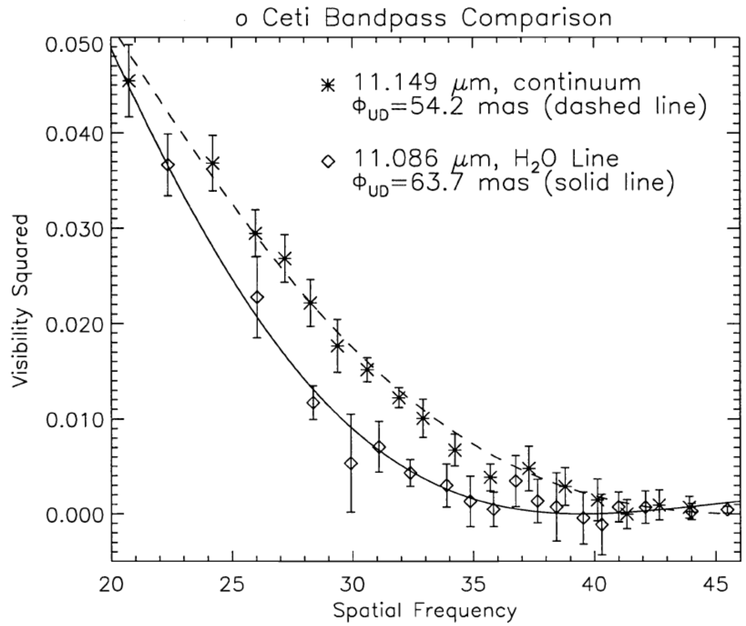
3 telescope measurements of Betelgeuse



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

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





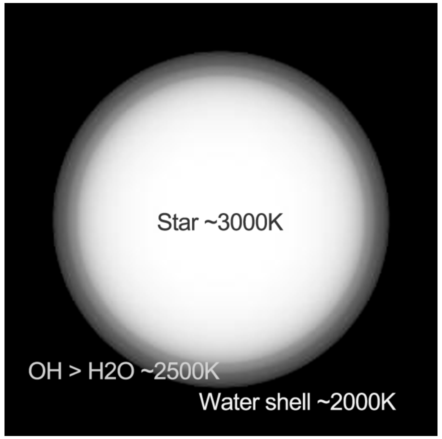
Previous ISI
Spectroscopic-interferometry
RF analog system

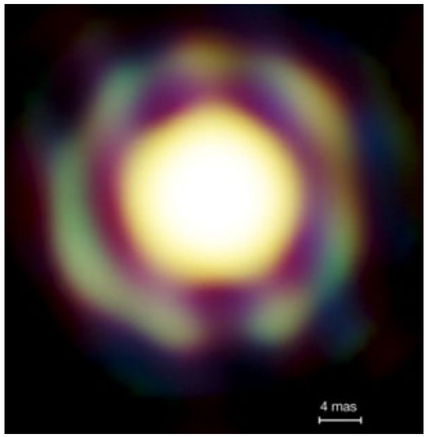
VY Cma
NH3 forms at ~40R*

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

Monnier et al. 2000
ApJ, 453, 868

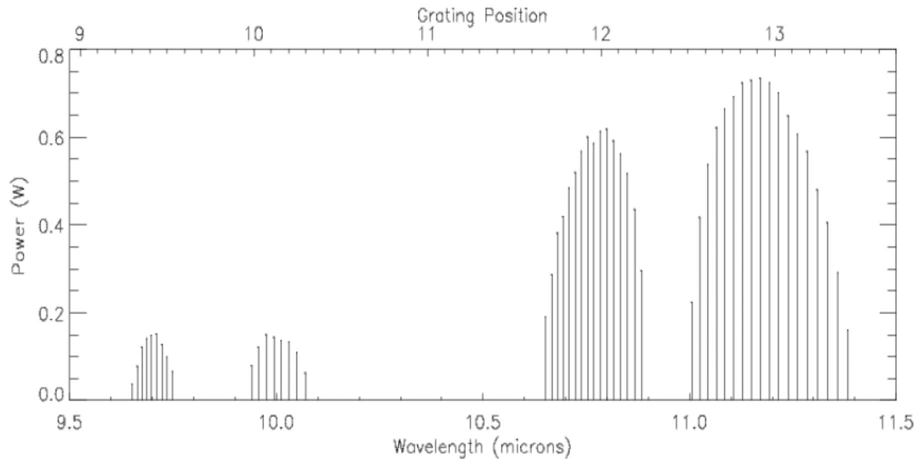
Weiner et al. 2003, SPIE, 4838, 172



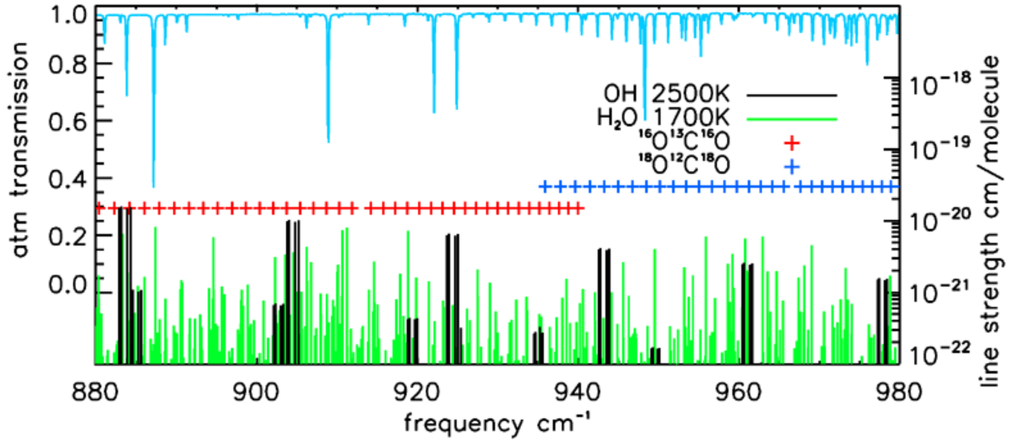


T Lep, VLTI, 1.4-1.9 μm,
Le Bouquin et al. 2009 A&A L

Spectral range covered, OH & H2O lines of interest



ISI $^{13}CO_2$ laser lines

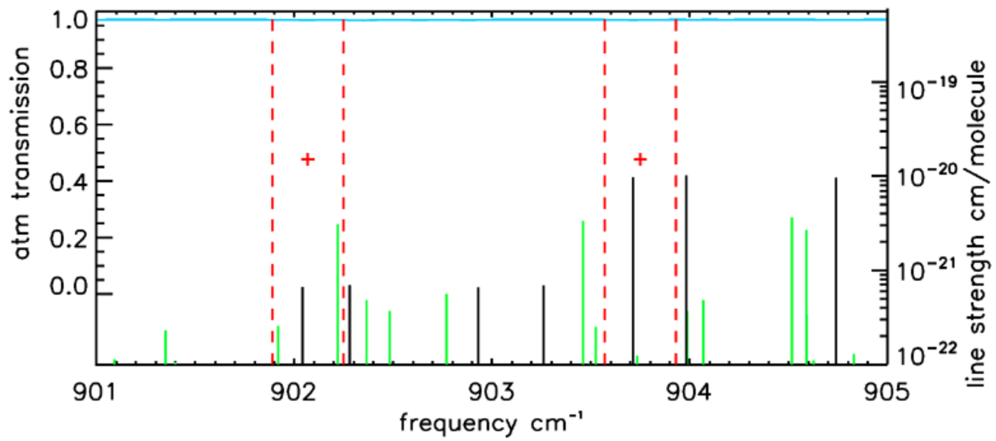


Previous ISI
Spectroscopic-interferometry
RF analog system

Monnier et al. 2000
ApJ, 453, 868

VY Cma
NH3 forms at ~40R*

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

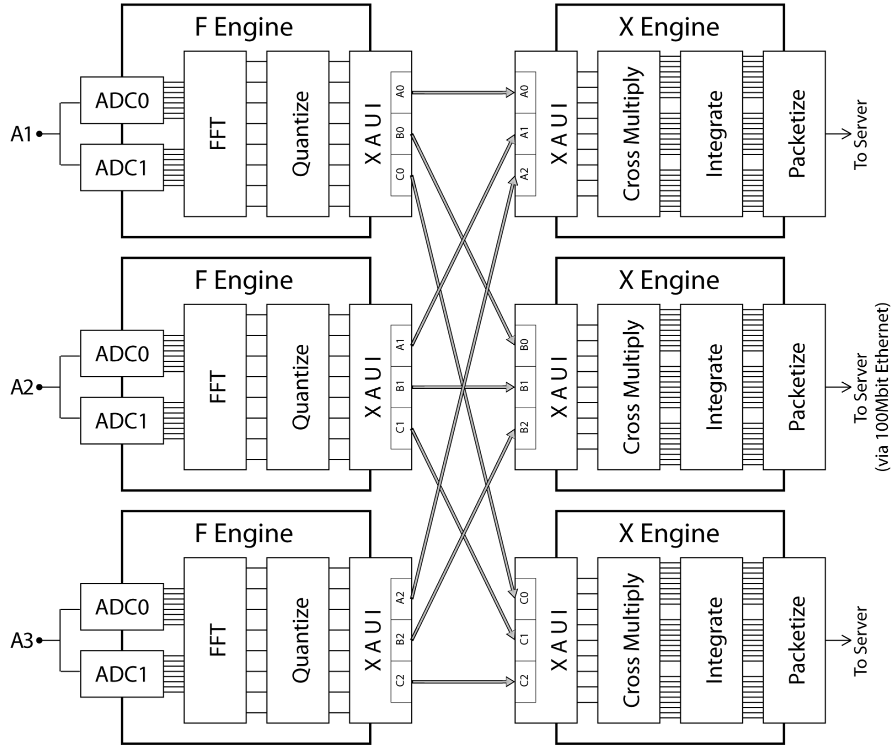


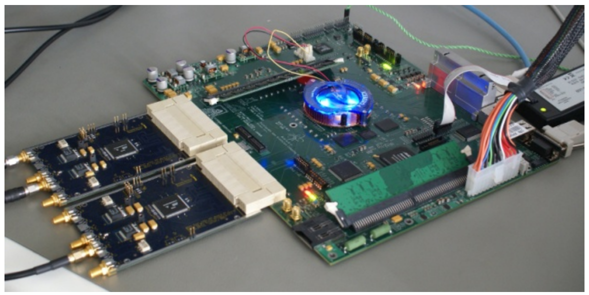
Simulation of αOri
OH black
H2O green
Band covered red

FPGA digital spectrometer-correlator

3 GHz BW, 64 channel
Resolution of 600,000

47 MHz per channel
Doppler width HWHM for
H_2O at 1000 K is 72 MHz

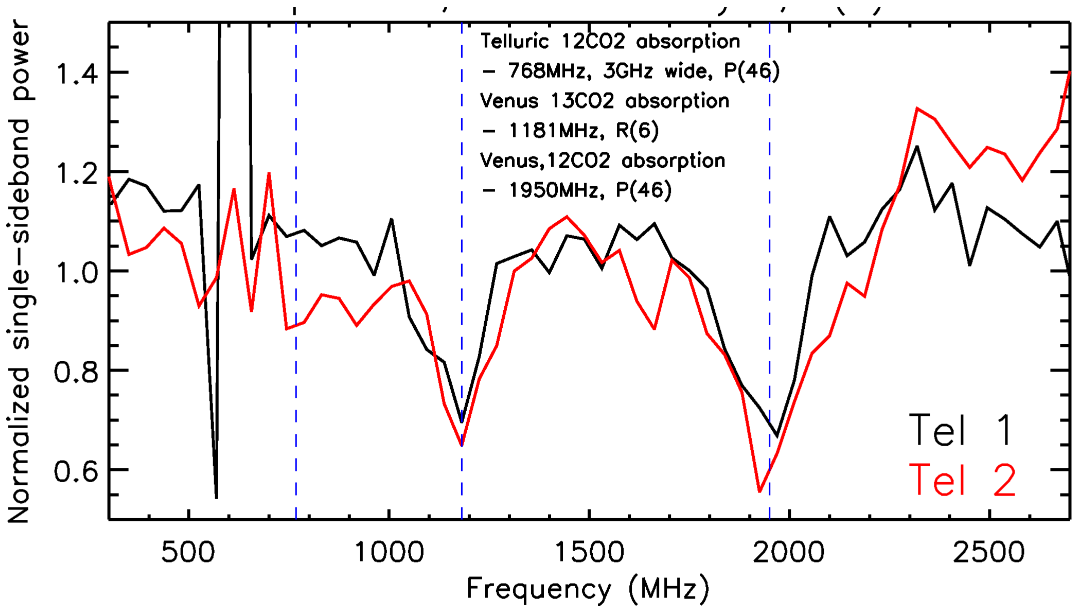


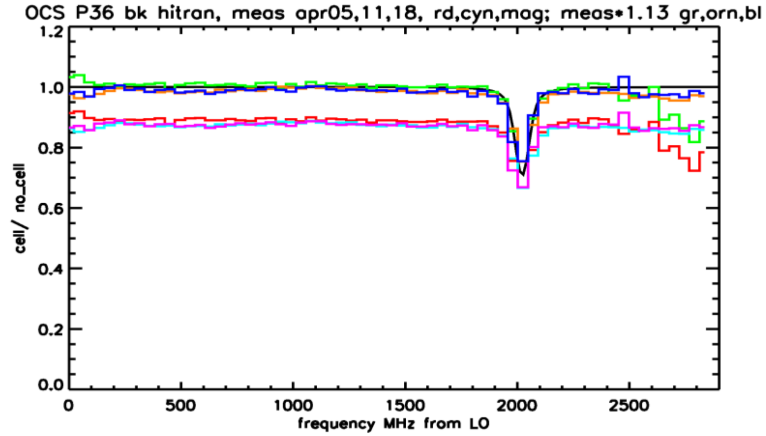


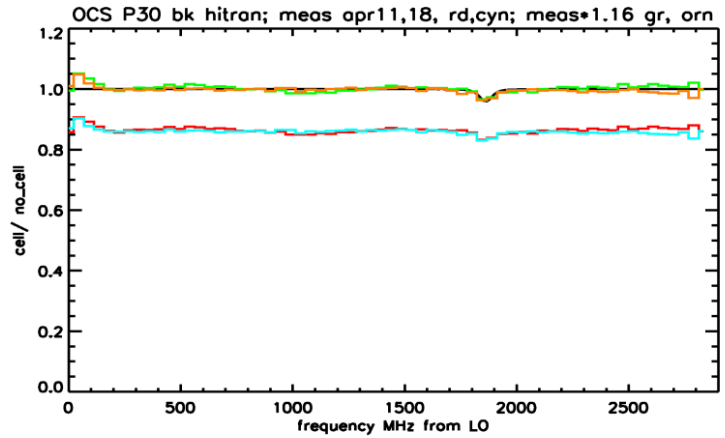
6 Gsamp/sec using interleaved ADCs
128 pt FFTs every 22 ns. Data swapped between boards for cross-correlation and accumulation.
45000 spectra, every ms.
Collaboration with Mallard, Werthimer, CASPER

Heterodyne spectrometer testing

Digital spectrometer R~600000
Spectrum of Venus

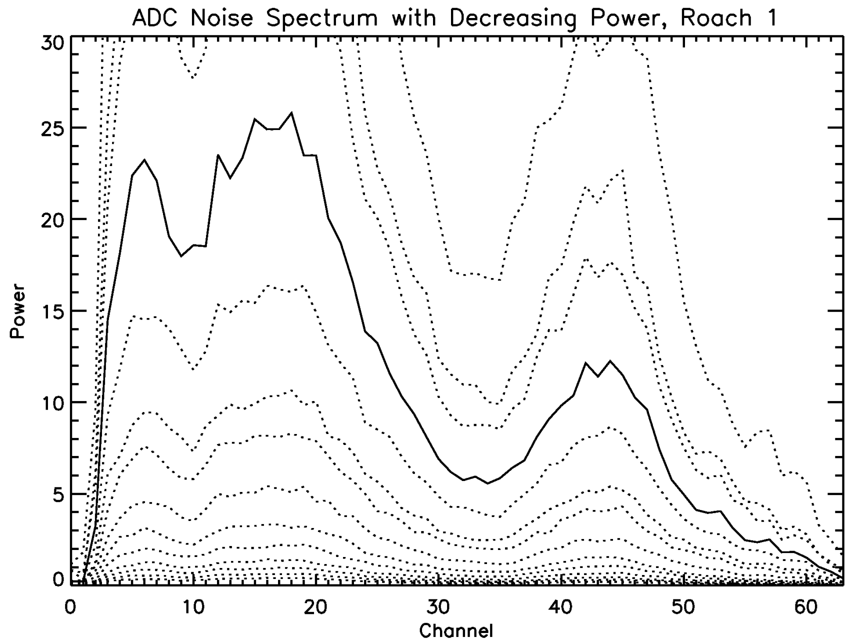


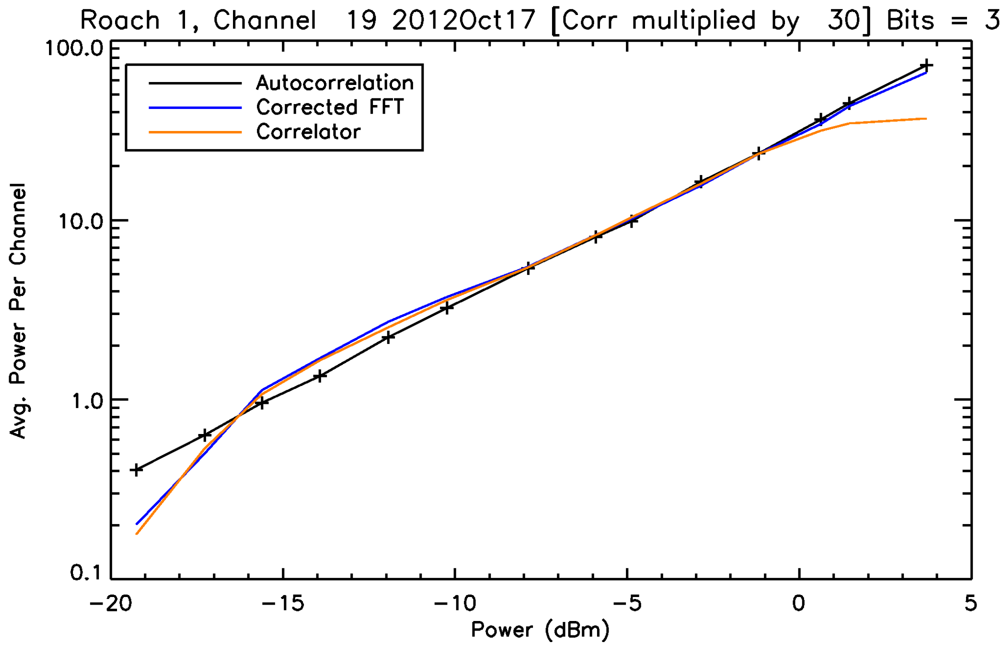


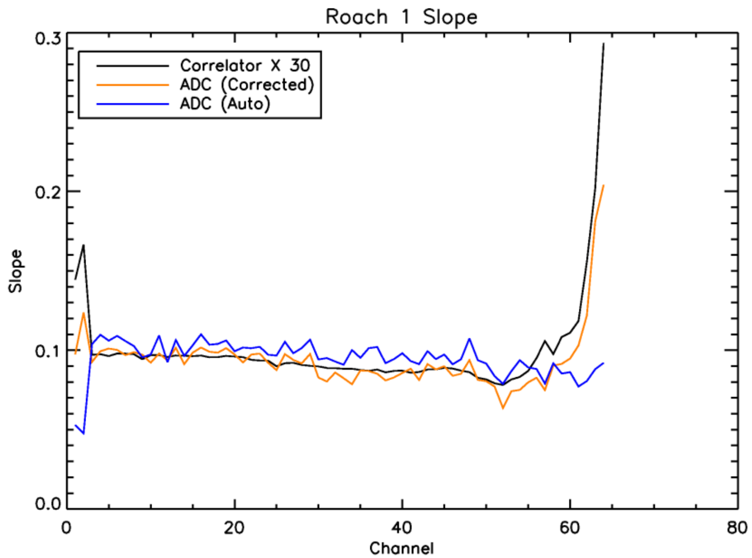


Laboratory testing, measuring
OCS 4 Torr, 14 cm cell

Lab tests of correlator performance





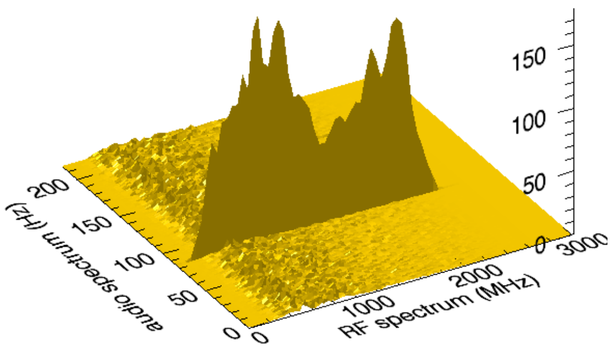


Inject full band noise at measured levels

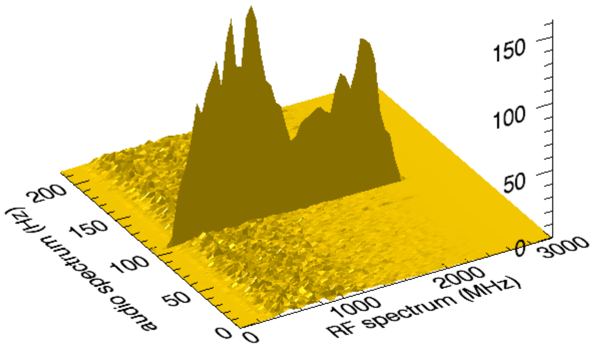
Meas w/ ADC and calc. autocorrelation, XF
Model Roach processing
Measure w/ correlator

Fit slope of correlated power for channels
Plot response of system

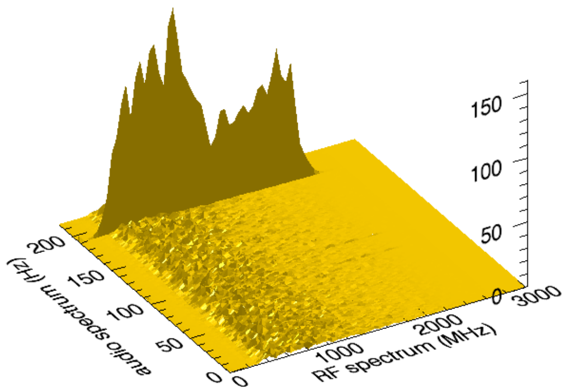
Spectrometer-correlator testing



ab fringe 86 Hz



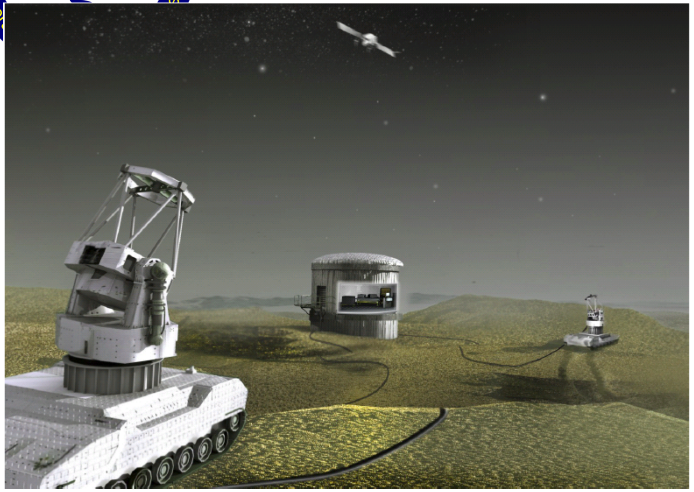
bc fringe 107 Hz



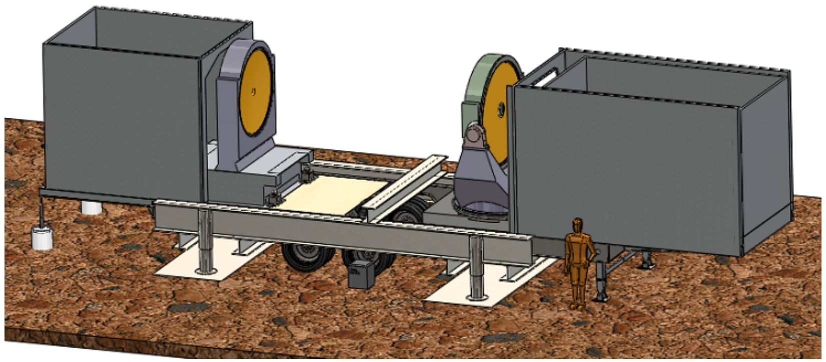
ca fringe 193 Hz

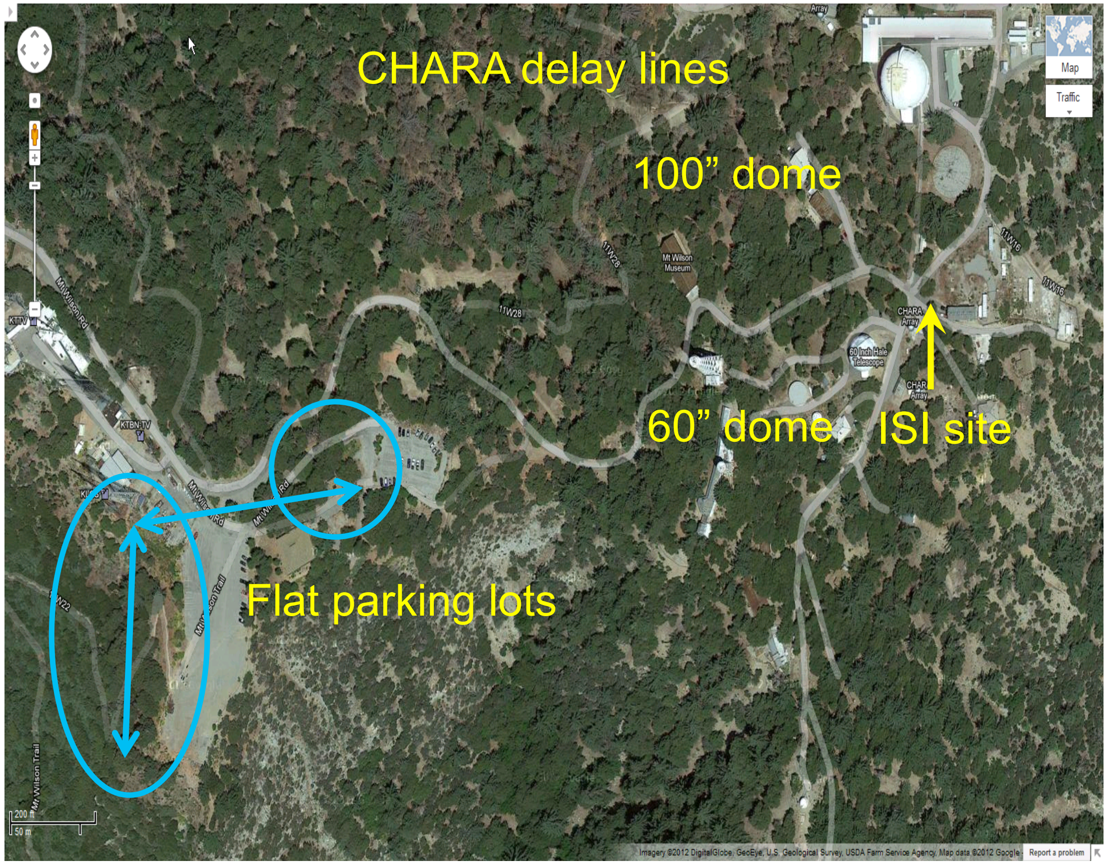
3 uncorrelated RF noise sources ~-8 dBm—3 “lasers” applied to 3 independent detectors
Lasers noise sources are combined with small RF correlated noise source ~-26 dBm
Correlated noise source modulated at: 1MHz+193Hz, 1MHz+107Hz, 1MHz.
10 sec of data
Correlated RF source is recovered at the appropriate audio frequencies: 86, 107, 93 Hz

DARPA program to image geo-synchronous satellites

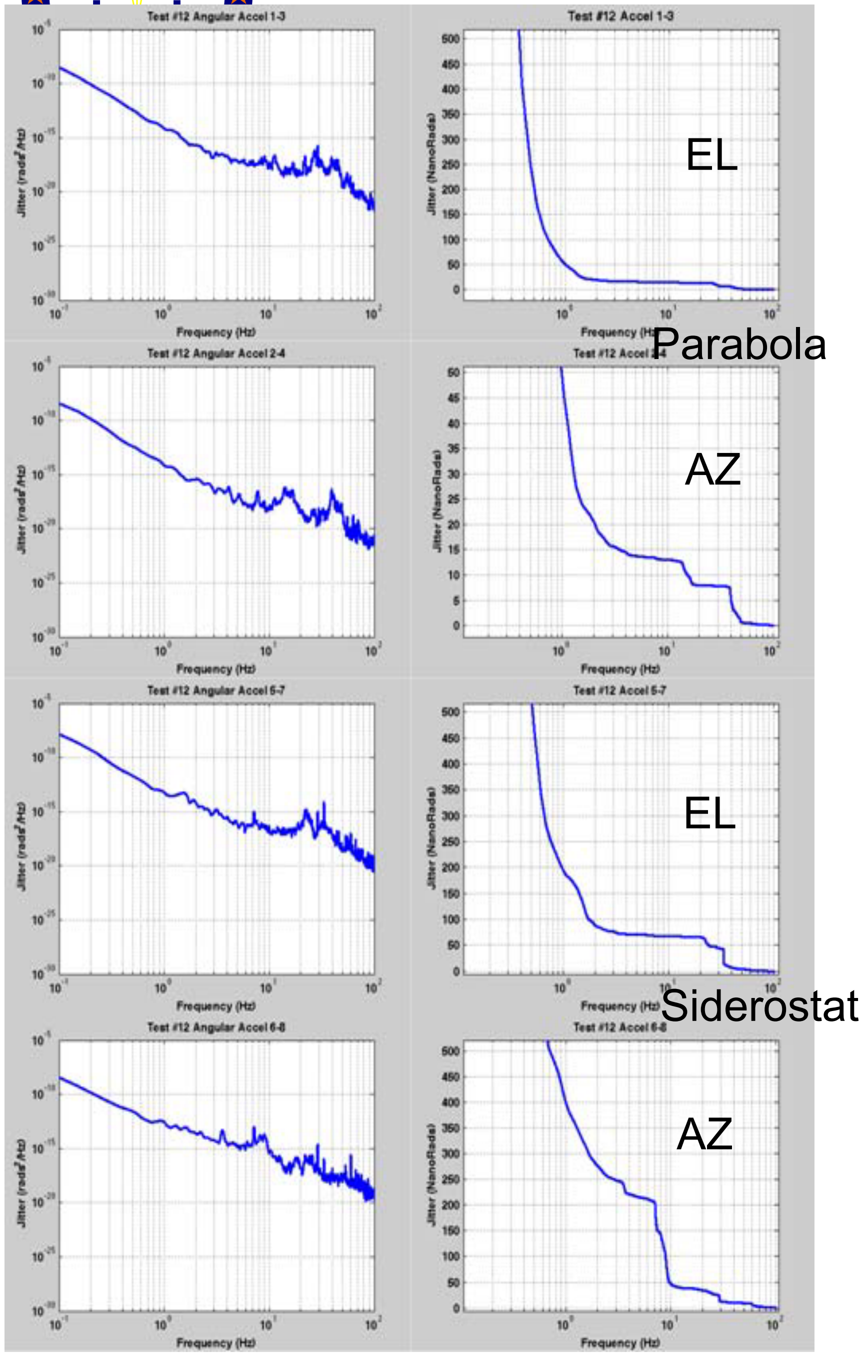


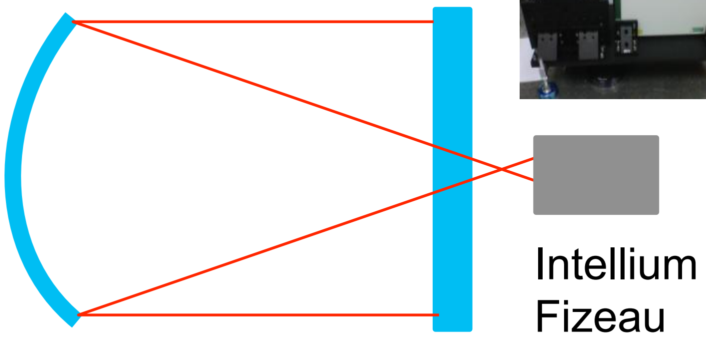
Interferometry of geo satellites
10 cm resolution @ 36000 km
~3 nrad ~ 0.6 mas, Mv=11
Many samples in UV plane
Telescopes w/ /AO
linked with optical fibers
Move baselines in 5 min
Conduct meas. at Starfire in NM



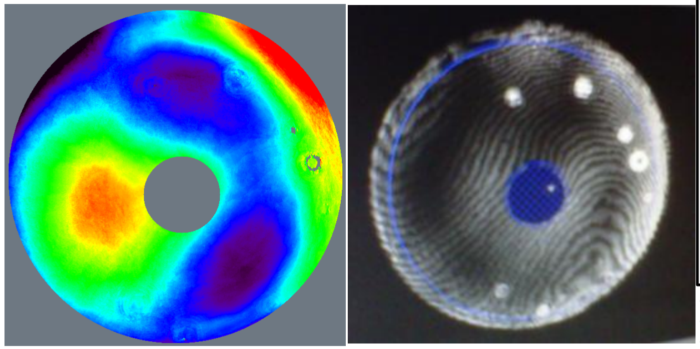


ISI Vibration tests/Optical wavefront tests

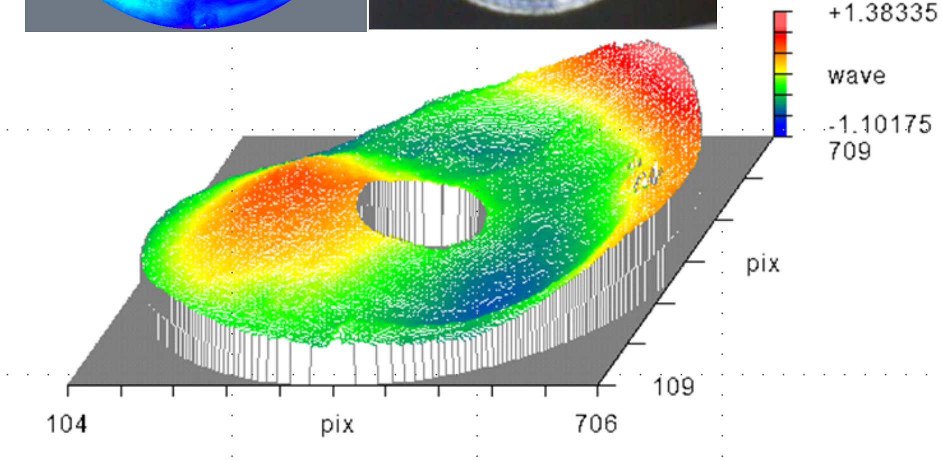




Double pass meas of ISI mirrors



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	



Dave Jurasevich APOD 2008 Dec 03