Astrometry

(Wide-Angle, Narrow-Angle, Narrower-Angle, Imaging, Differential Phase)

Michelson Summer Workshop

Frontiers of Interferometry: Stars, disks, terrestrial planets

Pasadena, USA,
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What you should learn from this talk

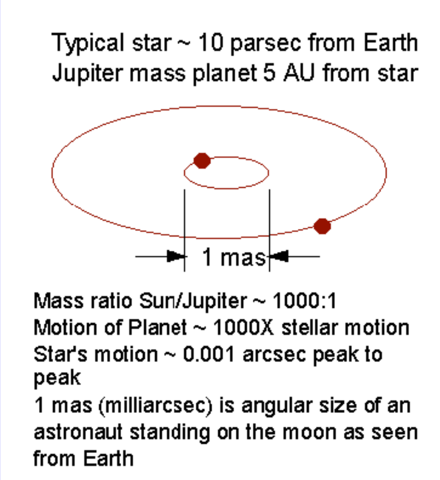
- Definitions
- Motivation
- Orders-of-magnitudes of the observables and requirements
- Types of Interferometric Astrometry
  - Wide-Angle (all-sky).
  - Narrow-Angle, or “Dual-Star” (separations of few 10s of arcseconds)
  - Very Narrow-Angle (~0.1-1 arcsecond, “speckle”)
  - Imaging (<0.1 arcsecond)
  - Differential Phase (<0.1 arcsecond)
- Descriptions
- Challenges & Strategies for meeting them.
- Some Results

What is astrometry and why should I care?

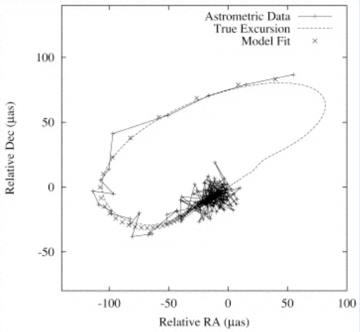
- Measuring the positions and motions of stars.
- Parallaxes - still the most fundamental & reliable way to measure distances in astronomy.
- Gives a direct handle on object masses, even unseen ones.
    - Planets are the obvious example

$$\Delta\theta \cong 1000 \frac{m_p / m_J}{M_* / M_S} \frac{a / \mathrm{AU}}{D / pc} \ \mu\mathrm{asec}$$

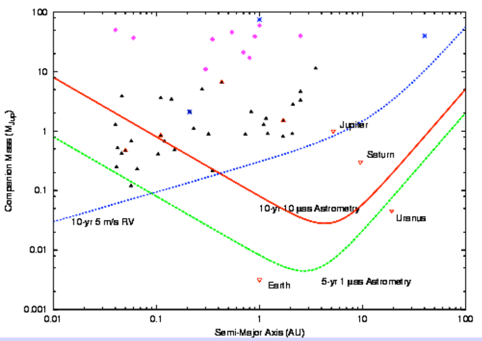
    - Gravitational microlensing
    - Galactic center, black holes

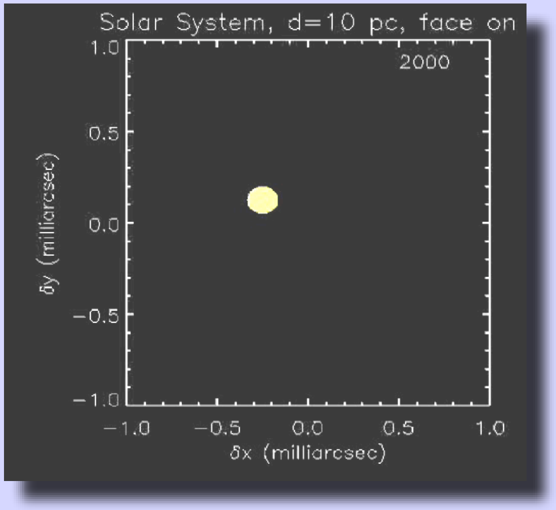

Typical star ~ 10 parsec from Earth
Jupiter mass planet 5 AU from star

Mass ratio Sun/Jupiter ~ 1000:1
Motion of Planet ~ 1000X stellar motion
Star's motion ~ 0.001 arcsec peak to peak
1 mas (milliarcsec) is angular size of an astronaut standing on the moon as seen from Earth



Boden, Shao & Van Buren (1998)



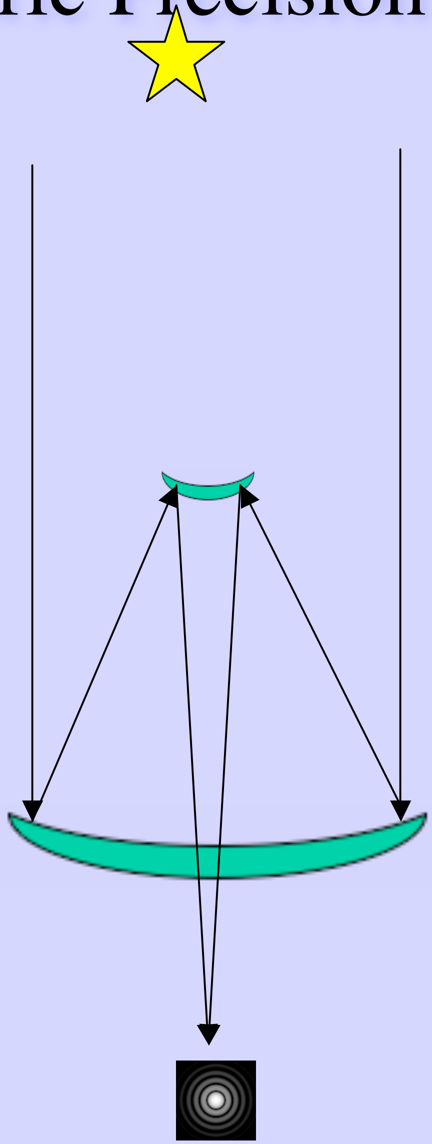


What levels of precision are needed?

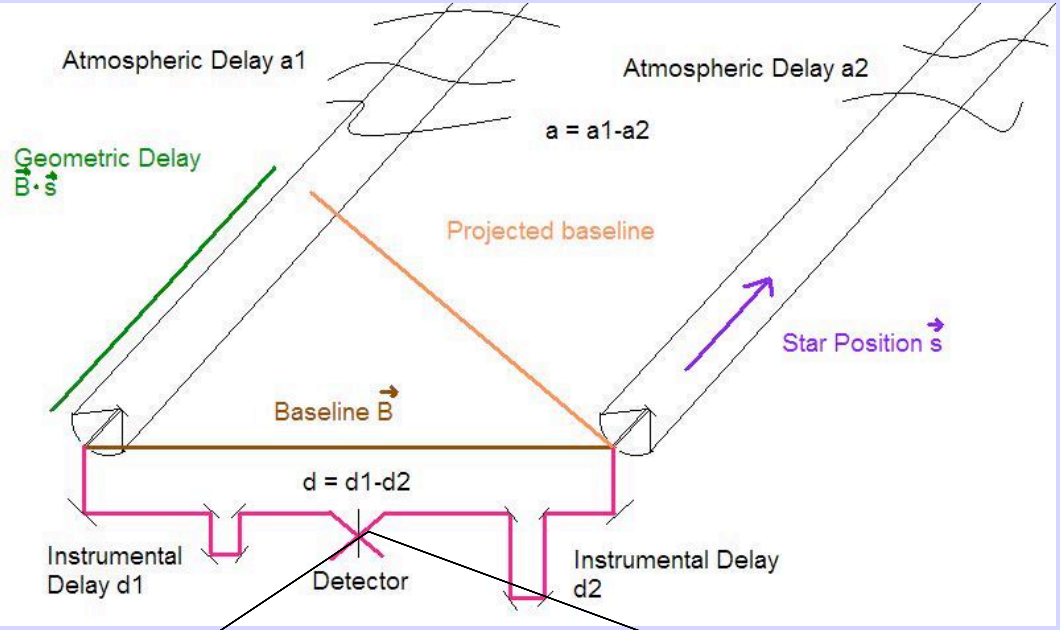
- For parallaxes state-of-the-art ~1 milli-arcsecond (1 mas ~ 4.8 x 10^{-9} rad).
  - Need μ-arcseconds
  - This should be tied to the entire sky, or “global”, though some exceptions exist.
  - Resulting fractional precision ~ 10^{-9} - 10^{-12}
- For planets in Galactic neighborhood (10 pc)
  - Jupiters ~ 0.1 mas
  - Earths ~ 1 μas
  - This can be tied to a nearby reference, no need for global astrometry.
  - Fractional precision depends on case:
    - For a planet in a single system with a background star, the astrometric signal is ~10 μas, star/reference separation is ~10 arcsec, giving a fractional precision of 10^{-6}.
    - For a binary star system containing a planet, the Planet/Star mass ratio is 10^{-3} and the planet/binary axis ratio is 0.1, hence the final required precision is 10^{-4}.

How to Achieve Good Astrometric Precision

- Measurement precision is given by $\sim \frac{\lambda}{B}\frac{1}{SNR}$
  - Hence we require large B
- Interferometry: a way to achieve high spatial resolution without the cost of a large telescope.
- Combine two or more smaller telescopes with separations in the 10-1000 meter range.
  - Gives few-milliarcsecond resolution
  - Then you have to get SNR ~10-1000.

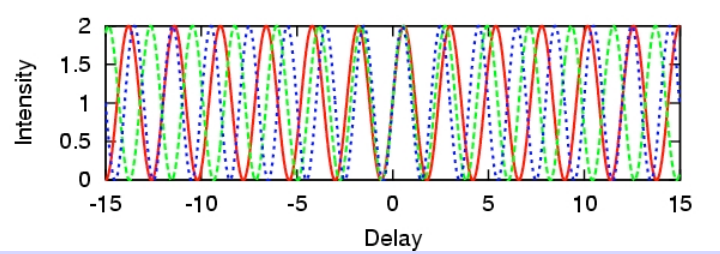


An Interferometer

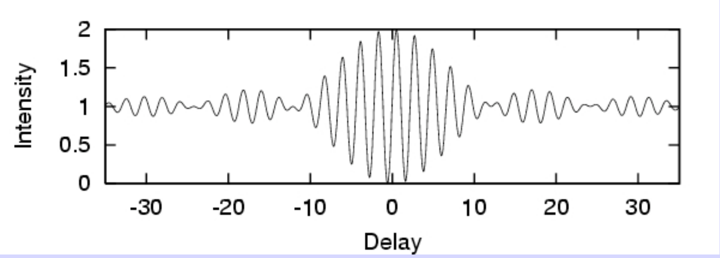


- At the point of beam combination (“focus”) of an interferometer a fringe pattern is formed.
- The frequency of the fringes depends on λ. For a broadband observation, the fringes cancel out everywhere except where the paths are matched, yielding:

$$d = \vec{B}\cdot\vec{s} + c$$



Narrow-band



Broad-band

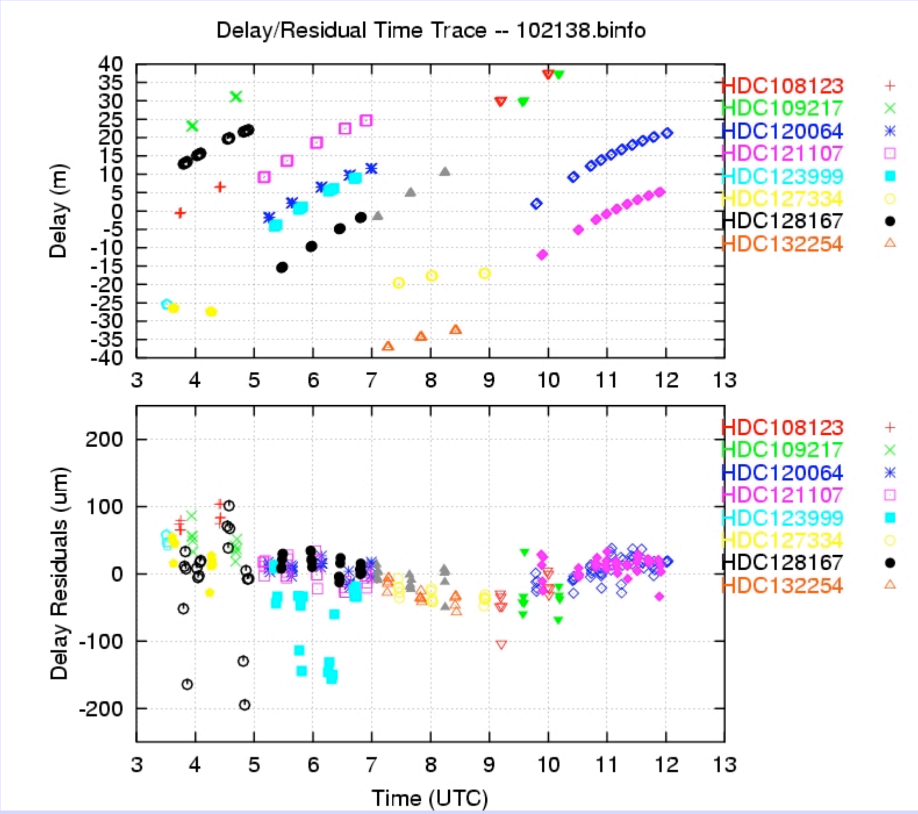
An Astrometric Observation

- Measure the fringe delays of many stars across sky. Solve the delay equation.

$$d = \vec{B} \bullet \vec{s} + c$$

- However, $\vec{B}$ is also unknown. The answer is to observe many stars and solve for both baseline and positions.
- Easy! We're done here, it's Miller time!

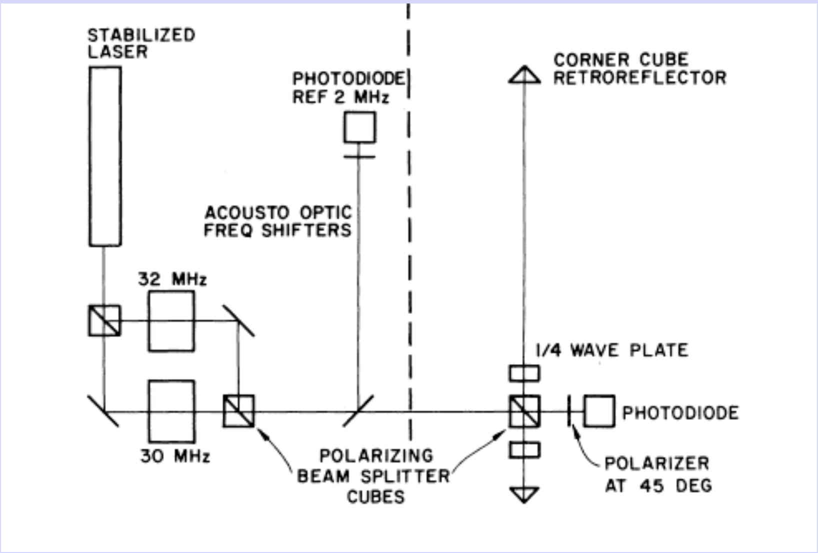
  Not so fast….



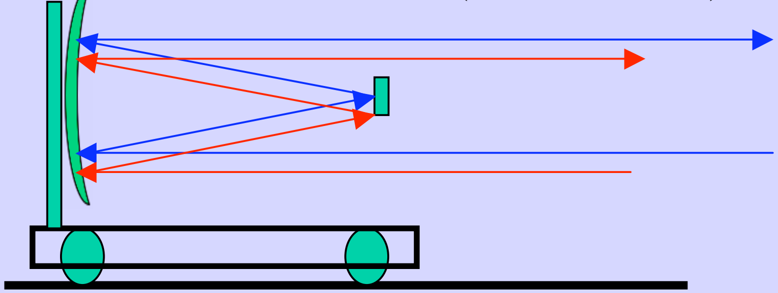
$$\sigma_s \approx rss[\frac{\delta d}{|B|}, k^{-1}\frac{\delta \phi}{|B|}, \frac{\delta B}{|B|}\Delta s]$$

Challenge #1: Measuring the Delay

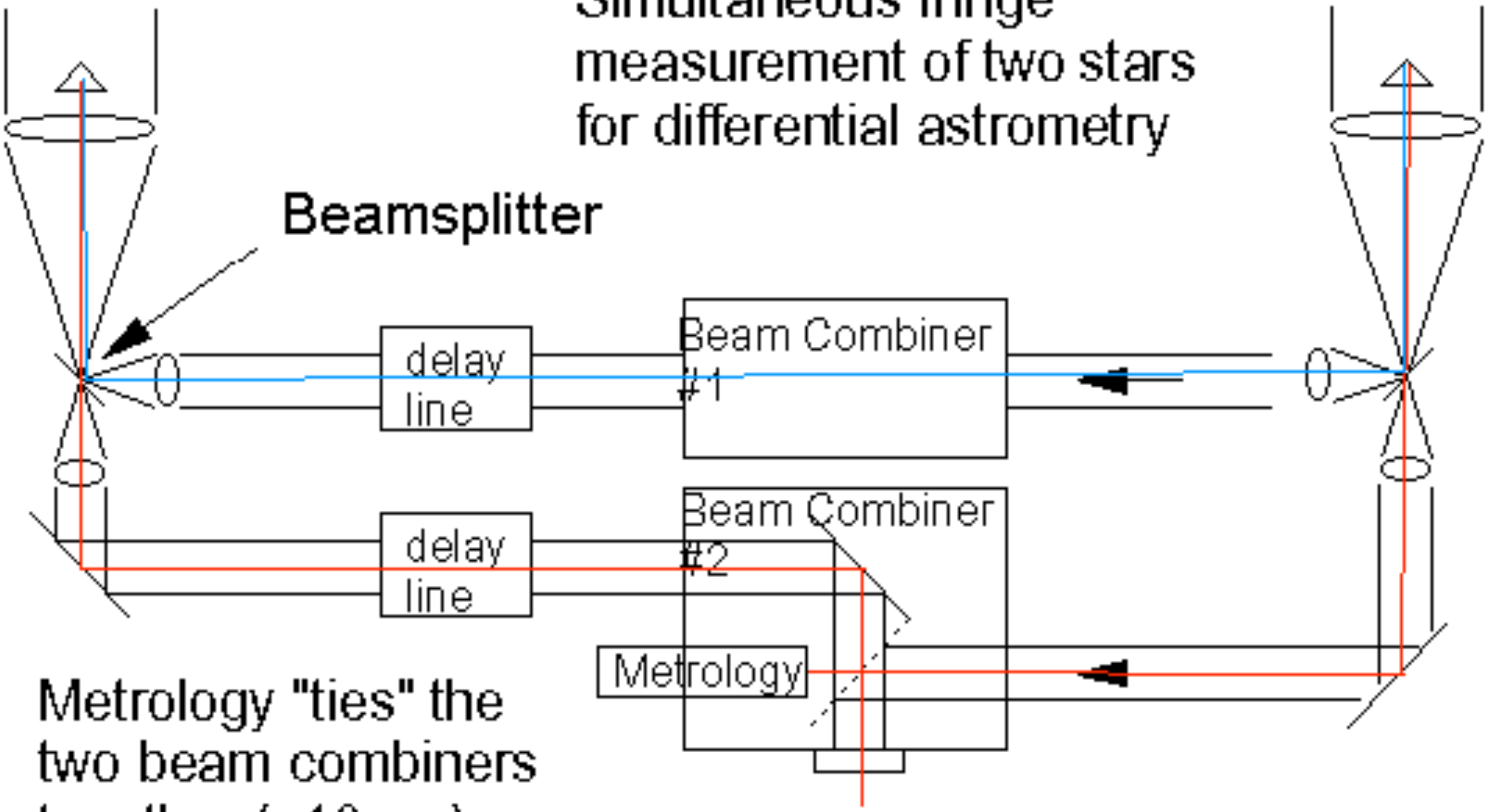
- Most pathlength measurements are done used heterodyne laser metrology.
- Frequency-stabilized laser (633nm, or 1.3 μm)
- Source plate splits into two polarizations with slightly different frequencies.
- Fraction of beams combined in a reference detector (generates tone).
- Measurement beam passes through path of interest, then recombined to generate second tone.
- Frequency differences in the two tones indicate pathlength change vs. time.
- Only measures path *changes.*
- nm-stability is easy, pico-meter doable.



(Shao et al. 1988)



Metrology Reference Points

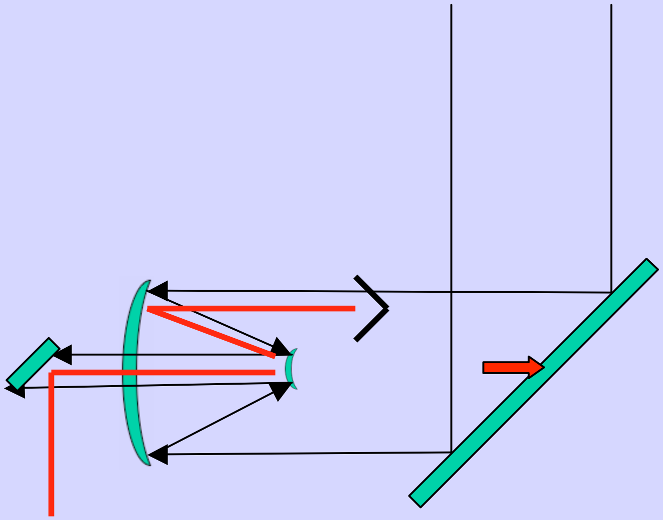


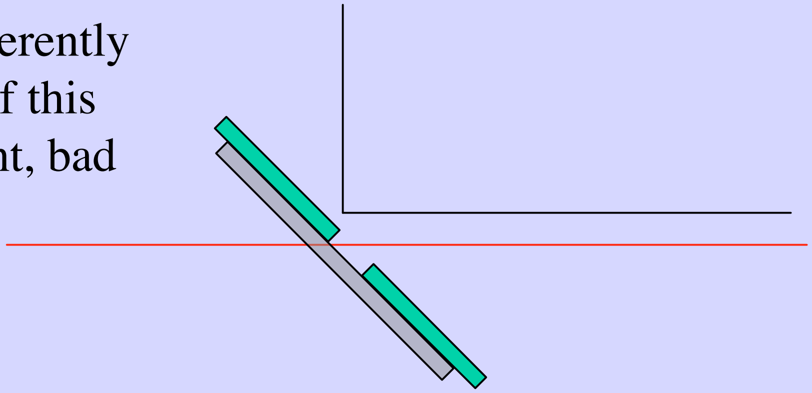
Simultaneous fringe measurement of two stars for differential astrometry

Metrology "ties" the two beam combiners together (~10 nm)

Instrumental Path Error Examples

- Internal laser metrology fiducial is not located at pivot points that define the wide-angle baseline.
  - Gives error term that looks like a correction to the baseline.
  - Need to know CC location to high accuracy (~50 μm).
- Field separator may affect transmitted metrology differently than reflected metrology. If this effect is position-dependent, bad things happen…





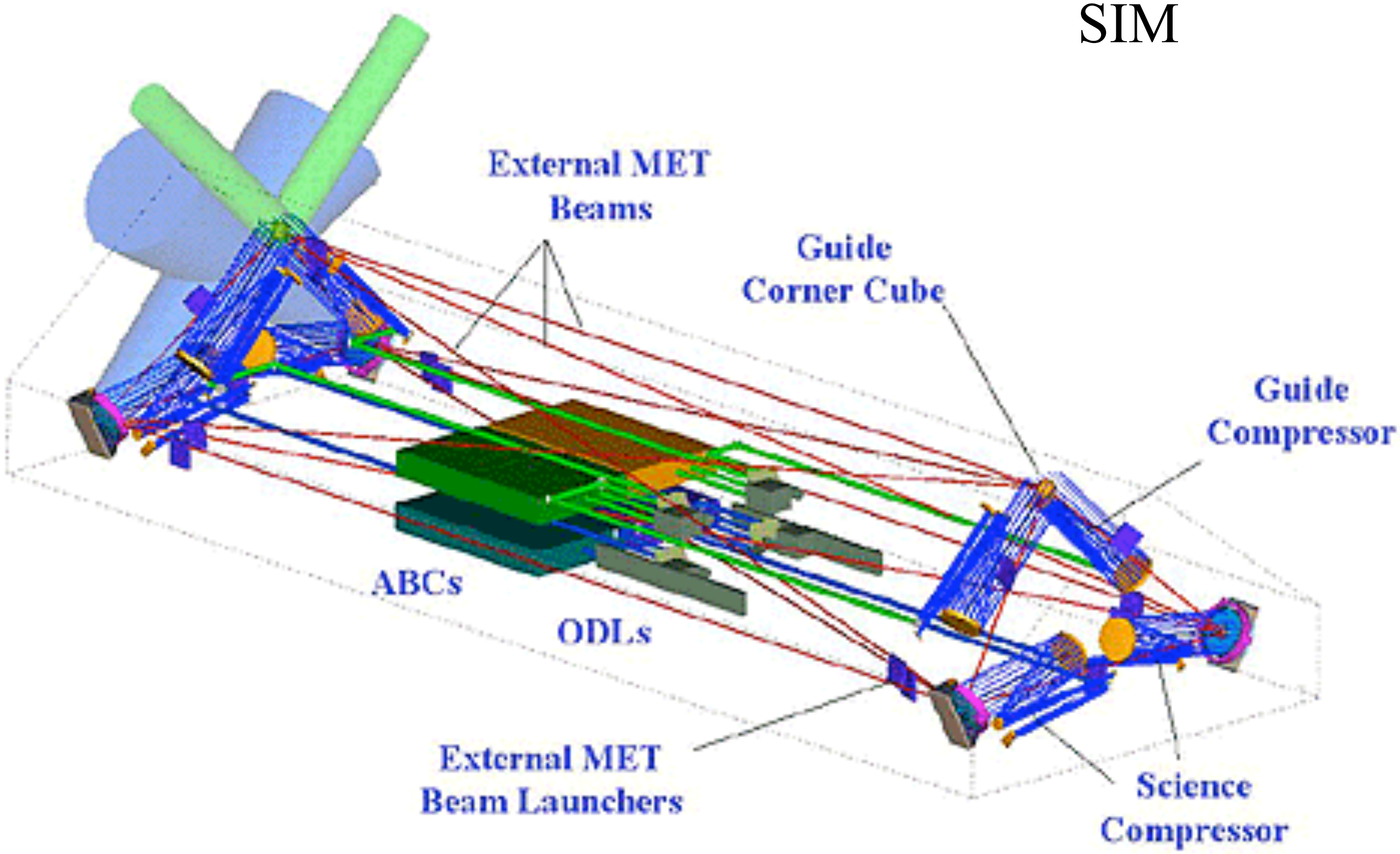
Challenge #2: Know your Baseline Vector

- Requires knowledge of the vector separating your two apertures with the same fractional precision as your astrometry.
  - For SIM (1 μas global, 10 m baseline) ~ 50 pico-meters (!)
  - For NPOI (1 mas global, 40 m) ~ 200 nm.
  - For PTI
    - NAA mode (0.1 mas/20 arcsec, 110m) ~ 5 micron
    - VNAA mode (10 μas/0.1 arcsec,110m) ~ 10 mm

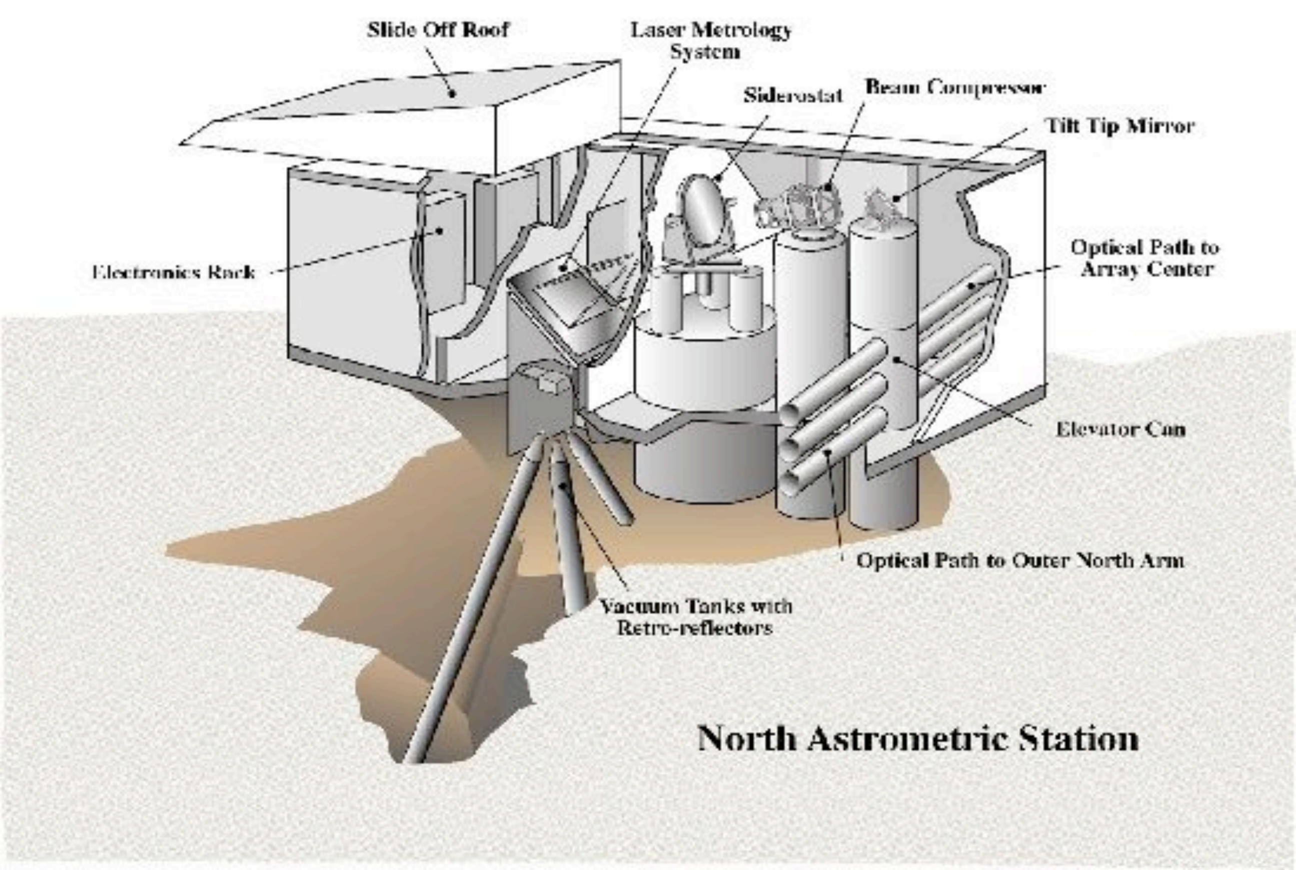
- In almost every case, no surveying can achieve this. One must use other stars to determine baseline geometry, and rely on various techniques to maintain stability.
  - SIM: multiple simultaneous interferometers sharing common metrology points.
  - NPOI: laser metrology ties to to bedrock references ensures stability, many sequential observations of stars to build up global solution.
  - PTI: sequential all-sky observations to establish baseline. Rely on mechanical stability in between baseline measurements.

Strategies for Achieving Baseline Stability

SIM



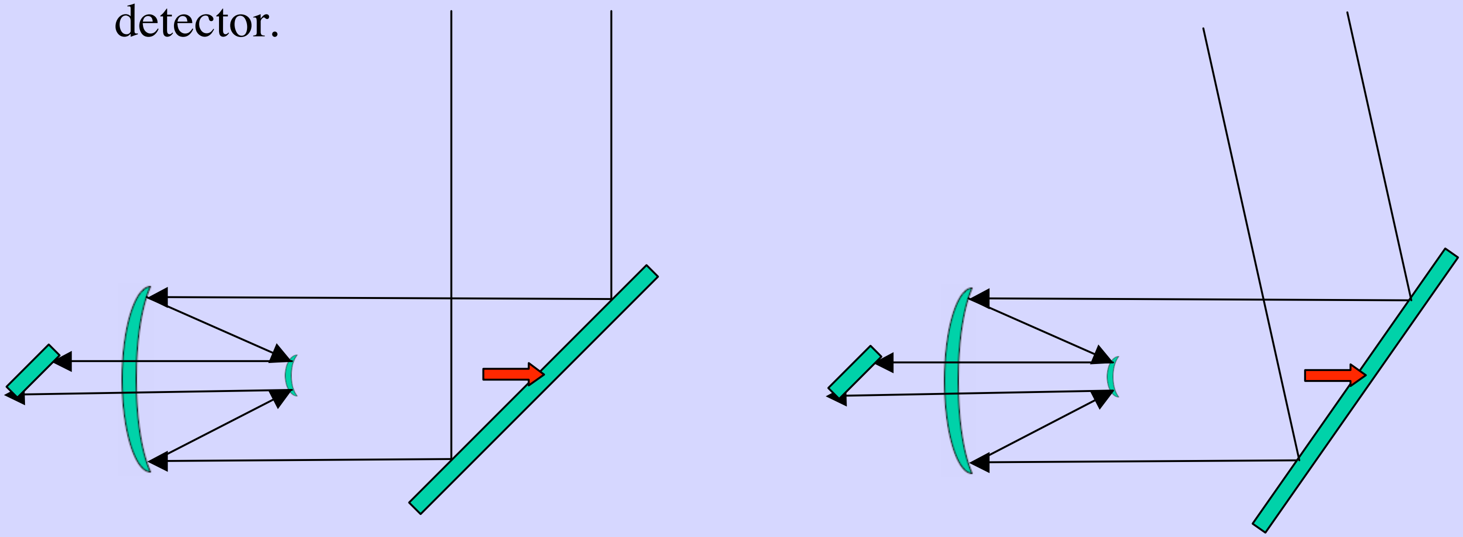
Strategies for Achieving Baseline Stability



North Astrometric Station

Challenge #3: Know your Aperture

- One often critical issue is knowing exactly how to define the end-point of your baseline vector, i.e. which fraction of the incoming wavefront gets sampled, and how does that translate into a baseline?
  - In Wide-Angle astrometry you move the siderostats (or telescope) to point to a new star.
  - In Narrow-Angle astrometry the telescope pointing doesn't change but subsequent optics move to repoint between stars.
  - In VNAA neither is moved; two stars end up on slightly different parts of the detector.

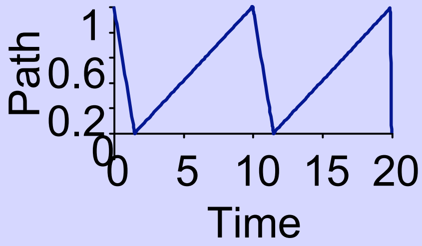


Challenge #4: Measuring Phase

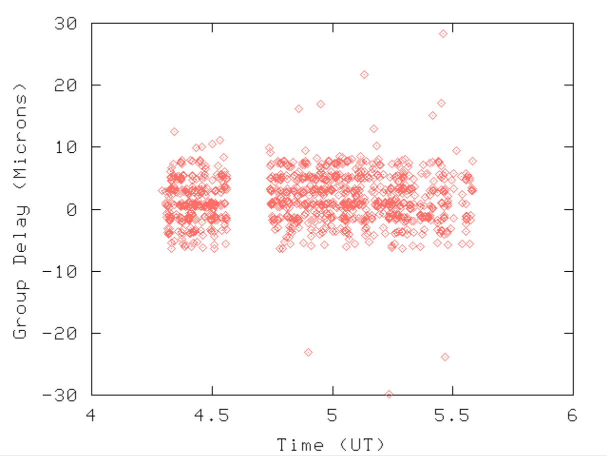
- Fringe has to be found and tracked.
  - Typically use the ABCD algorithm.
  - 4 rapid intensity measurements (labeled “A”, “B” etc) while the internal delay is swept by 1 wavelength. Let X=A-C, Y=B-D. Then:

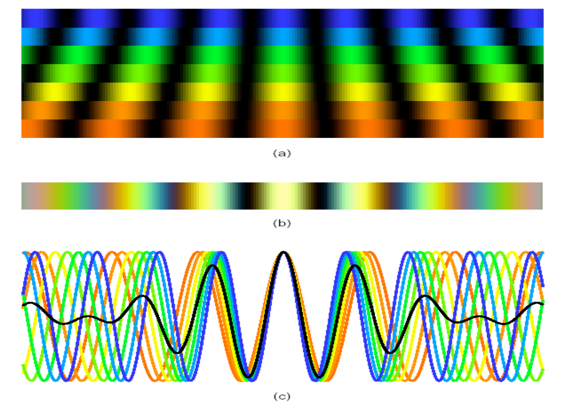
$$\phi = \arctan\left(\frac{Y}{X}\right)$$

$$V^2 \propto \frac{X^2 + Y^2 - \text{bias}}{N}$$

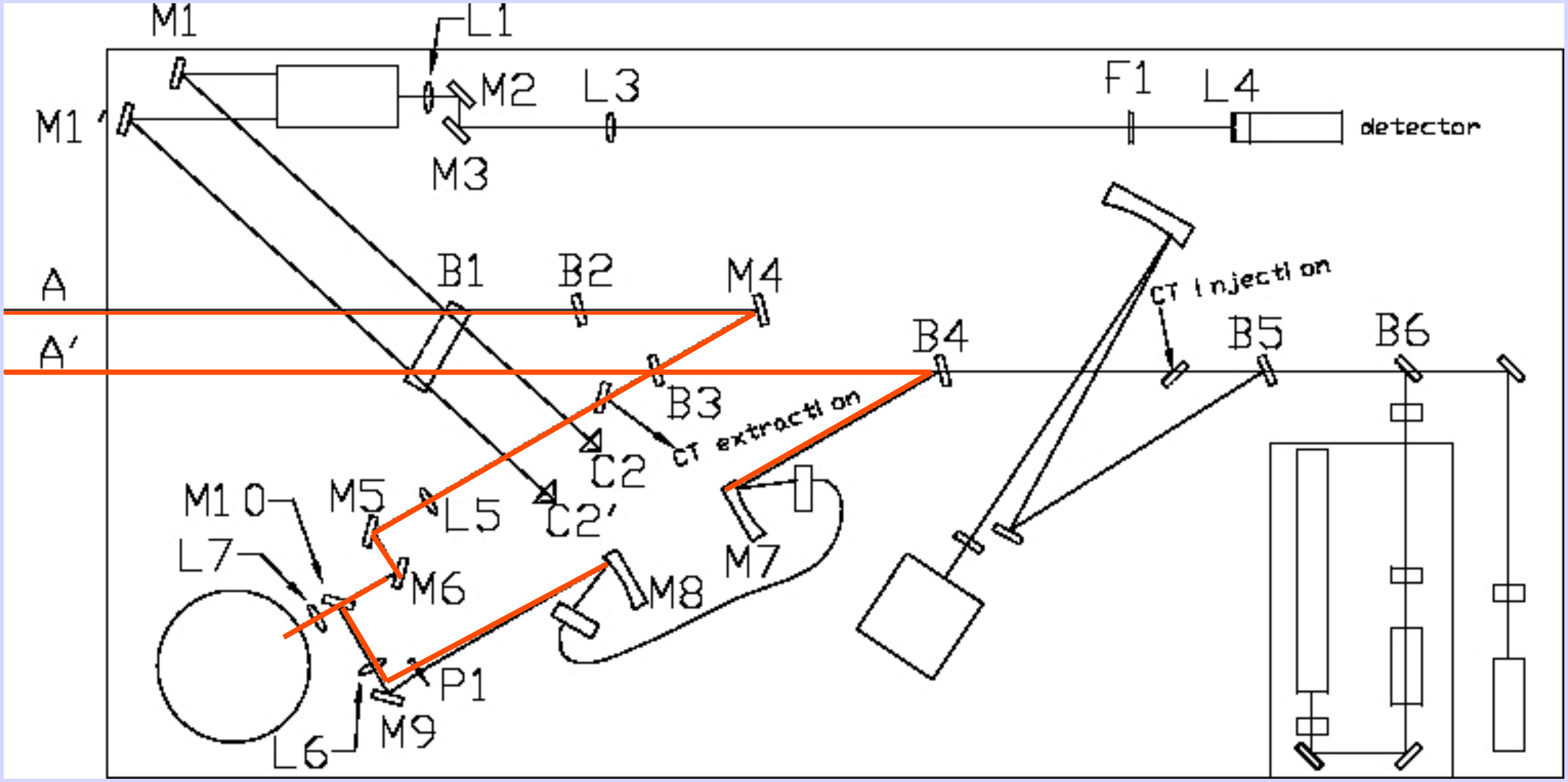


  - Unfortunately this has fringe ambiguities (2π wraps).
    - Solution is to measure phase is several wavelength “channels” and solve for group delay.
  - Danger Will Robinson: Phase is not Delay!
    - Techniques that measure phase will have to have to know λ to that same precision.





A Beam Combiner



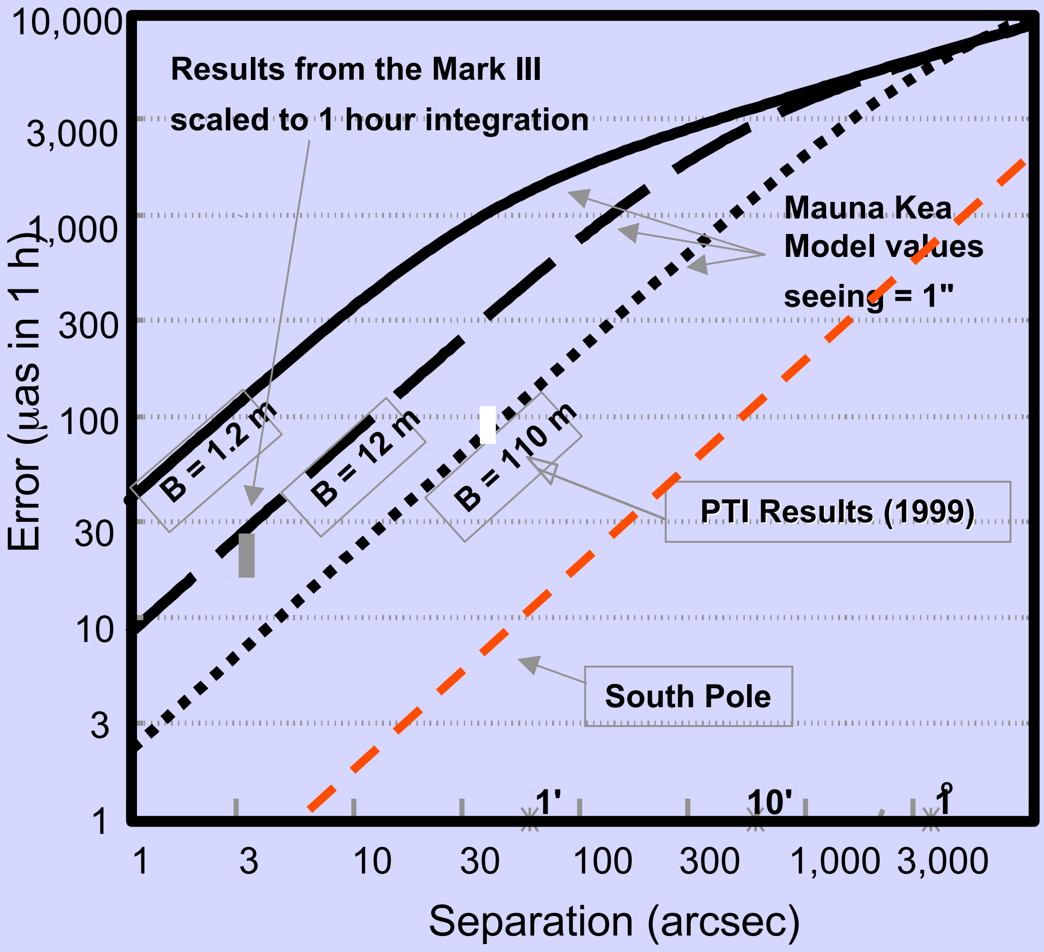
Challenge #5: Atmospheric Turbulence

- The atmosphere is highly turbulent, with eddies of different refractive index blowing in front of the telescope, causing “seeing”.
- The starlight wavefront is disrupted in ~10 ms, over scales of ~10 cm; the fringe pattern is smeared out or broken up.
- This usually limits interferometers to small apertures and short exposures, limiting their sensitivity ($m_K \sim 7$).
  - This has led to the use of adaptive optics (r_0) and phase referencing (τ_0).
- Over narrow fields (~30-60 arcsec) atmospheric error is correlated and can largely be subtracted out.
- Differential astrometry most sensitive to high-altitude turbulence
- Need to consider unusual instrument sites, i.e. South Pole (no jet stream).

$$\sigma_d^2 \propto \frac{1}{t}\int dh C_n^2(h) V(h)^{-1} h^2$$

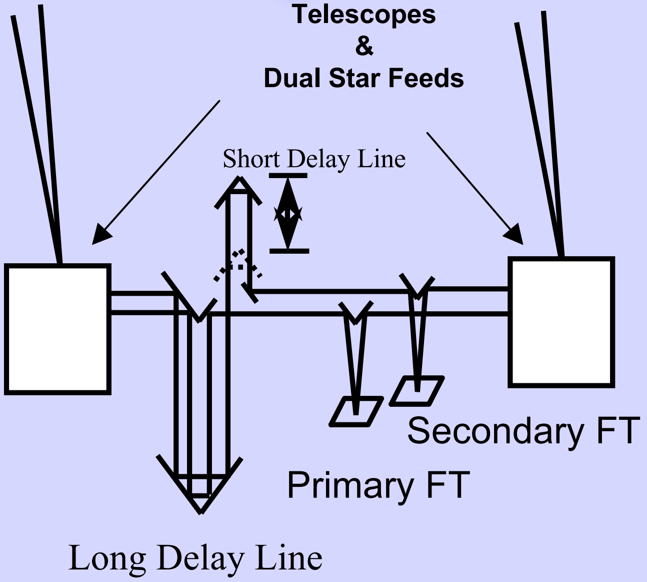
Types of Ground-based Astrometry

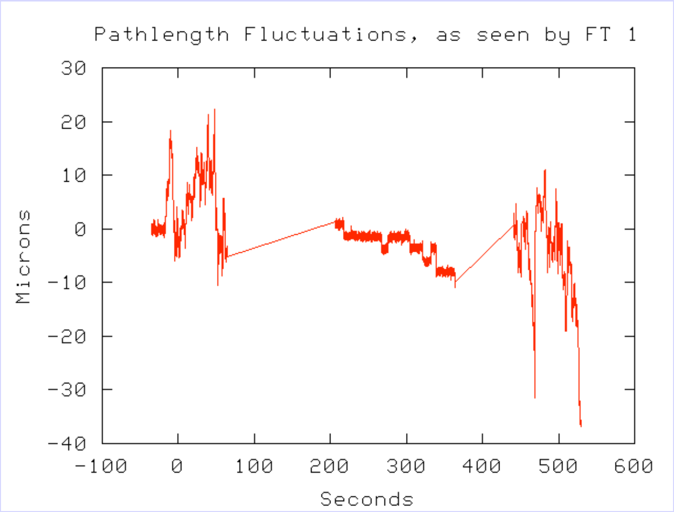
- "Wide-Angle"
  - Atmospheric effects are uncorrelated.
  - ~1-5 mas performance.
  - MkIII and NPOI interferometers.
- "Narrow-Angle"
  - Less than ~1 arc-minute
  - Atmospheric errors subtract out (mostly)
    - This does not help the sensitivity problem, though.
  - Very high performance over small angles.
    - 10-100 micro-arcseconds.



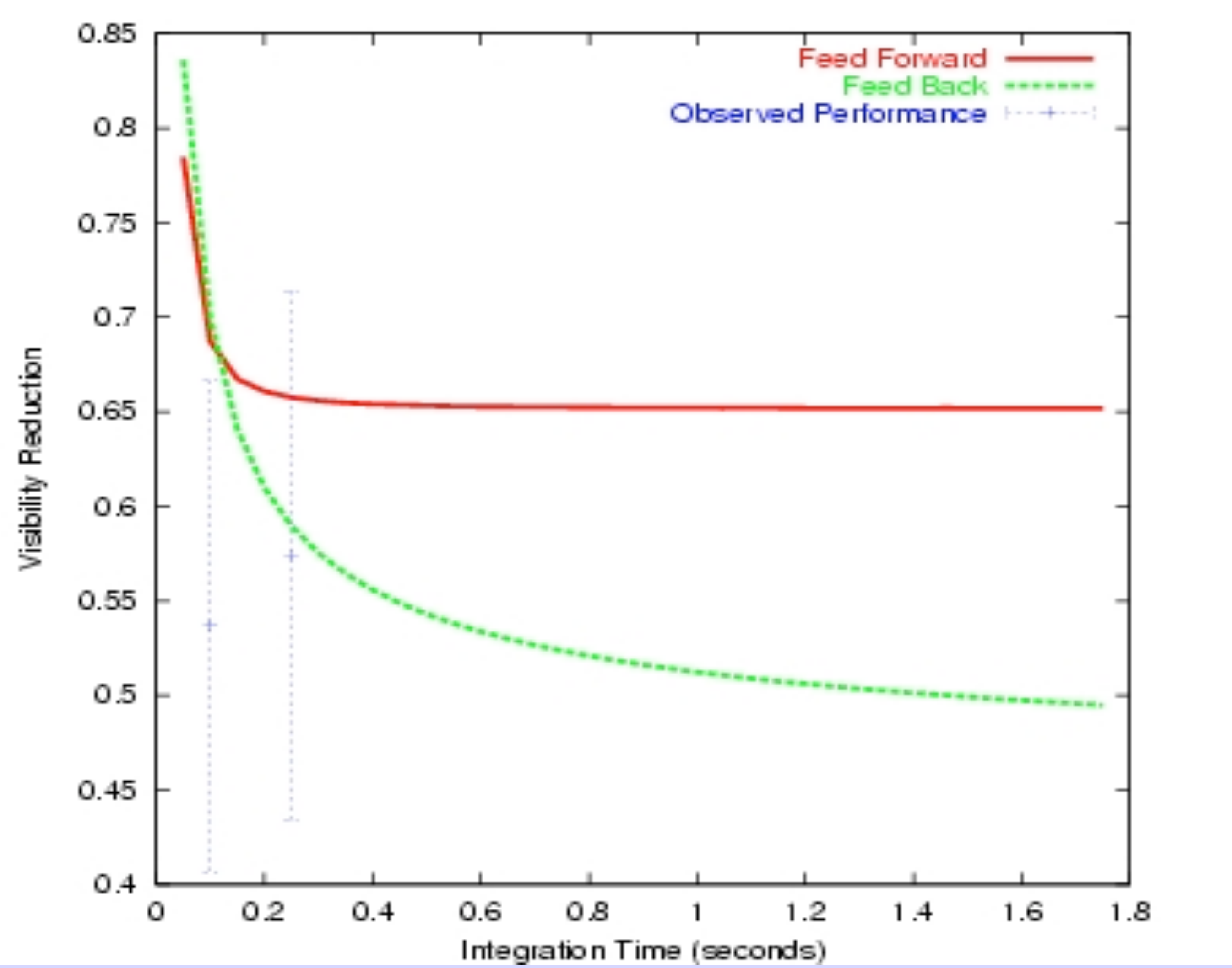
What is Phase Referencing ?

- Analogous to NGS adaptive optics on a large telescope:
  - Fringe track on a bright star within the isokinetic patch of the target star (30-50 arcsec).
  - Measure fringe motion induced by atmosphere.
  - Correct using optical delay lines.
- Allows integration times longer than would ordinarily be possible.
  - Gives time for high-precision measurement, but doesn't improve limiting magnitude.
- Well suited for astrometry since we're looking at nearby (and thus bright) stars by design.





The Effect of Phase Referencing on V^2



Challenge #4: Atmospheric Dispersion

- In a plane-parallel, perfectly calm atmosphere, and using an evacuated delay line, observing a monochromatic source, there would be no net delay effect due to the atmosphere.
- In other words….
  - Index of refraction depends on wavelength (star color)
  - It fluctuates with temperature, pressure.
  - Non-plane-parallel atmosphere
- Multi-color techniques have been used to find the fringe phase as a function of wavelength, and solve for path effect.
  - Limited by water vapor (has different index vs. wavelength slope).

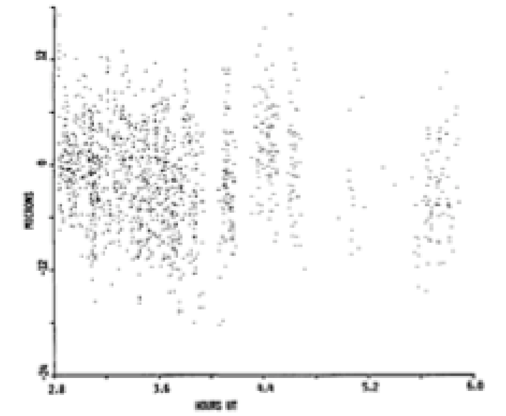


Fig. 1. One-color fringe position for β Cas, 25 Nov. 1986, at 1 sec/point.

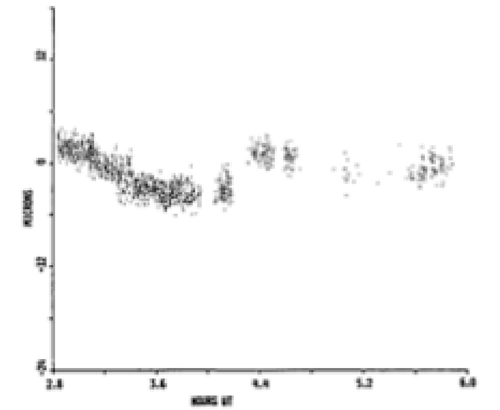
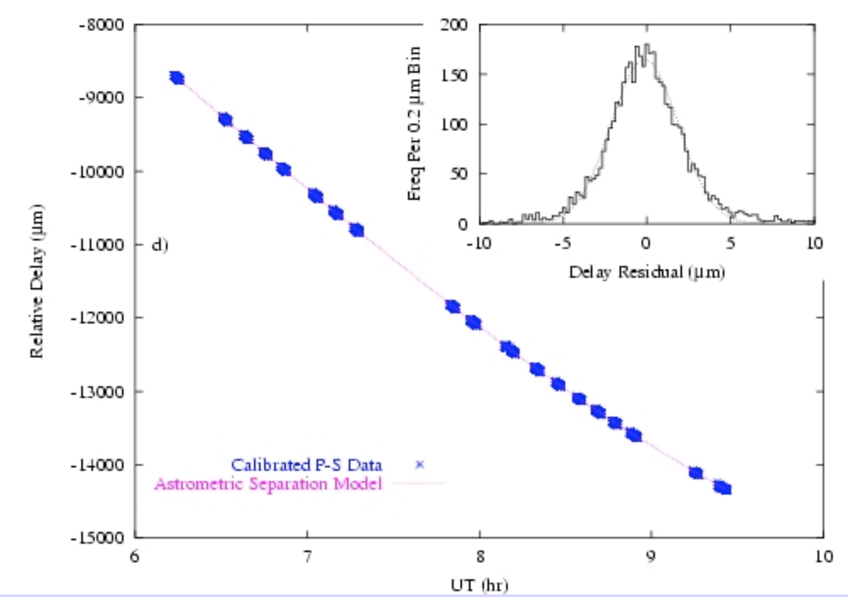
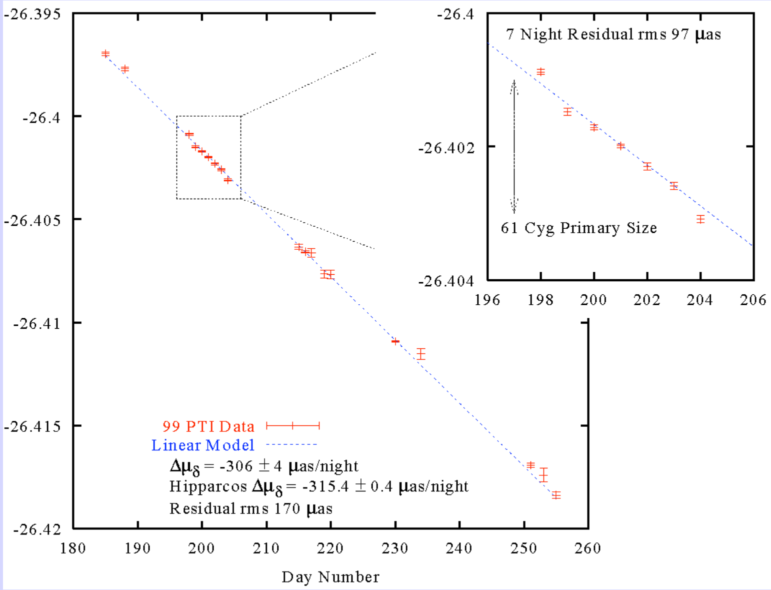


Fig. 2. Two-color fringe position for β Cas, 25 Nov. 1986, at 1 sec/point.

Colavita, Shao & Staelin (1987)

Narrow-Angle Astrometry Example: 61 Cyg



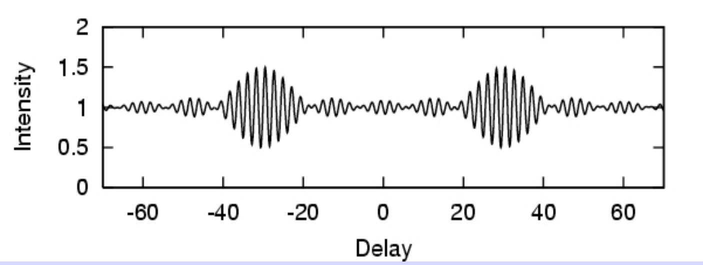


- Narrow-Angle Astrometry was/is going to be used on the Keck & VLTI Auxiliary telescopes to search or massive planets in distant orbits around nearby stars.
- Typical precision goals are 20 μarcseconds.
- The technique was developed and demonstrated at PTI in 1998-1999.

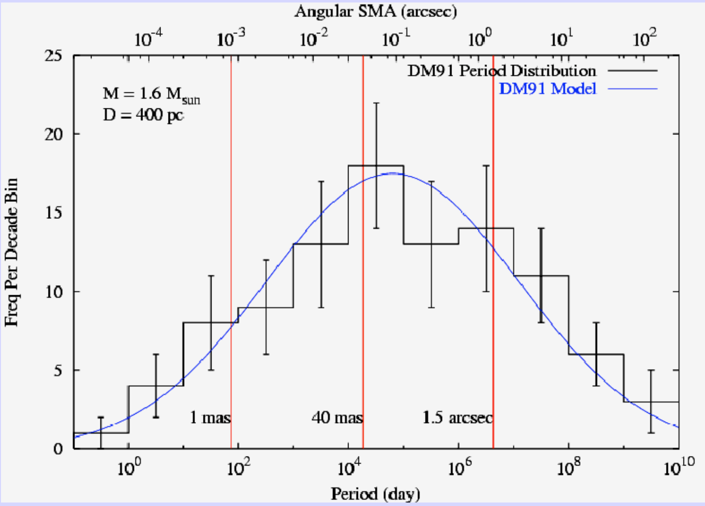
Figure by A. F. Boden & ISC

Very Narrow-Angle Astrometry

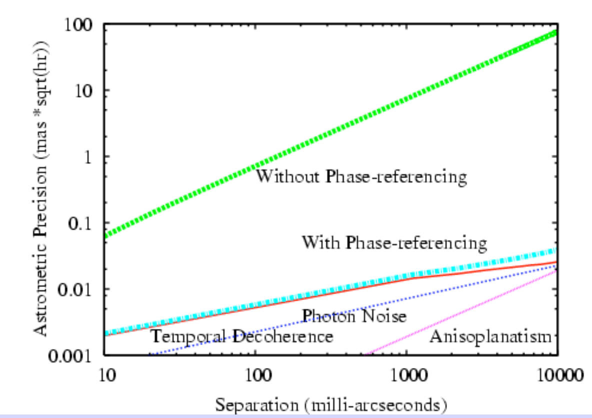
- A binary star produces a double fringe packet.
  - The delay difference between packets tells you the angle between the stars (projected onto the baseline).



- Most stars are in multiples, and the distribution peaks at apparent separations of ~0.1 arcsec.



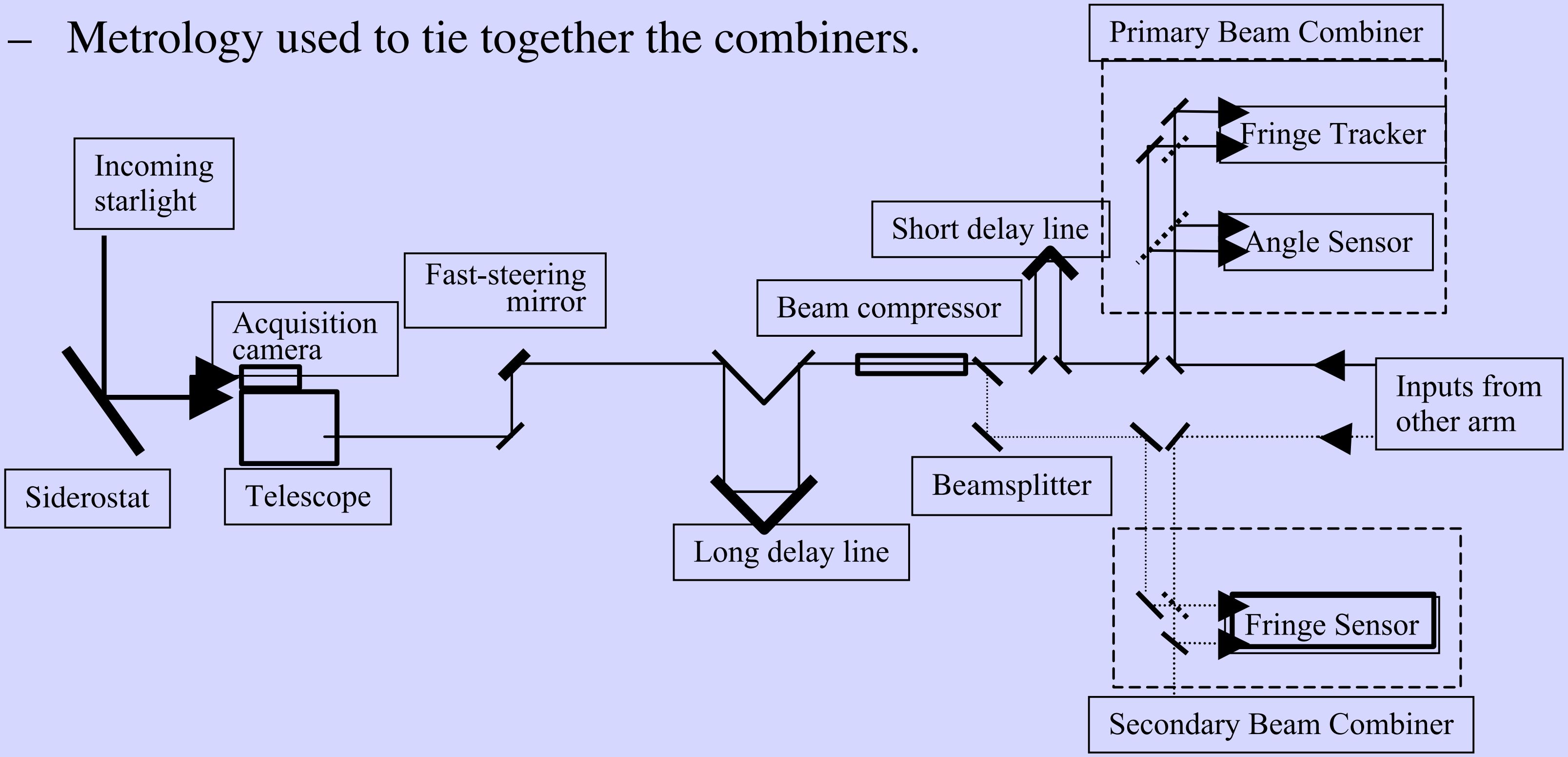
- A planet is stable orbiting one component in a binary, as long as $a_{Planet} <\sim 0.1\ a_{Binary}$



Calculations indicate that sufficient precision to detect planets is possible.

VNAA Experiment Layout

- VNAA has been implemented at PTI
  - Light is split after main delay lines into two sets.
    - One for fringe tracking to stabilize path errors
    - The other is used to slowly “scan” in delay and trace out the double fringe packet.
  - Metrology used to tie together the combiners.



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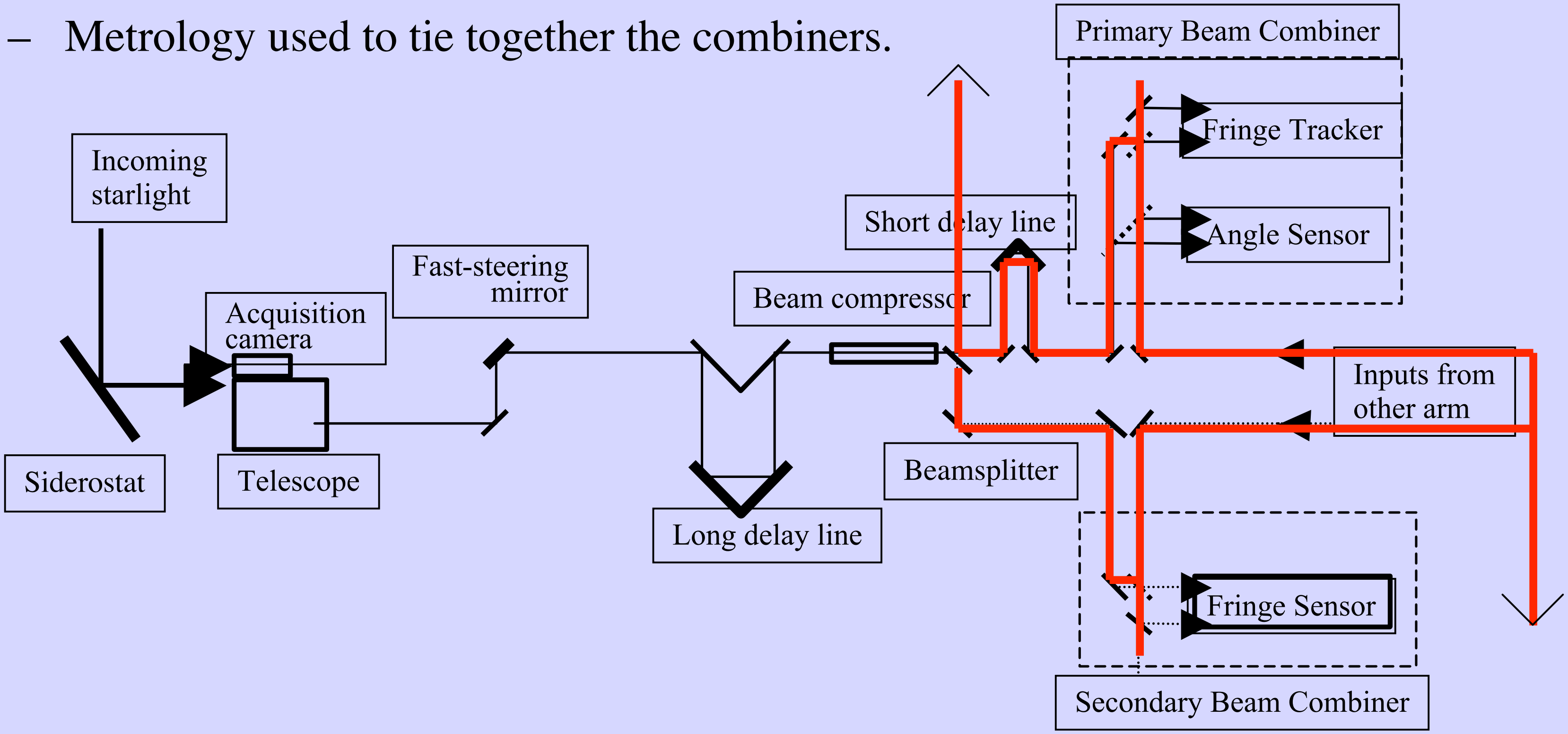
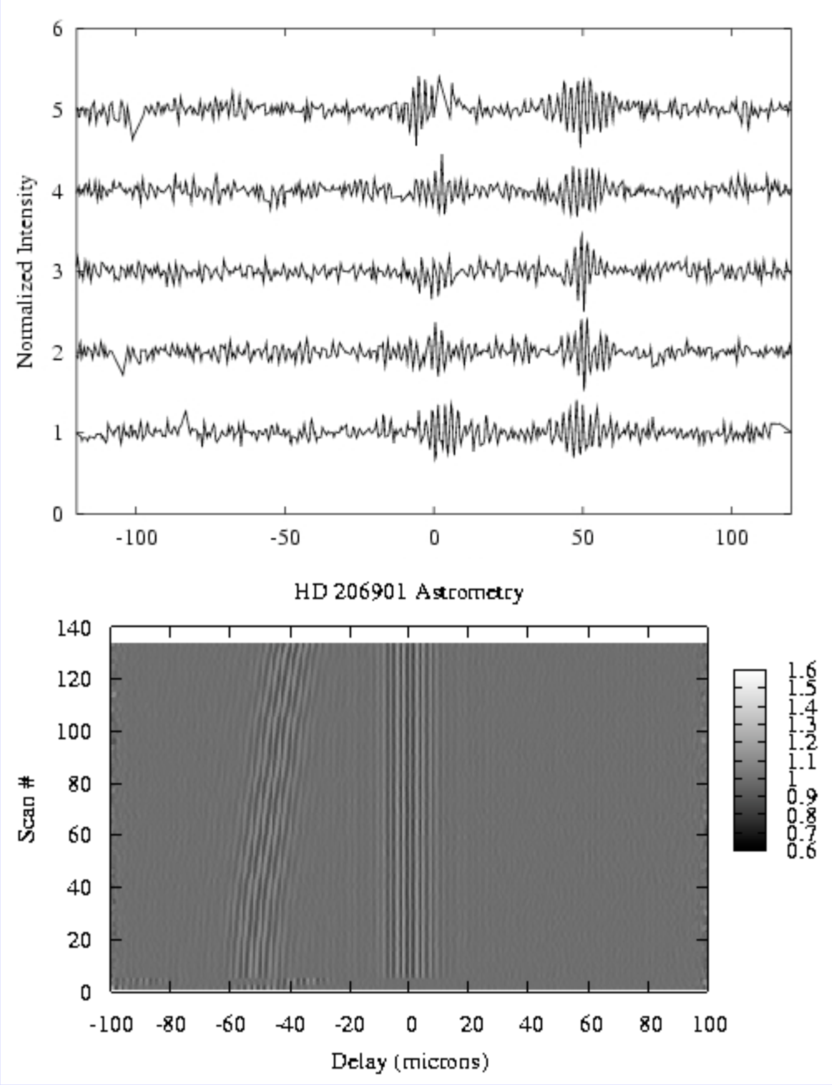


Very-Narrow Angle Astrometry Data

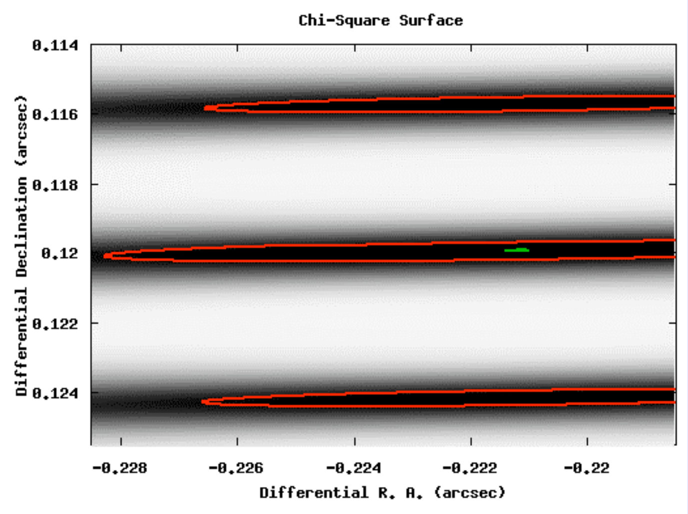
- Data Shown: HD 171779 (G9III + K0III binary, 192 yr period)
    - 0.2 arcsecond separation.
- Half the light used for fringe tracking, half for scanning the fringe.
- Scan period 1.5 sec.
- 2000 scans/star/night.
- We fit a “double-fringe” model to the data, using a least-squares method, solving for the differential delay.

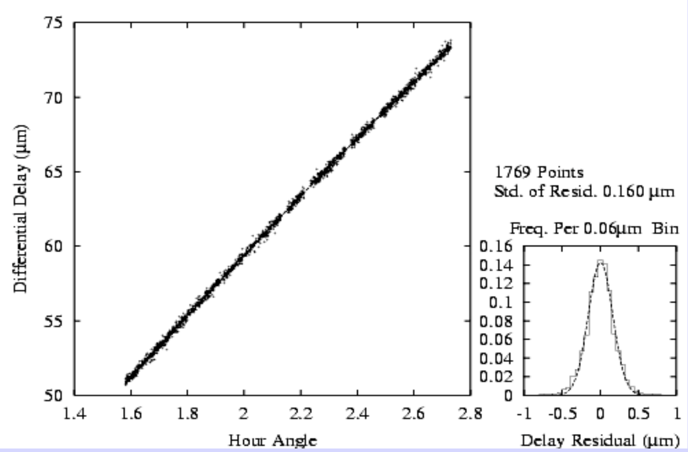
$$\Delta d = \vec{B} \cdot \Delta\vec{s}$$



A Model Fit to VNAA Data

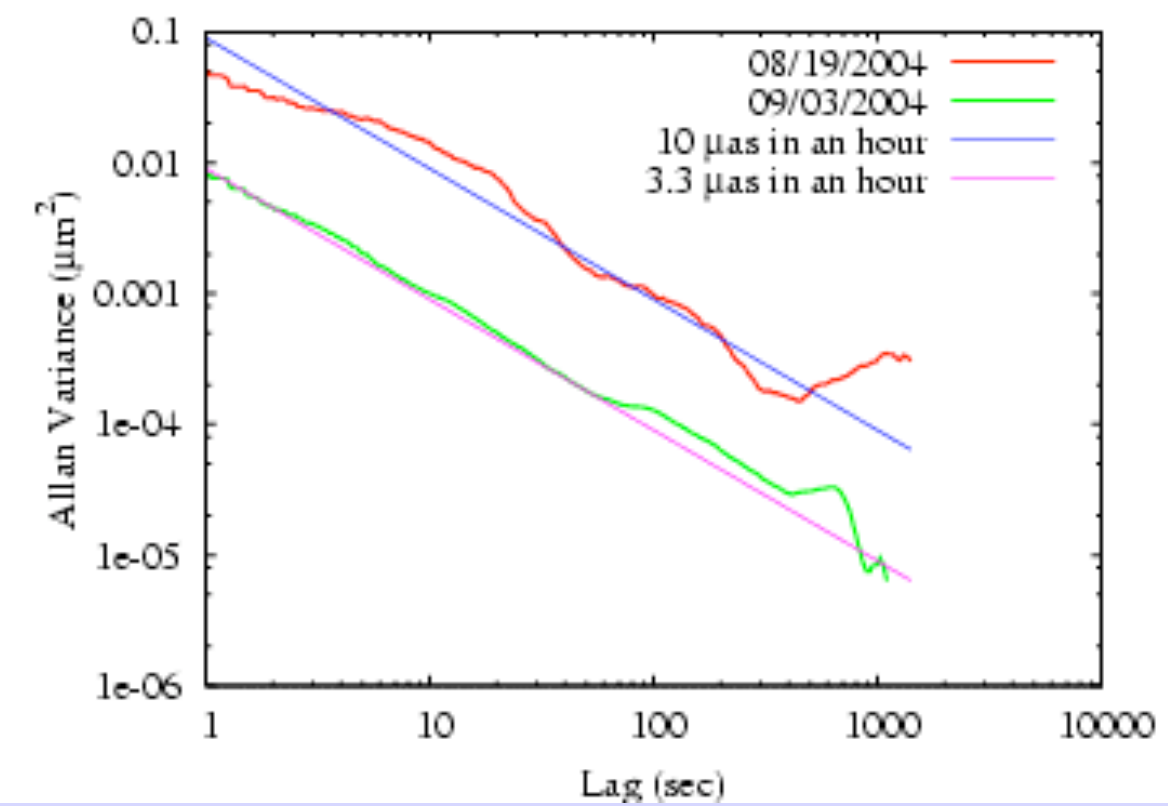
- Fringe model is very oscillatory
  - Many local minima, corresponding to one-wavelength ambiguity.
- Astrometry is constrained in one direction only, || to baseline.
- Proper approach is to calculate χ^2 (RA,δ) surfaces for each scan, and co-add.
  - Earth-rotation, co-adding breaks ambiguity.
  - Data shown: 1-σ error ellipse 8 x 144 μ-arcseconds.
- Individual scans show Gaussian behavior in the fit residuals.



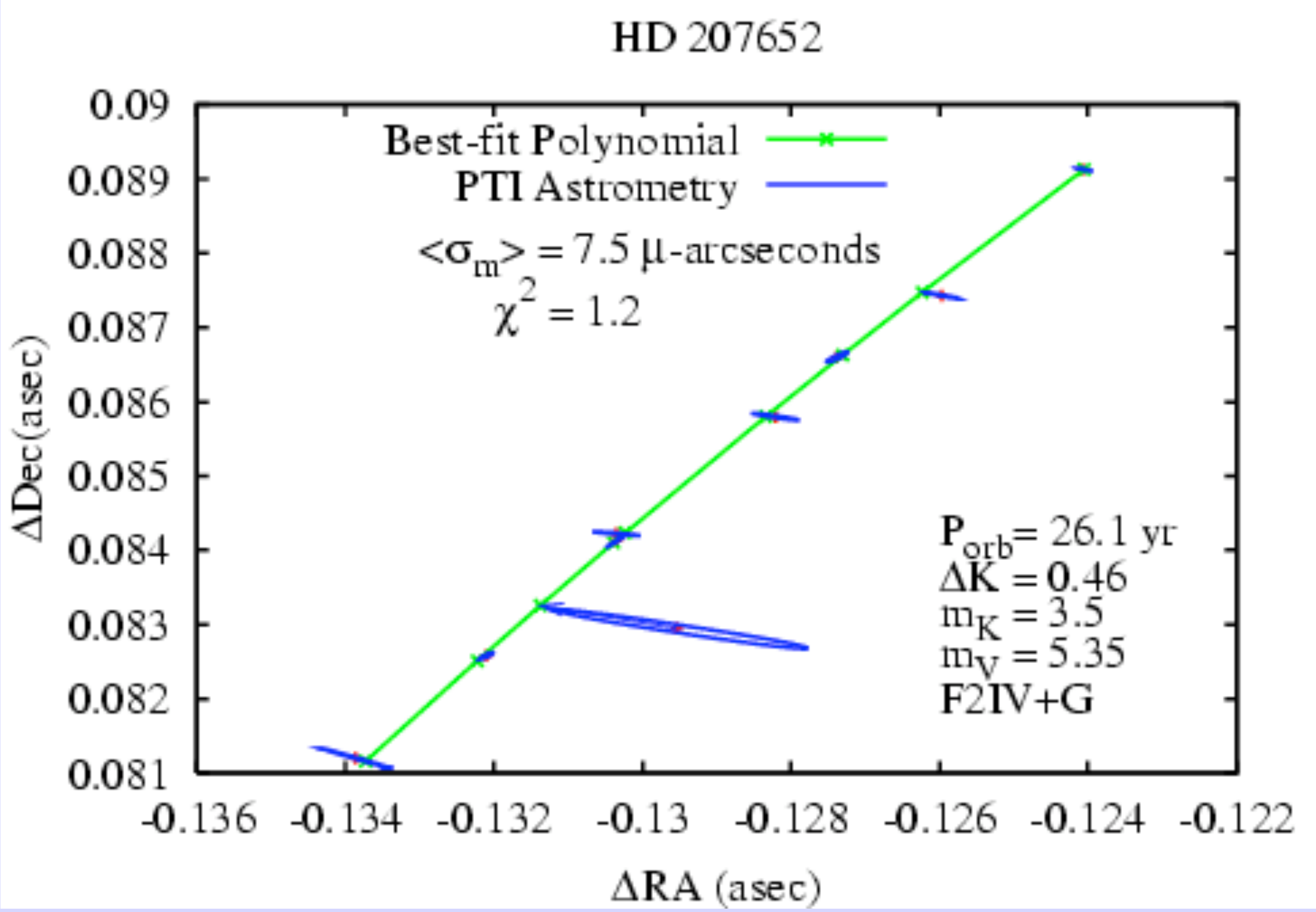


VNAA Short-term Noise Performance

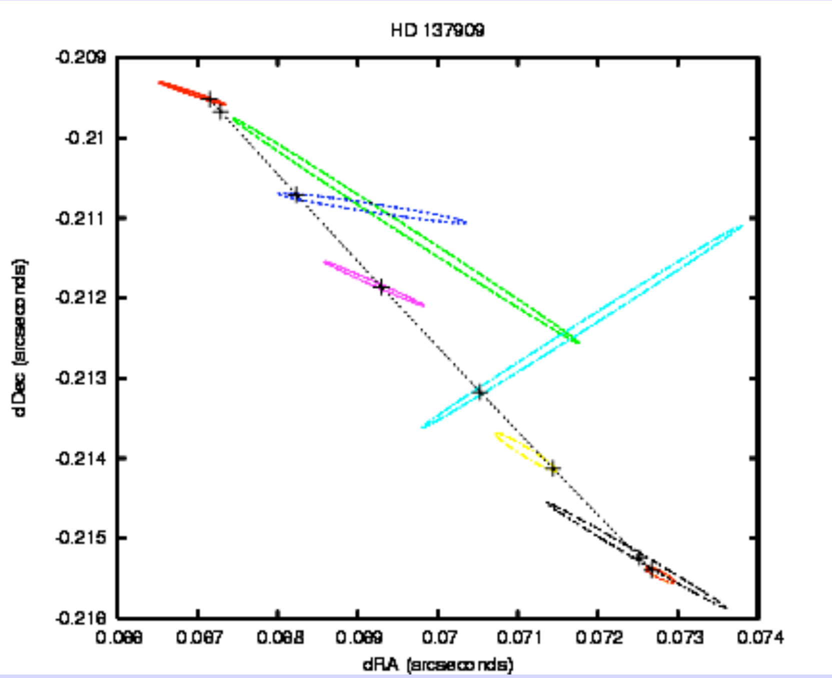
- Fit residuals are white to at least 1000 seconds.
- Performance is in the range 3-10 micro-arcseconds in an hour.
  - Correlates with seeing as inferred from fringe tracker.
- Systematics expected below ~ 10 micro-arcseconds.
  - Dispersion
  - Beam-walk
  - Water-vapor effects

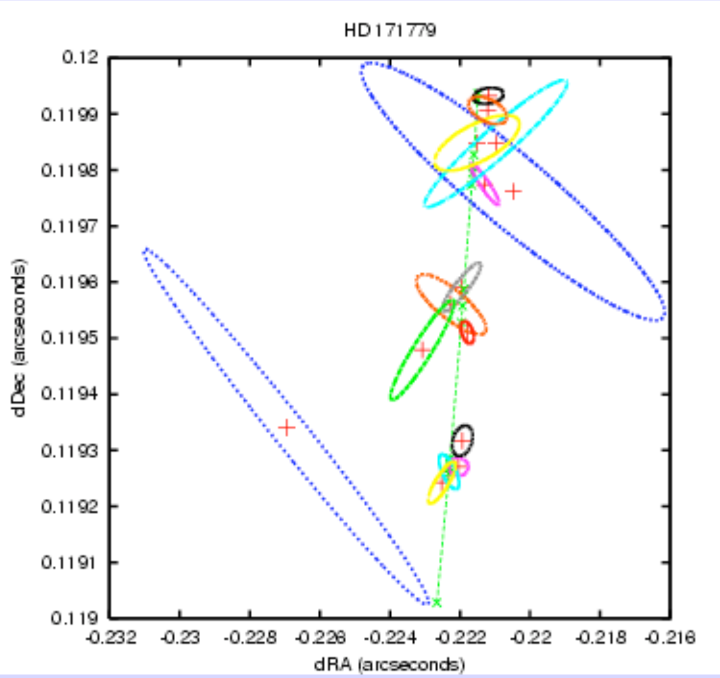


Typical VNAA Data



Repeatability

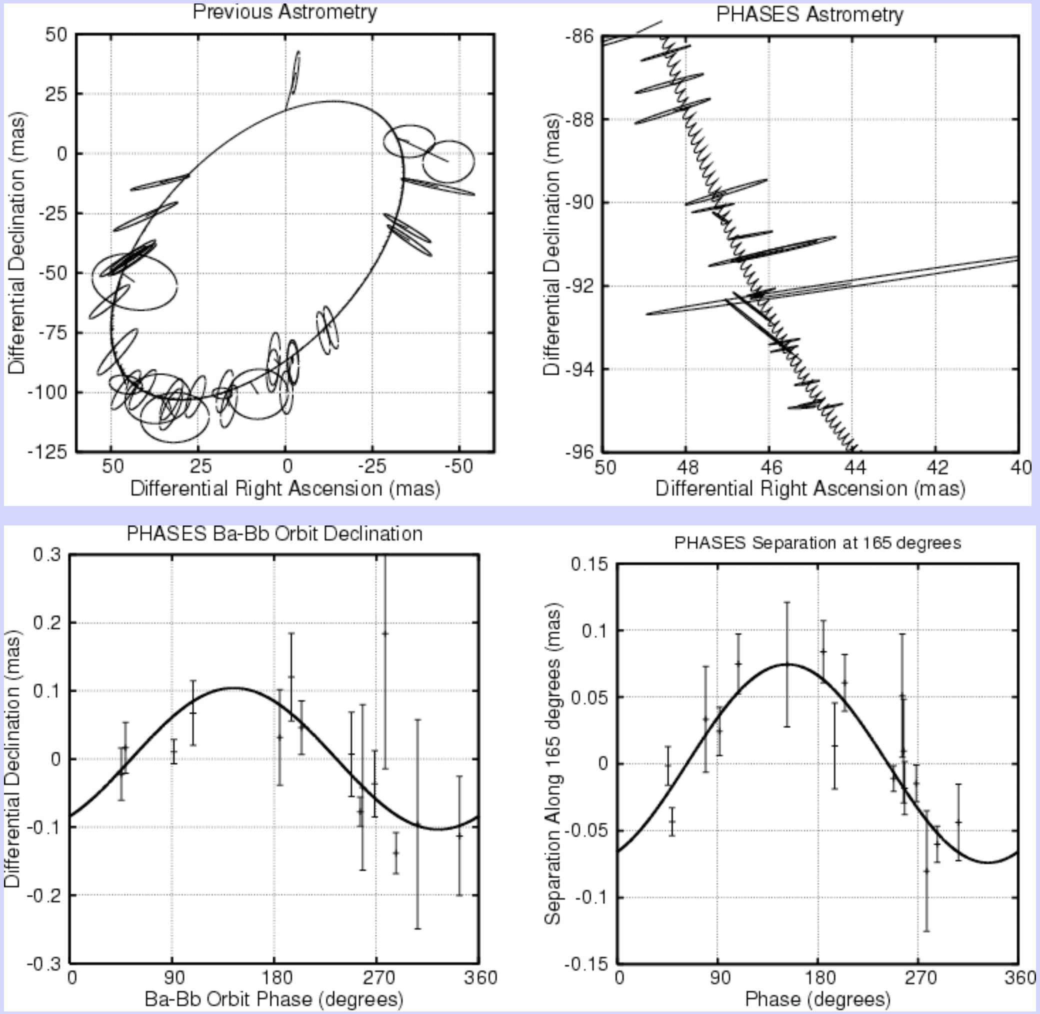




- Typical formal error ellipse 5 x 100 micro-arcseconds.
- Fit to linear trend yields: $\sqrt{\chi_r^2} \approx 3$
  - Implied repeatability ~ 15 x 300 micro-arcseconds.

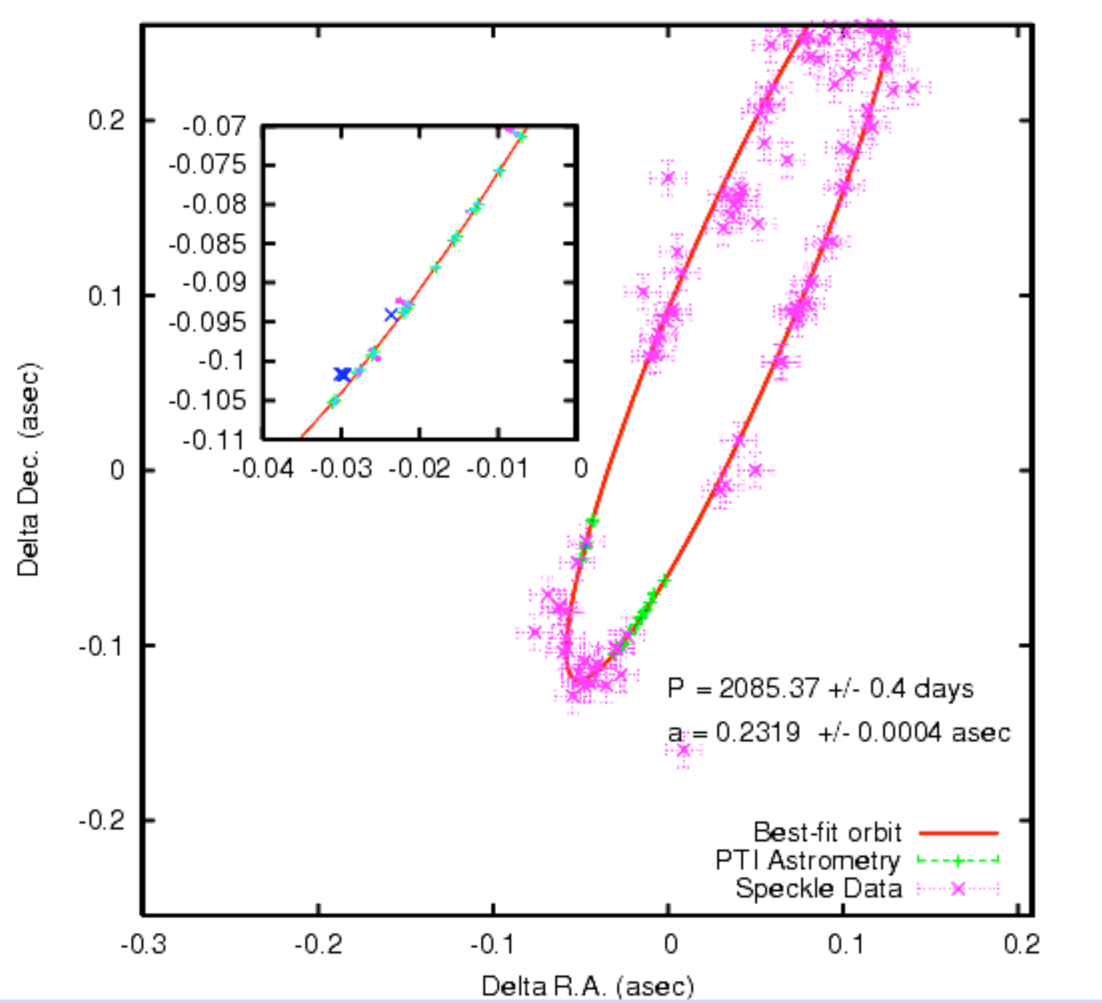
Orbit determinations using VNAA

- V819 is a triple system
    - 5.5 yr wide pair
    - 2.2 day inner system,which eclipses.
- Apparent narrow orbit size is determined to be 108 ± 9 μarcseconds. The wide separation is 73 ± 0.6 mas (limited by duration of observations)



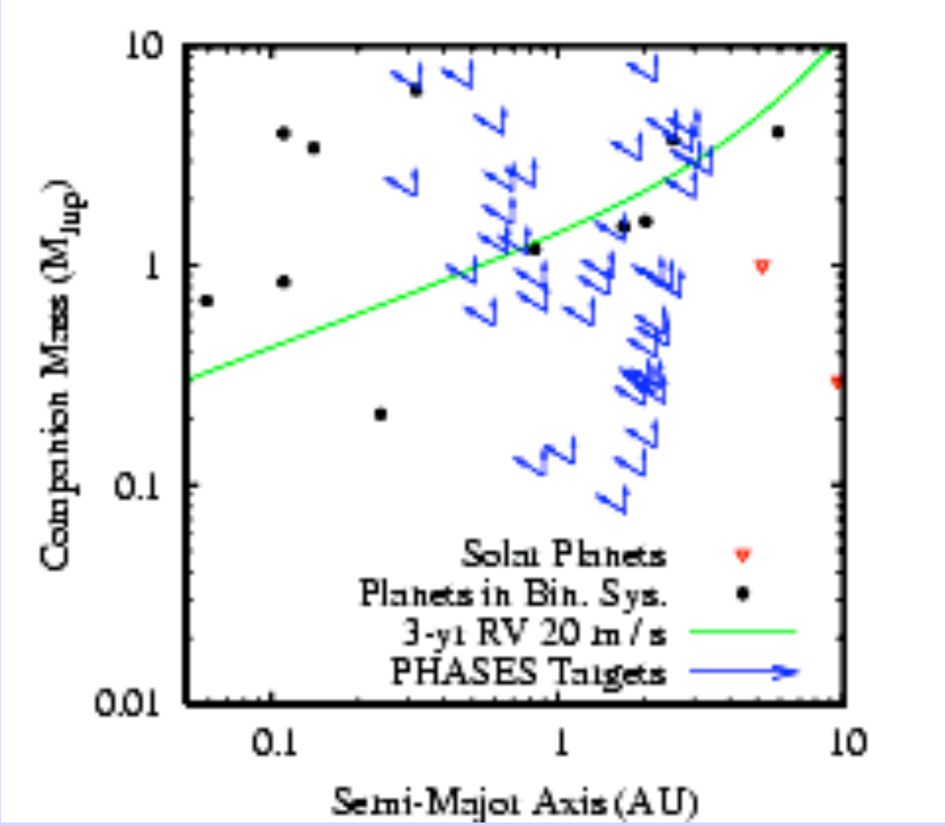
Binary Orbits

- We have begun to observe several known "speckle" binary systems (e.g. HD 202275).
- Results compare favorably with previous data.
- Can determine apparent orbital geometry to ~0.2 %
- a=0.2319 ±0.0004 arcseconds.



The PHASES Survey

- A survey of ~50 binary stars: “PHASES”
  - Brighter than K~4.5
  - Binary separation less than 1 arcsecond
  - 36 systems with minimum detectable mass < 1 M_J
  - Average minimum detectable mass 0.7 M_J
  - 17 systems with maximum stable period < 2 years.



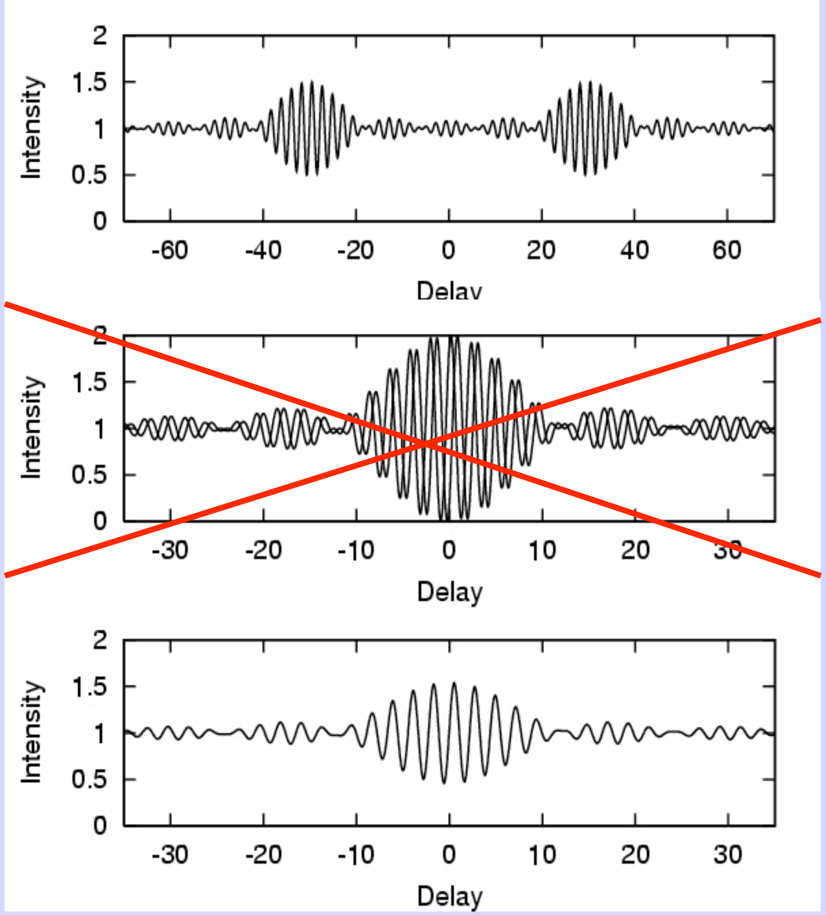
Imaging Astrometry

- A binary star produces a double fringe packet.
- The delay difference between packets tells you the angle between the stars (projected onto the baseline).
- If very close, the fringes overlap, reducing the fringe contrast (visibility).
- The fringe visibility of a pair of sources is given by

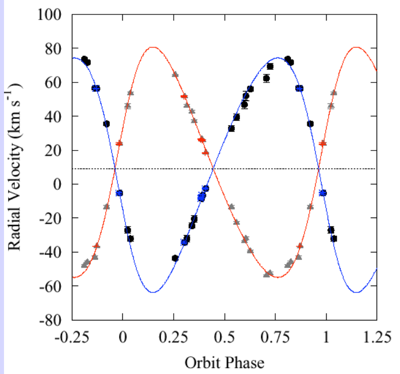
$$V^2 = \frac{1 + R^2 + 2R\cos(2\pi \vec{B} \cdot \vec{s} / \lambda)}{(1+R)^2}$$

- The overlap criterion is the "delay beam"

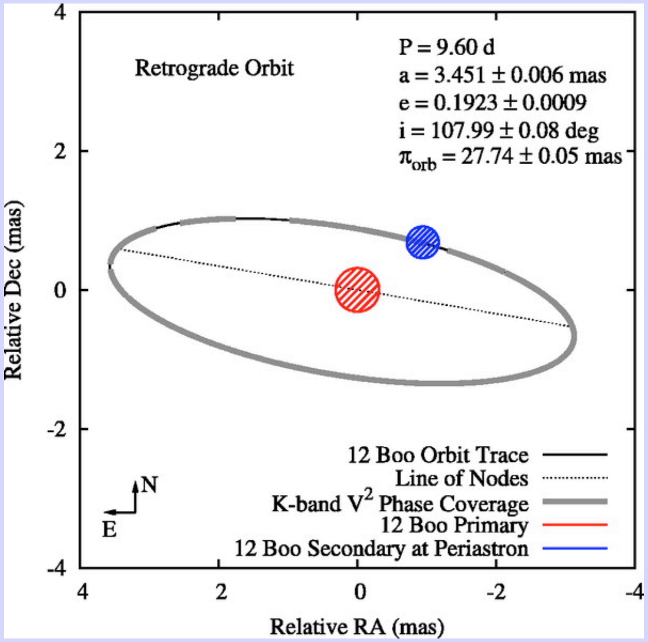
$$\theta = \frac{\lambda}{B} \frac{\lambda}{\Delta\lambda}$$

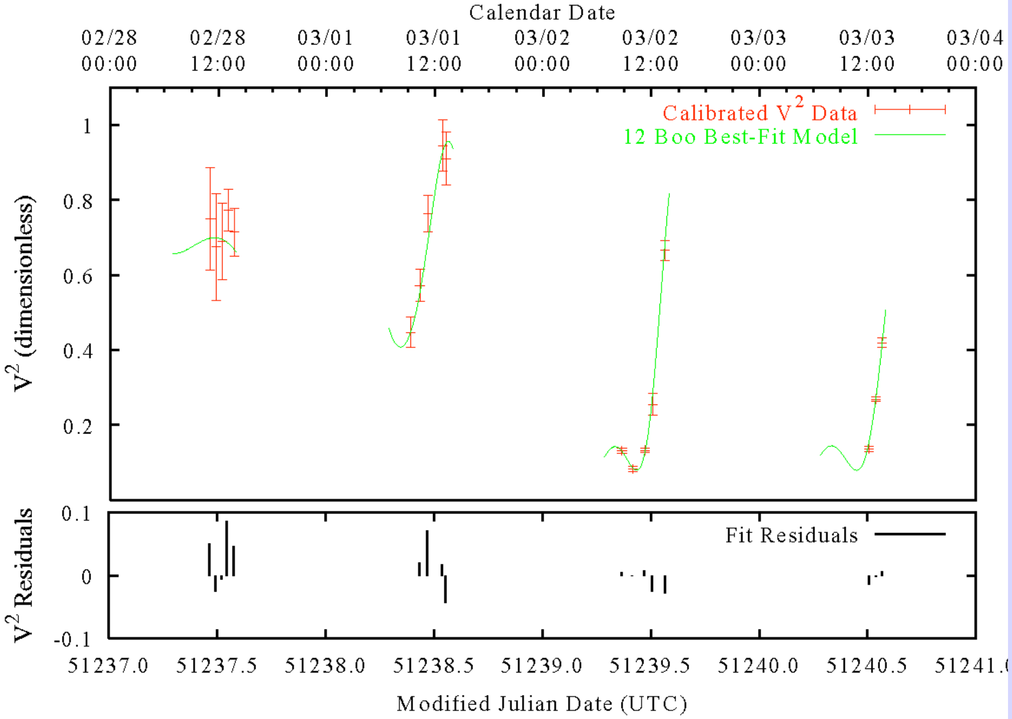


Interferometric Imaging: 12 Boo



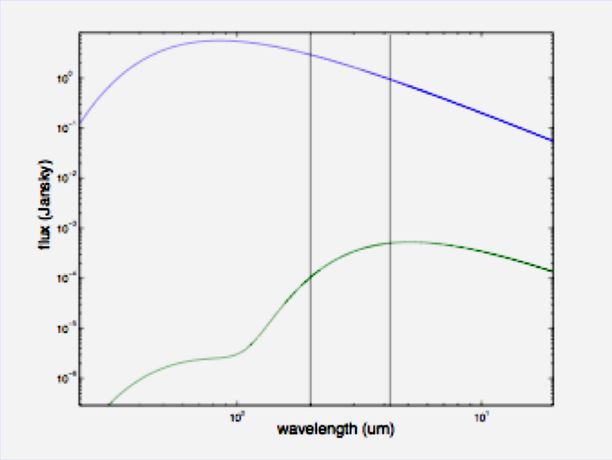
Measurements of fringe visibility (V^2) are used to solve for the orbit to high precision.

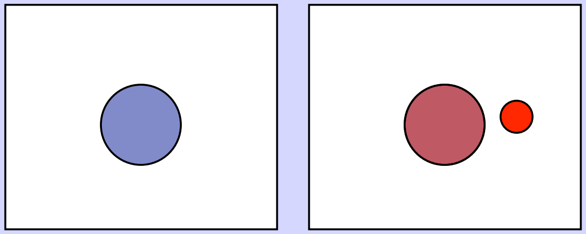




Differential Phase Techniques

- Phase = the location of the fringe.
  - If you know the baseline this gives the location of the source.
- Differential phase techniques make use of the fact that in some cases the center-of-light for a system of interest depends on the wavelength of observation.
  - For a Hot Jupiter the contrast varies strongly between 2 and 5 μm (at 2 the system looks single. At 5 it looks like a high-contrast binary)
  - The expected phase difference between the two colors is ~0.1 milliradians.





Summary

- Astrometry is the art of measuring stellar positions to high precision.
  - Micro-arcseconds to milli-arcseconds
  - Fractional precisions of 10^{-4} to 10^{-12}
  - Useful for planet-finding, parallaxes and mass measurement.
- Astrometry comes in many flavors, depending on the field of view.
- The best results are possible only from space, but science can still be done on the ground. Preferably some form of differential technique should be used.
  - Over small angles atmospheric effects cancel.
  - ~20 micro-arcsec over 0.1 arcseconds is being published.
- Phase referencing is crucial in astrometry, by making it possible to find close reference stars. Also, by separating the tracking and science measurements one can optimize each separately.

Backup Slides