Calibration of Interferometric Data

EuroSummer School

Observation and data reduction with the Very Large Telescope Interferometer

Goutelas, France
June 4-16, 2006

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Michelson Science Center/Caltech
8 June 2006

Outline

Introduction – What I'll be Talking About

Visibility (Amplitude) Calibration & Role of Calibration Objects

Stellar Angular Sizes: Estimates & Proxies

Stellar Multiplicities

Choosing Calibrators

Observing Targets & Calibrators – Practical Considerations

A Case Study: Altair by van Belle et al

Summary & Closing Remarks

Refererences

Charge to the Lecturer

From the SOC:

Name: Dr Andy Boden
Type: lecture (L5)
Length: 1.5 hours
Title: Calibration of interferometric data

Your lecture will address the specific topic of visibility amplitude calibration in interferometry and more exactely the comparison of fringe contrast measured on an object of unknown visibility with that measured on a reference source whose visibility is a priori known.You will explain how calibrators have to be chosen, how diameters are measured and what are the accuracies to be expected. You will explain what are the difficulties and the potential traps. We suggest you give a quick overview of existing softwares and work in the field to set the stage for the practice session that follows (P5). We would be happy if your talk could be illustrated with elements from your own research.

Introduction: What is Calibration?

What:

School Organizers asked me to discuss “interferometric visibility amplitude calibration”

Calibration (n): “the act of checking or adjusting (by comparison with a standard) the accuracy of a measuring instrument”

For our purposes today I’d like to suggest an alternative definition:

Calibration: the transformation of observables into a space where they have direct bearing on the scientific question, and a critical evaluation of the precision (repeatability) and accuracy (correctness) of that transformation

Visibility Calibration & Role of Calibrator Sources

Interferometer: a device that measures the interference (*coherence*) of wave-like phenomena (e.g. incident starlight)

In Astronomical Interferometry we use the *degree* (amount) of *interference* (*visibility*) as proxy for source morphology (e.g. size, shape, features)

- (Fringes from) unresolved sources have “high” (unit) visibility
- (Fringes from) resolved sources have “low(er)” visibility (this is where the science is…)
- [This was all discussed by C. Haniff]

But suspect our *interferometer* (and its *environment*) is imperfect at measuring coherence – so how do we assess the degree of imperfection?

Measure *system* coherence using sources with “known” (i.e. modelable) properties

Visibility Calibration & Calibrator Sources (2)

Interferometer measures *coherence* of target
» Calibrators measure *incoherence* of interferometer

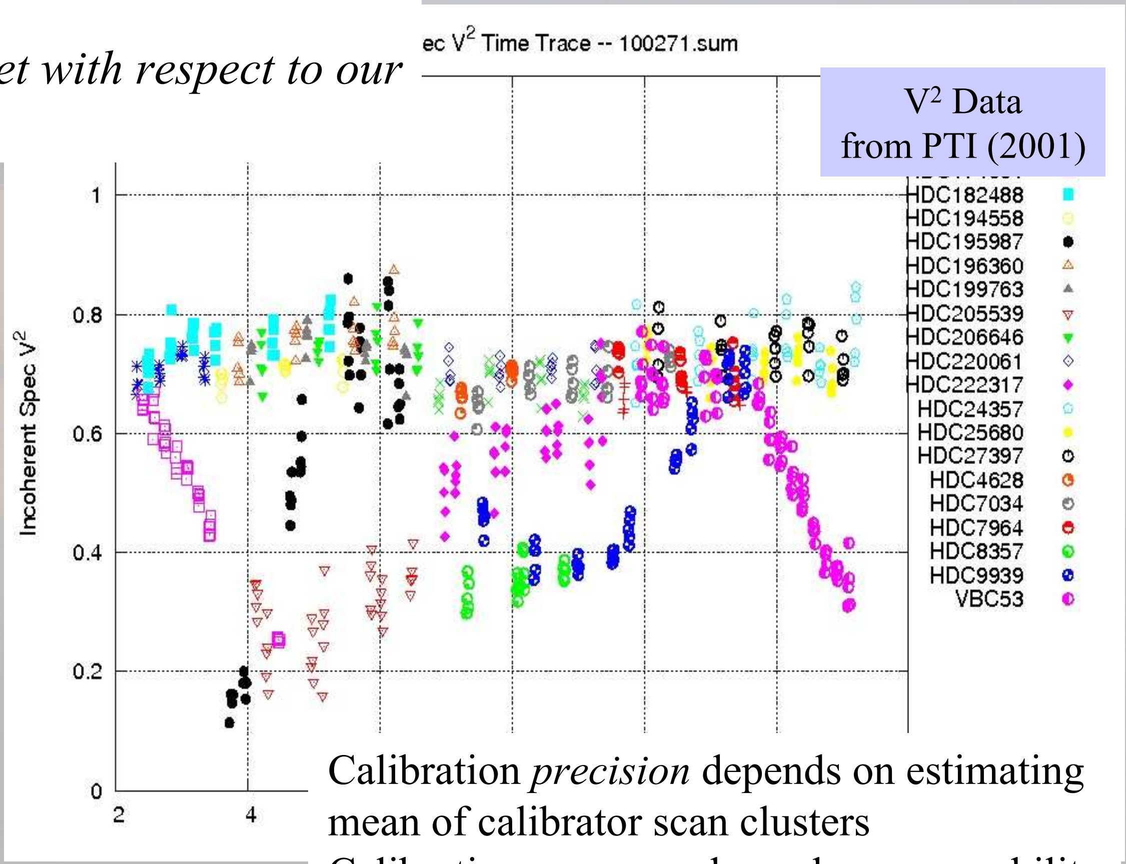
Effectively we measure our target with respect to our calibration sources

Simplest calibration model: calibration multiplicatively applied

$$V_{trg}^2 \equiv V_{meas-trg}^2 / V_{sys}^2$$

$$V_{sys}^2 \approx V_{meas-cal}^2 / V_{model-cal}^2$$

V^2_{sys} : System visibility,
transfer function,
interferometric efficiency factor,
point-source response



V^2 Data from PTI (2001)

Calibration *precision* depends on estimating mean of calibrator scan clusters
Calibration *accuracy* depends on your ability to predict calibrator properties => visibility

Calibrator Sources (3)

Formally, *anything* can be a calibration source.

However, assessing our measurement *accuracies* we must account for uncertainties in our ability to predict the properties of the calibration source:

$$V_{trg}^2 = (V_{model-cal}^2 / V_{meas-cal}^2) V_{meas-trg}^2$$

$$\delta V_{trg}^2 \propto (\partial V_{model-cal}^2 / \partial model)\, \sigma_{model}$$

Traditionally (realistically) this has meant that we choose calibrators whose properties are as simple as possible – single stars!

Attributes of a Good Calibrator Star

What are the attributes of a "good" calibrator?

- Bright – lots of signal

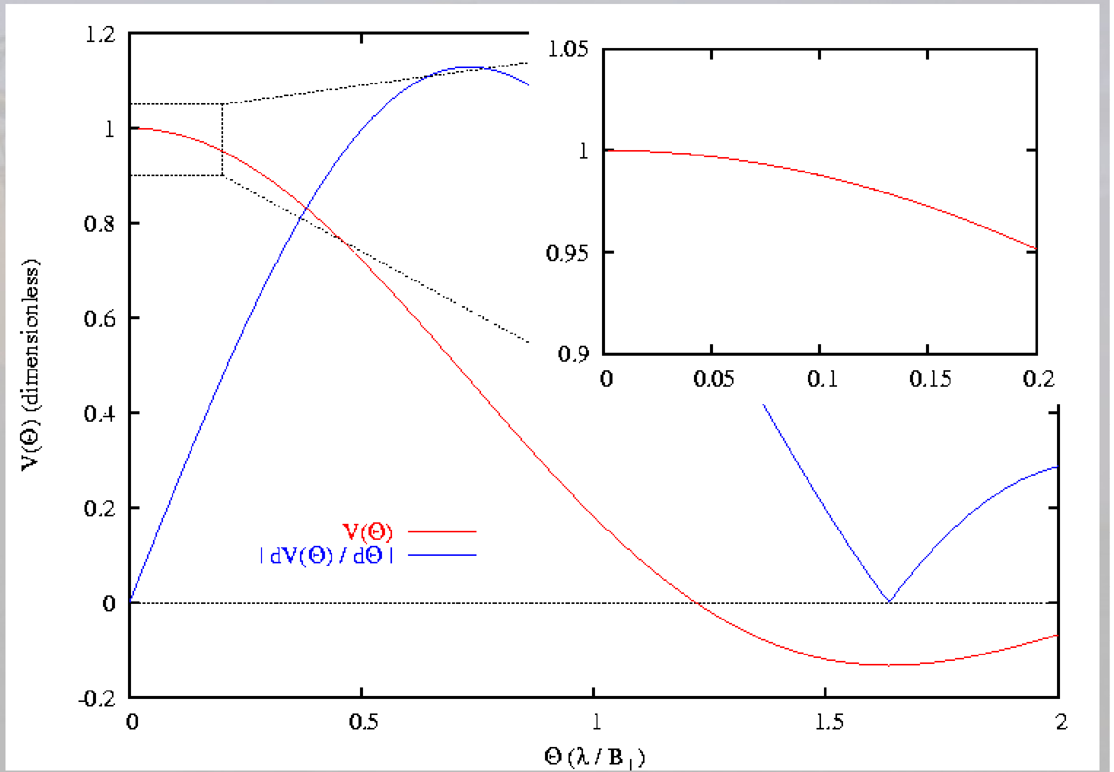
$$SNR \propto NV^2$$

- Point-like (unresolved) – little modeling error (e.g.):

$$\sigma_{V^2-sys} \propto \left|\frac{\partial V^2}{\partial \theta}\right| \sigma_\theta$$

- These two properties are fundamentally at odds with each other (bright stars are not point-like…)

- *So how big do stars appear anyway?*



$$V^2 = \left[\frac{2J_1(\pi\theta B/\lambda)}{\pi\theta B/\lambda}\right]^2$$

Estimating Stellar Angular (Apparent) Sizes

How Big Do Stars Appear?

One Solution is to "know" the linear size and distance:

$$\theta_{sun} = d_{sun} / D$$

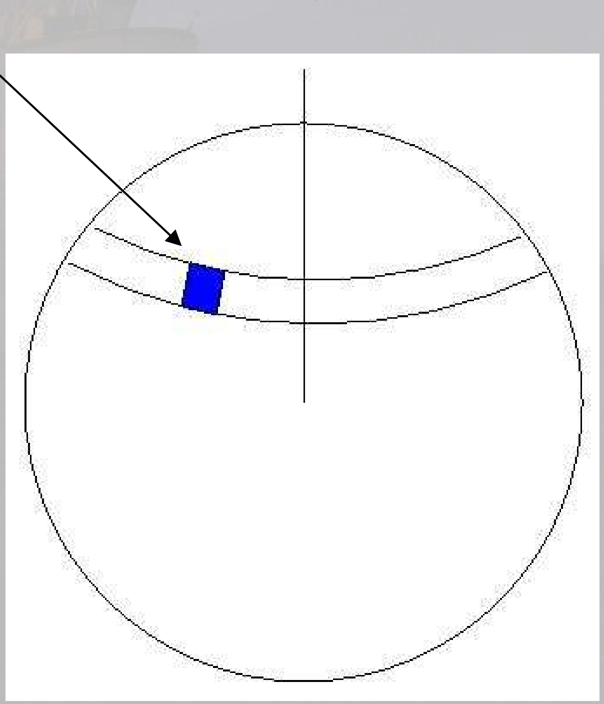
$$\cong [0.01 AU]/[10\, pc] = 10^{-3}\, arc\sec \equiv 1\, mas$$

More Practical (Model) Solution: Imagine stars are spheres whose radiating surfaces (photospheres) are at an ("effective") temperature T…

Further imagine the star's photosphere is a Lambertian blackbody radiator…

$$A = \oint dA = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, r^2 \sin\theta = 4\pi r^2$$

$$dA = r^2 \sin\theta\, d\theta\, d\phi$$



Estimating Apparent Sizes of Stars (2)

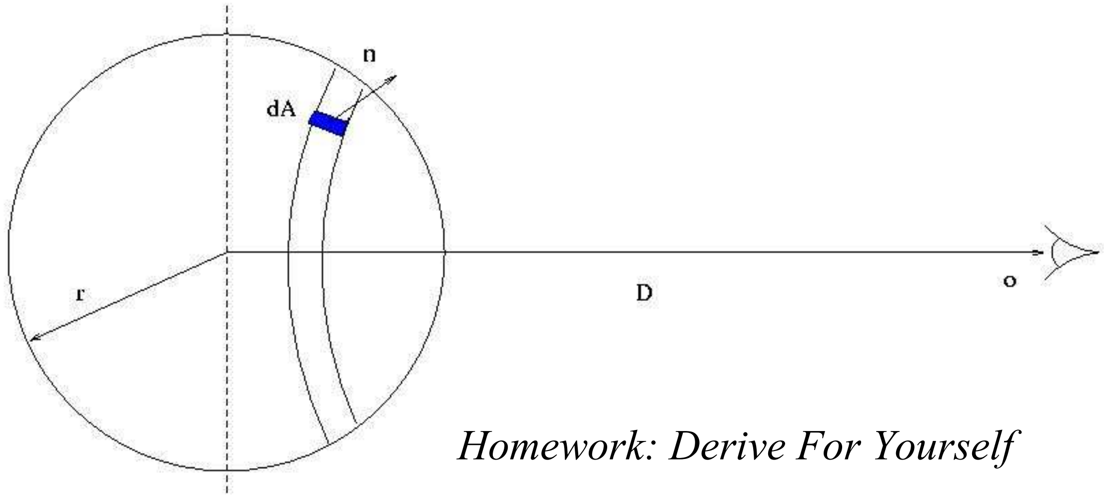
Radiation per unit star surface area into unit solid angle:

$$\sigma T_{eff}^4 \frac{\hat{n} \bullet \hat{o}}{\pi} = \frac{\sigma T_{eff}^4}{\pi} \cos\theta$$

Radiation per unit star surface area per unit area at D:

$$\frac{\sigma T_{eff}^4}{\pi} \cos\theta / D^2$$

Integrated (Bolometric) Flux at Distance D:



Homework: Derive For Yourself

$$F_{Bol} = \int_{2\pi} dA \frac{\sigma T_{eff}^4}{\pi} \cos\theta / D^2 = \frac{r^2}{\pi D^2} \sigma T_{eff}^4 \int_{2\pi} d\theta\, d\phi \sin\theta \cos\theta$$

$$= \frac{1}{2} \frac{4r^2}{D^2} \sigma T_{eff}^4 \left[\frac{1}{2} \sin^2\theta \right]_0^{\pi/2} = \frac{1}{4} \Theta^2 \sigma T_{eff}^4$$

This relationship ***defines*** *effective temperature* for a star

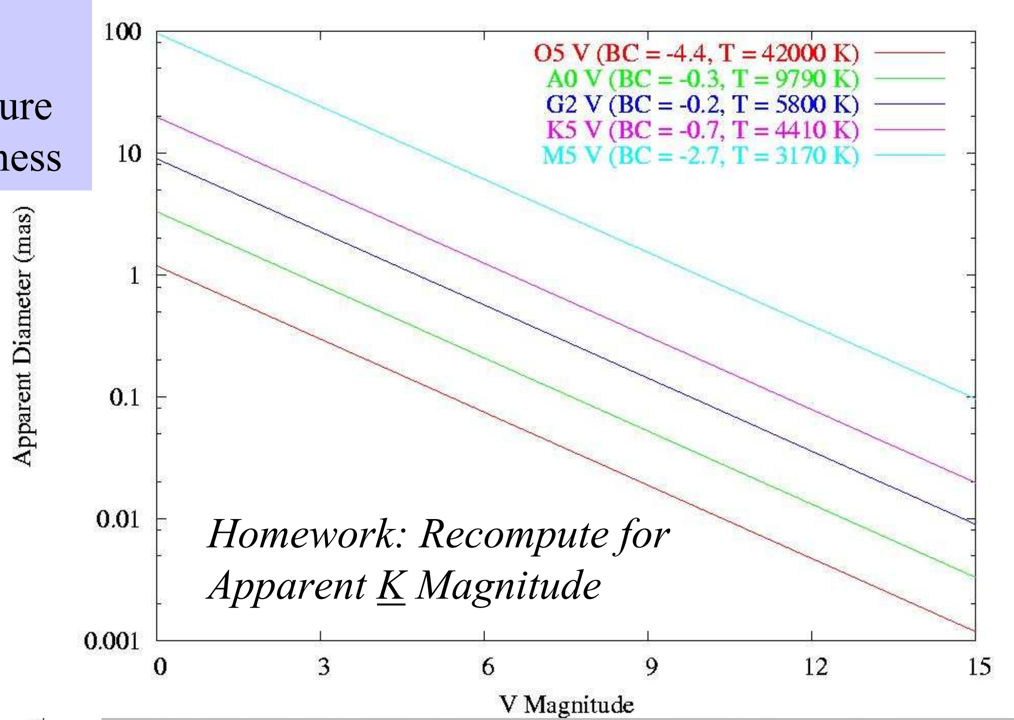
VLTI

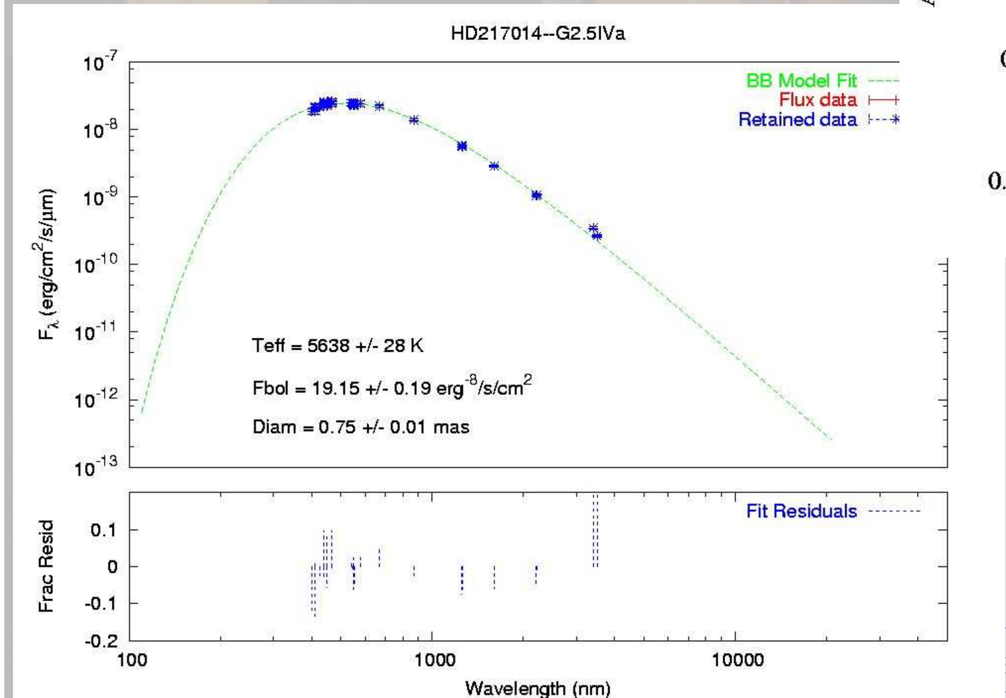
Estimating Angular Sizes of Stars (3)

- So estimating apparent size is *easy*: all you need is *bolometric flux* and *effective temperature*!
- In this sense effective temperature is just a <u>proxy</u> for surface brightness

$$\Theta = \sqrt{\frac{4F_{Bol}}{\sigma T_{eff}^4}}$$

$$= 8.17mas \bullet 10^{-0.2(V+BC)} \bullet \left[\frac{T_{eff}}{5800\,K}\right]^{-2}$$





- Because stellar size is proportional to (sqrt of) brightness, bright & "point-like" does not formally exist
- Source resolution is a question of instrument resolution and sensitivity
- For given apparent brightness, "hotter" stars appear smaller

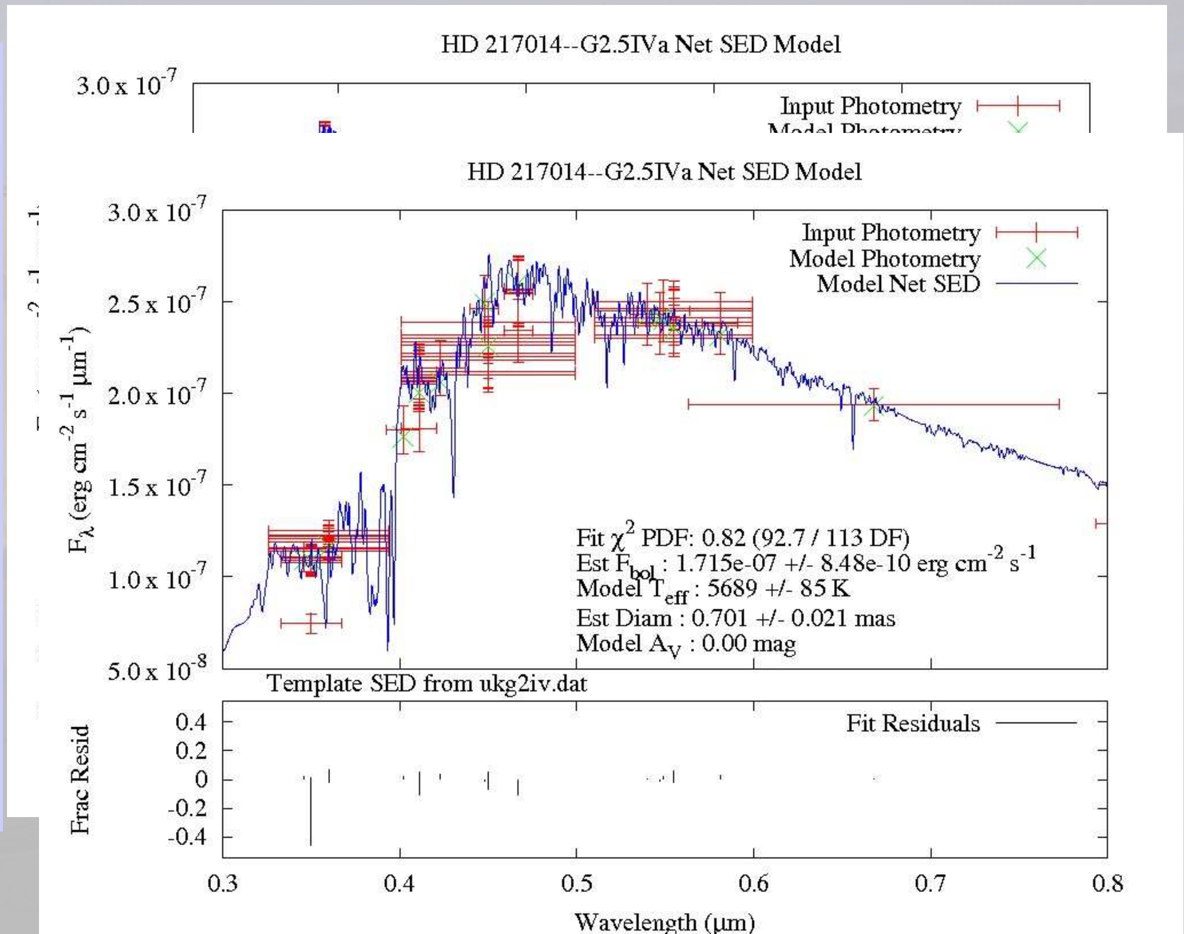
State of Art: High-Fidelity Spectral Energy Distribution Modeling

…because stars are definitely *not* black-body sources…

Prevalence of high-resolution stellar templates (e.g. Kurucz, Lejeune, Cohen, Pickles) makes it possible to do detailed source SED modeling

Such modeling can *greatly* improve confidence in *bolometric flux* estimation (particularly when extinction is involved for sources outside the local "bubble").

However it leaves *open* the issue of *effective temperature calibration* for the templates.



Calibrator Diameter/Effective Temperature: My Personal View

There are astronomers who claim to accurately *know* the effective temperature (surface brightness) of a star based on other observable properties (e.g. color, spectral type, spectral line strengths).

There are at least as many astronomers who think that those in the first category are *self-delusional*!

Disclaimer – my *personal* view:

- Effective temperatures are *measured* with measured angular diameters
- Errors on effective temperatures estimated by indirect means (e.g. not by angular diameter measurement) are typically *underestimated* by a factor of a few.
- It is *CRITICAL* that realistic errors in calibrator angular diameters are properly treated as a systematic error source in the analysis.
- The best way to mitigate these systematic errors is to work with (largely) unresolved calibrators (minimizing $\delta V^2/d\ \theta$)

Stellar Multiplicity

The other pitfall in calibrator selection is stellar multiplicity:

- In general binaries are thought to make *bad* calibrators because they greatly compound the modeling uncertainty issues

- However nature is apparently quite fond of making binary stars…

Stellar Multiplicity – What Do We Know?

- Our knowledge of multiplicity is dominated by the landmark work by Duquennoy & Mayor (1991)
- Two out of three solar-like stars have a stellar companion *in the field*
- This "companion fraction" is likely significantly higher in pre and early main-sequence phases
- Results are suggestive companion fraction may increase with primary mass
- For our purposes only a fraction of the total binary population are troublesome (i.e. spatial frequency, brightness ratio)
- Critical not to forget importance of multiplicity vetting (and to plan for the unanticipated "discovery")

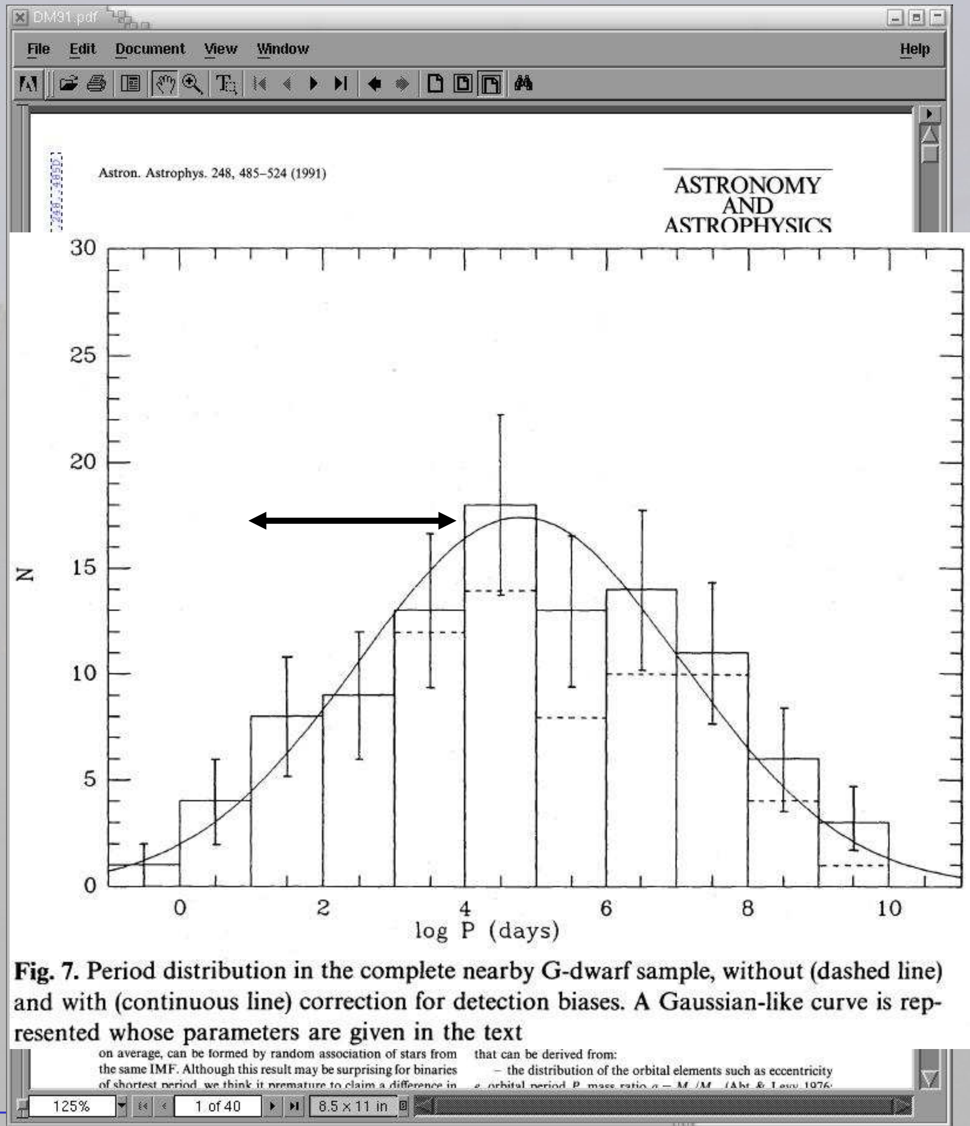
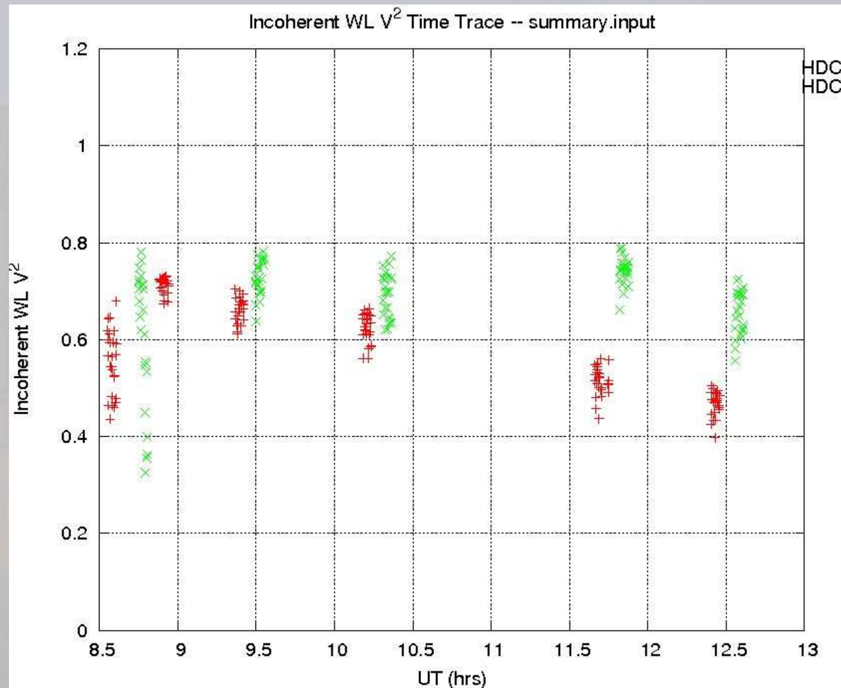


Fig. 7. Period distribution in the complete nearby G-dwarf sample, without (dashed line) and with (continuous line) correction for detection biases. A Gaussian-like curve is represented whose parameters are given in the text

Stellar Multiplicity Identification

- Multiplicity identification in observation planning requires information synthesis from:
  - Simbad
  - Binary Catalog Info (e.g. Batten, WDS)
  - Astrometric Catalogs – Hipparcos! (deviations from simple five-parameter fit as indicator of addition dynamics)
- Consequently we structure our planning tool packages (getCal, ASPRO) with this information synthesis in mind
- Despite best intentions, some a priori multiplicity will slip through (particularly in unvetted sensitivity space of VLTI and KI…)



HD 143xxx Binarity Discovery “Image” (KI 18 May 2006)

Choosing Calibrators: Where Can I Find Them?

So where can I find candidate calibrators for my science target?

1. Specialized Calibrator Catalogs (references provided)
   - These sources are typically well-vetted & well-modeled
   - These catalogs typically contain 100's of sources covering 10,000's of sq degrees on sky (i.e. a calibrator every ~100 sq deg, or typically ~ 10 deg separation between your target and the nearest calibrator)
   - Heavily biased toward brighter (apparently larger) stars
2. From Larger/More General Catalogs (e.g. Hipparcos)
   - These sources are typically less well vetted than in the specialized catalogs – much more caveat emptor (more on that later)
   - However, you have *many* more sources to choose from – allowing more flexibility (i.e. better match to my target) in terms of sky location, brightness, and color

There exist software applications (e.g. ASPRO, getCal) that suggest calibrators from these two sources (and do more to help you plan your experiment) – *topic for this afternoon's practical session*

Recommend you model the SED for your calibrators – best way to understand your objects (particularly important for unvetted sources)

Calibration Strategy: Choosing and Applying Calibration Models

You're just after the "point-source" response of the interferometer – how hard can it be?

Two general schools of thought:

1. Global Instrument and Environment Calibration

   (e.g. Mark III; Mozurkewich et al 1991)

   relatively few calibrator observations modeled by functions that capture conceptual model of instrument & sky response

   [Few calibration observations => more time for science!]

2. Local Calibration ("All Calibration is Local")

   "Many" calibration observations taken and applied in spatial and temporal proximity to science observations

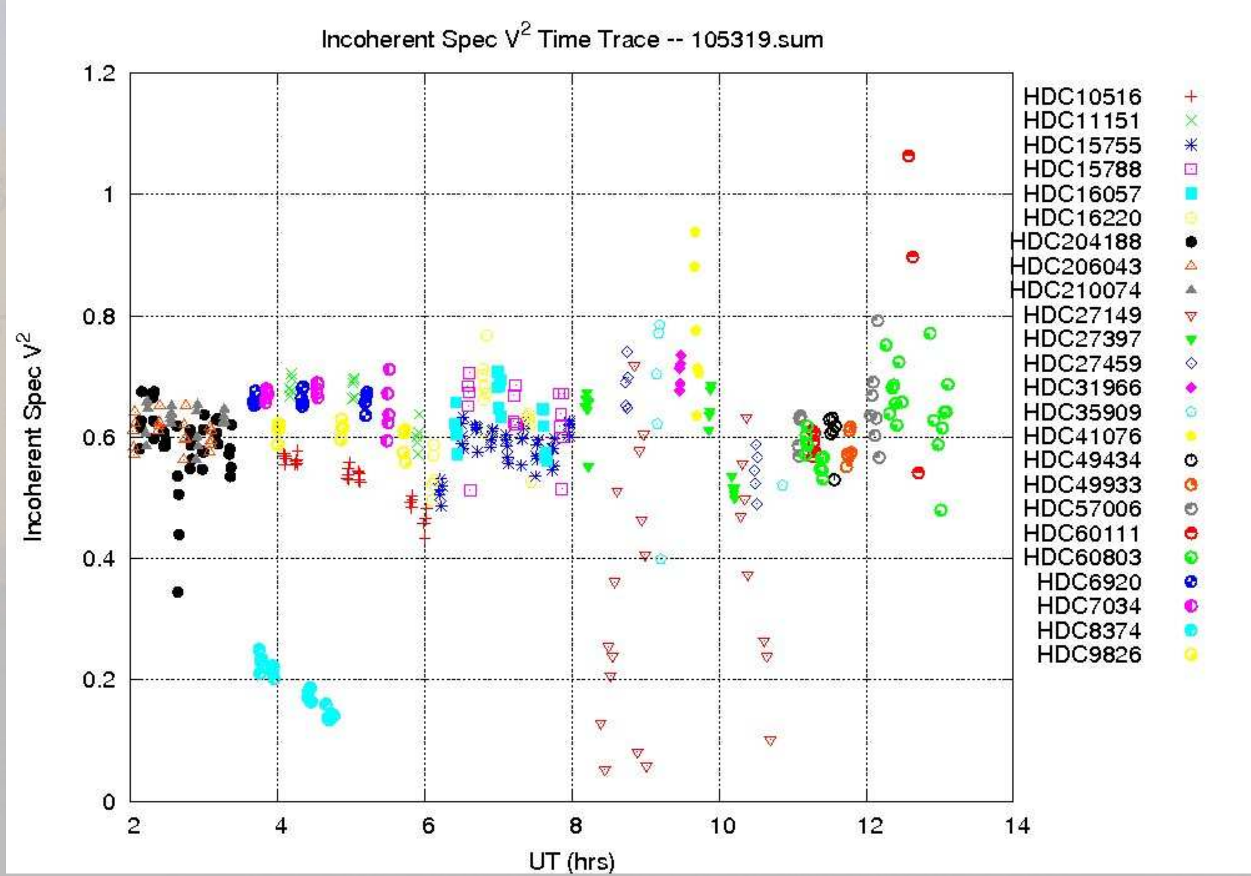
   PTI & KI (e.g. Boden et al 1998); NPOI (e.g. Hummel et al 1999)

Your choice will be determined by the character of your instrument (namely temporal and angular stability)

Spatial Variability

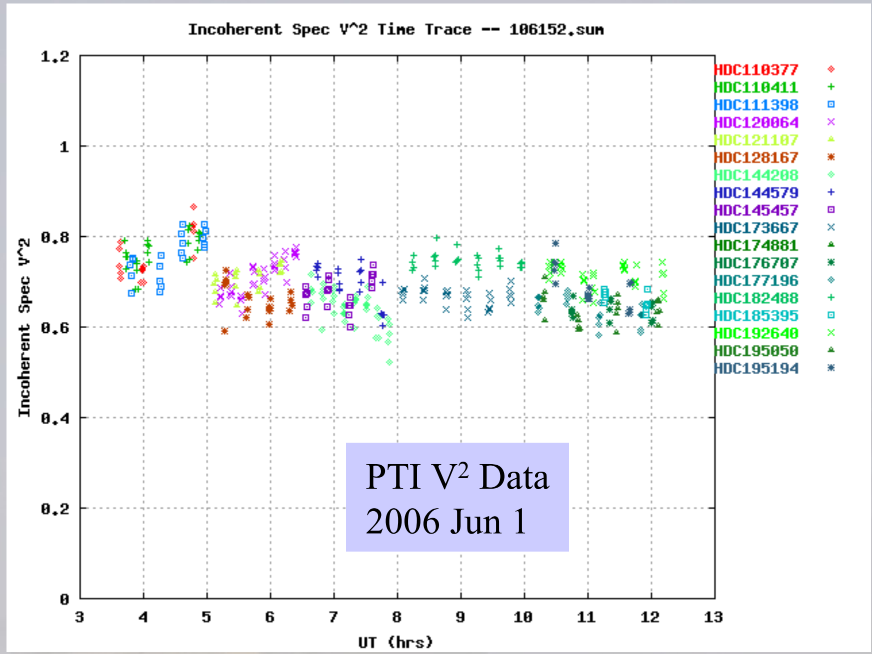
Instrumental response can be variable on spatial scales!

Your calibration strategy must adapt

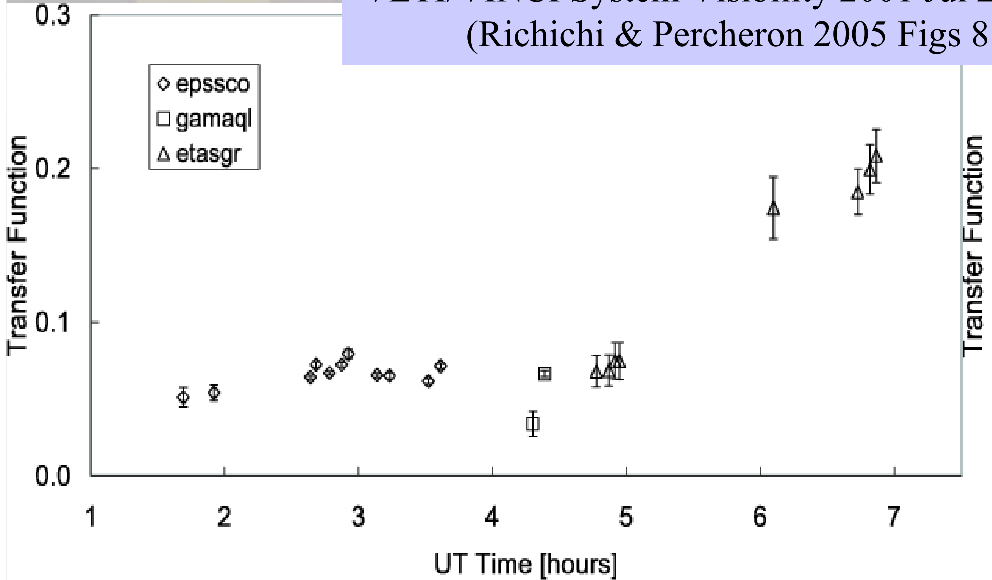


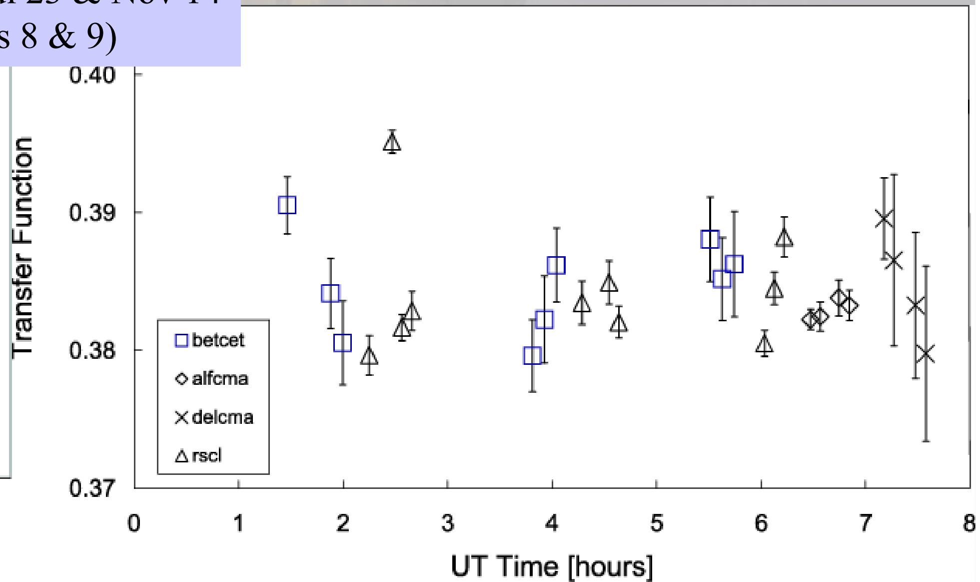
Time Variability of the System Visibility

It is critical to assess and include possibility of time-variability in instrument response model

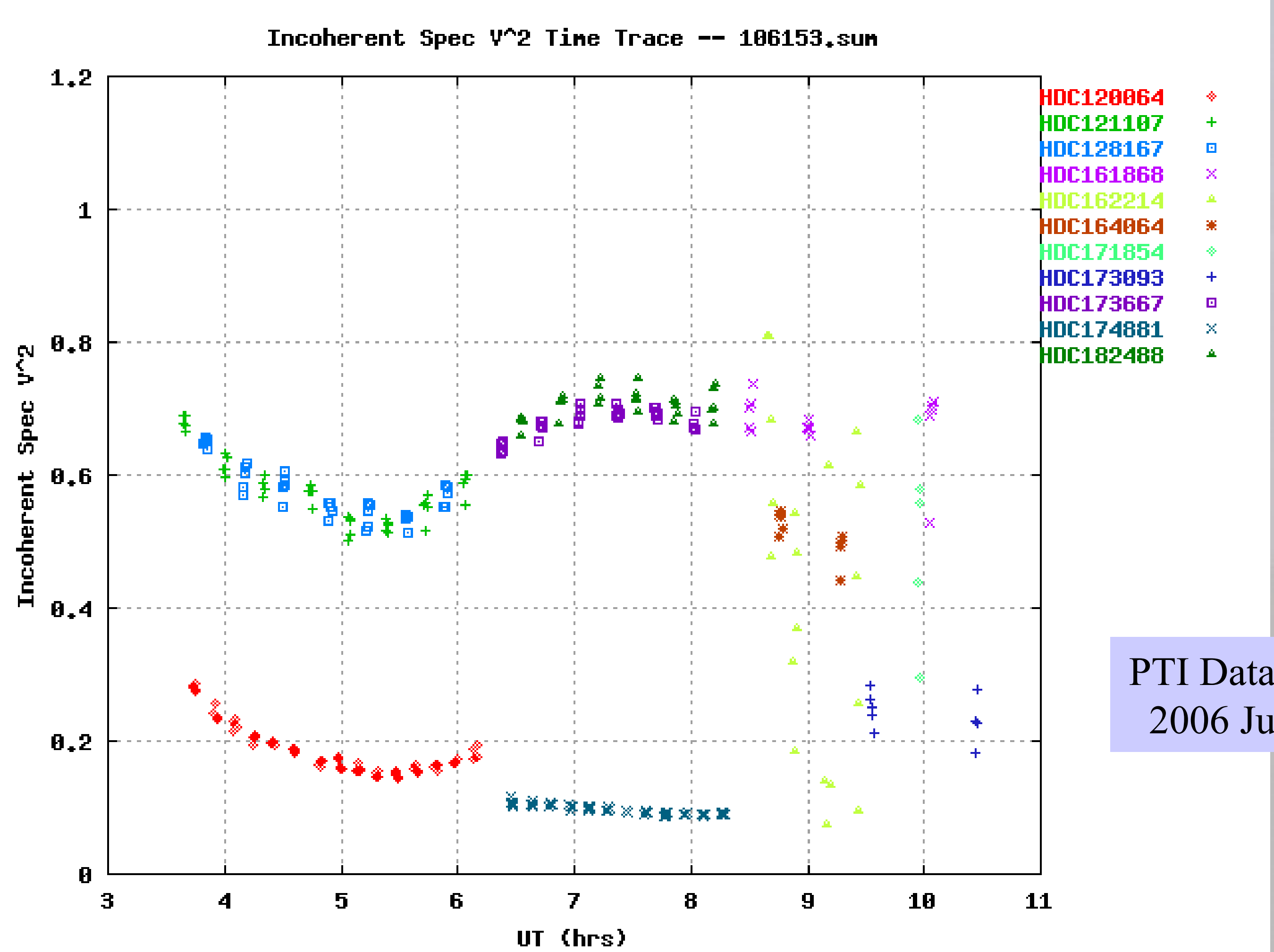


VLTI/VINCI System Visibility 2001 Jul 23 & Nov 14
(Richichi & Percheron 2005 Figs 8 & 9)





Not Picking on VLTI!



PTI Data from 2006 June 2

Choosing and Applying Calibration Models

3. Do I really *Need* more than one calibrator?
   – Of course, if you know the "right answer", you only need one!
   – Recommend two – three if all objects are unvetted for multipicity
   – Probably a middle ground: choose one or two "local" calibrators from unvetted sources (i.e. Hipparcos), and then a calibration "anchor" from one of the calibrator catalogs
4. Choose calibrators that are (as) observable (as your science target)
5. How often should observe the calibrators?

   Defined by your (instruments) calibration model
   – Local calibration – equal time on science target and calibrator ensemble
   – Global calibration model – driven by residual calibration noise functions (Mark III experience was spending ~25% of time on calibration observations)

Calibration Calculations

Actual calibration calculations are typically handled by "standard pipeline" components – not something you have to do yourself (i.e. see lectures and practical sessions next Monday)

To give you a sense of how these calibration applications work:

- Create a time-variable system visibility estimate at the time of each science observation (function of calibrator properties, geometry)
- If multiple calibrators are available, inner-compare independent system visibility estimates, flag discrepancies among independent system visibility estimates
- Compute composite system visibility model and apply it to science observation
- Compute u-v coordinates for science observation

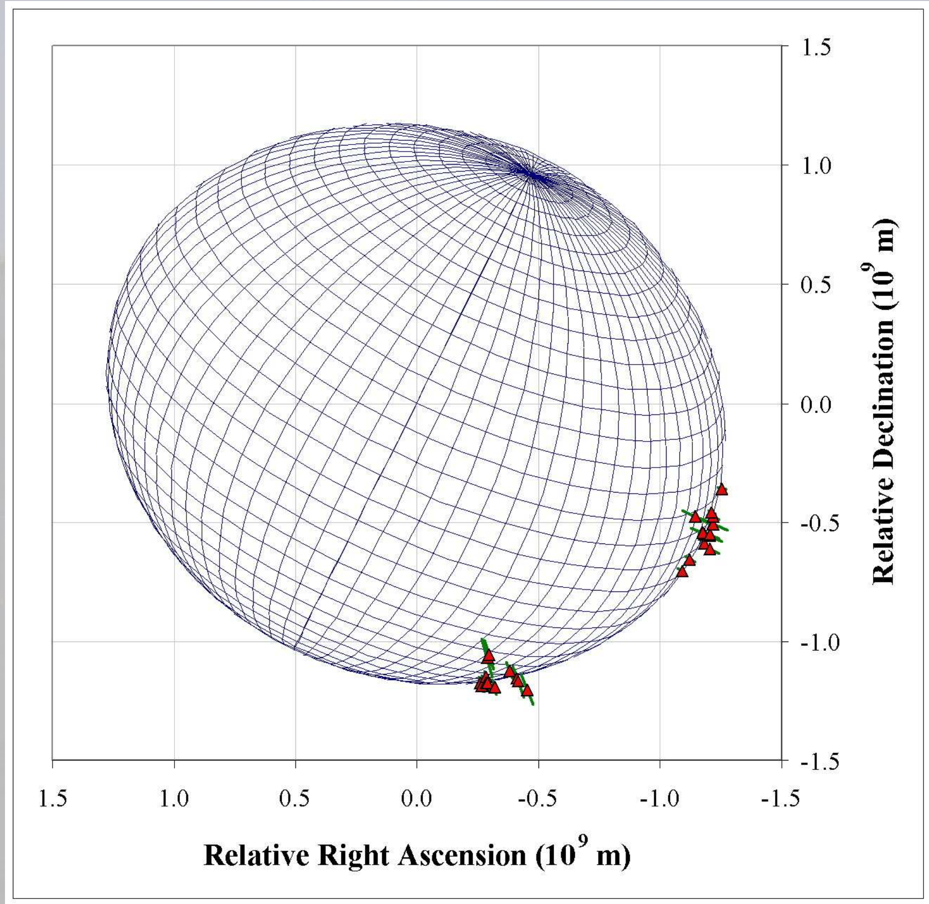
Practical Calibration Example: Altair by van Belle et al

van Belle et al observation of rotational oblateness of Altair (van Belle et al 2001)

Altair was among brightest known rapid rotators – oblateness observation among the "holy grails" of stellar interferometry

Detection of oblateness depends on:

- Relative changes in the calibrated visibility
- Visibilities measured on different baselines

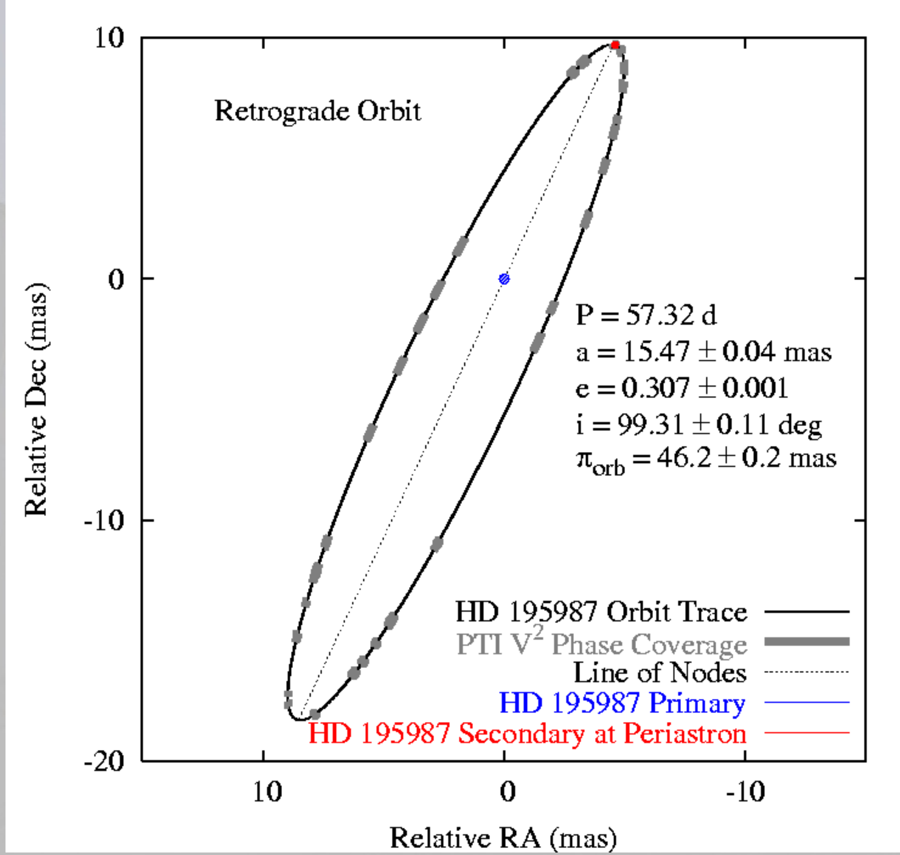


van Belle et al 2001

Altair – van Belle et al (2)

Because result depended on cross-baseline comparisons:

- Critical to use the *same* calibrators on the two different baselines (this sounds obvious, but not everybody has done this!)
- van Belle team also worked with myself and G. Torres to analyze statistics of a multi-baseline PTI orbital solution for HD 195987 – no sign of baseline bias
- van Belle established that a experiment control did NOT exhibit signs of oblateness



Torres et al 2002

Summary

Calibration observations are necessary to characterize instrument and environmental limitations

- Interferometer measures *coherence* of target, calibrators measure *incoherence* of interferometer

Bright point sources are ideal calibrators – and (depending on your instrument) don't exist

- This led to consideration of methods for estimating stellar angular diameters
- Caution concerning claimed accuracies of effective temperatures
- Critical for astrophysical analyses to carry sources of systematic error through into derived results

Effectively single stars are typical the only appropriate choice for calibrators

- That led to considerations about multiplicity vetting

Pulling all this together into an experimental strategy

- Instrumental stability is the limiting consideration and drives all

Closing Remarks/Recommendations

It's good if your results are precise. It's better if they are accurate.

When you see claims of an amazing interferometry result, I recommend a healthy skepticism in assessing it.

Pipeline components are great, but never loose touch with the raw observations; look – critically – at them as much as possible.

Anyone who won't show you their raw and calibrated data is probably hiding something.

Never underestimate the importance of a good control in your experiment.

References

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