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Science with Astrometry

Gerard van Belle
PRIMA Instrument Scientist
3 Jun 2008

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Caveat Emptor

- "Science with Astrometry" is a very broad title
- This talk will *not* be very broad
- Instead, I will emphasize astrometry with optical interferometry
    - This is, after all, the VLTI Summer School
    - I will, in fact, be telling you what I think you should know, not what the title directs me to tell you
    - You are free to disagree with me and fall asleep at any time

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What is Astrometry?

- Merriam-Webster: “a branch of astronomy that deals with measurements (as of positions and movements) of celestial bodies” (ca. 1859)
- Science of how pretty lights move in the sky

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Brief History of Astrometry I.

(in 4 bite-sized chunks)

- Hipparchus (ca. 190-120 BC)
  - First catalog of stars
    - At least 850 stars, original did not survive
  - Invented brightness scale
- Tÿcho Brahe (1546-1601) / Johannes Kepler (1571-1630)
  - Brahe: The finest naked-eye astronomer of classical times
    - Planetary observations consistently accurate to 1’, stars to 32-48”
    - First to extensively carry out **redundant** observations
    - Worked out tables for correction of atmospheric refraction
  - Kepler: Used his mathematical genius to analyze Brahe’s data
    - Derived planetary laws of motion

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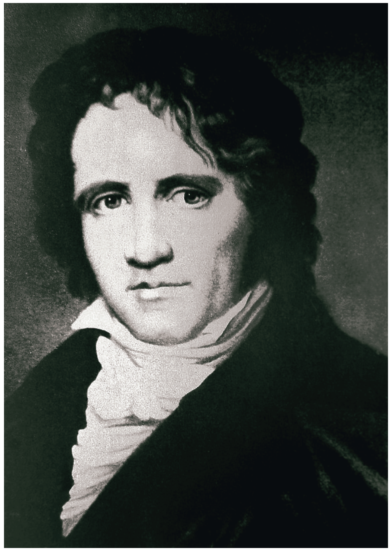
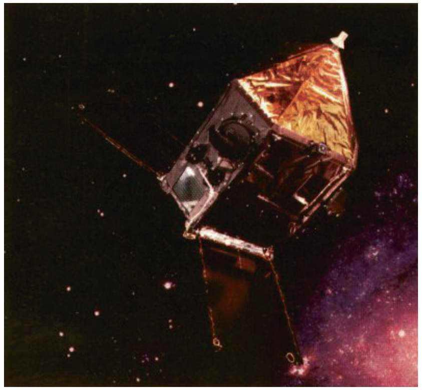
Brief History of Astrometry II.

(in 4 bite-sized chunks)



- **Friedrich Bessel** (1784-1846)
  - Founder of modern astrometry
  - Fundamenta Astronomiae (1818)
    - 3,222 star positions
  - 61 Cyg (1838)
    - Parallax of 0.3”
    - “Signaled the official end to the dispute over Copernicanism”
- **Hipparcos** (1991.25)
  - ESA space mission
  - Recovered from launch failure
  - Hipparcos catalog has 120,000 stars with ~2-4mas accuracy
  - Tycho catalog has ~1Mn stars with 20-30mas accuracy



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Science with Astrometry

- Distances
  - A **fundamentally** enabling parameter
- Dynamics
  - Proper motions
  - Planetary systems
  - Galactic, extragalactic dynamics
- Relativity
  - Gravitational deflection of light

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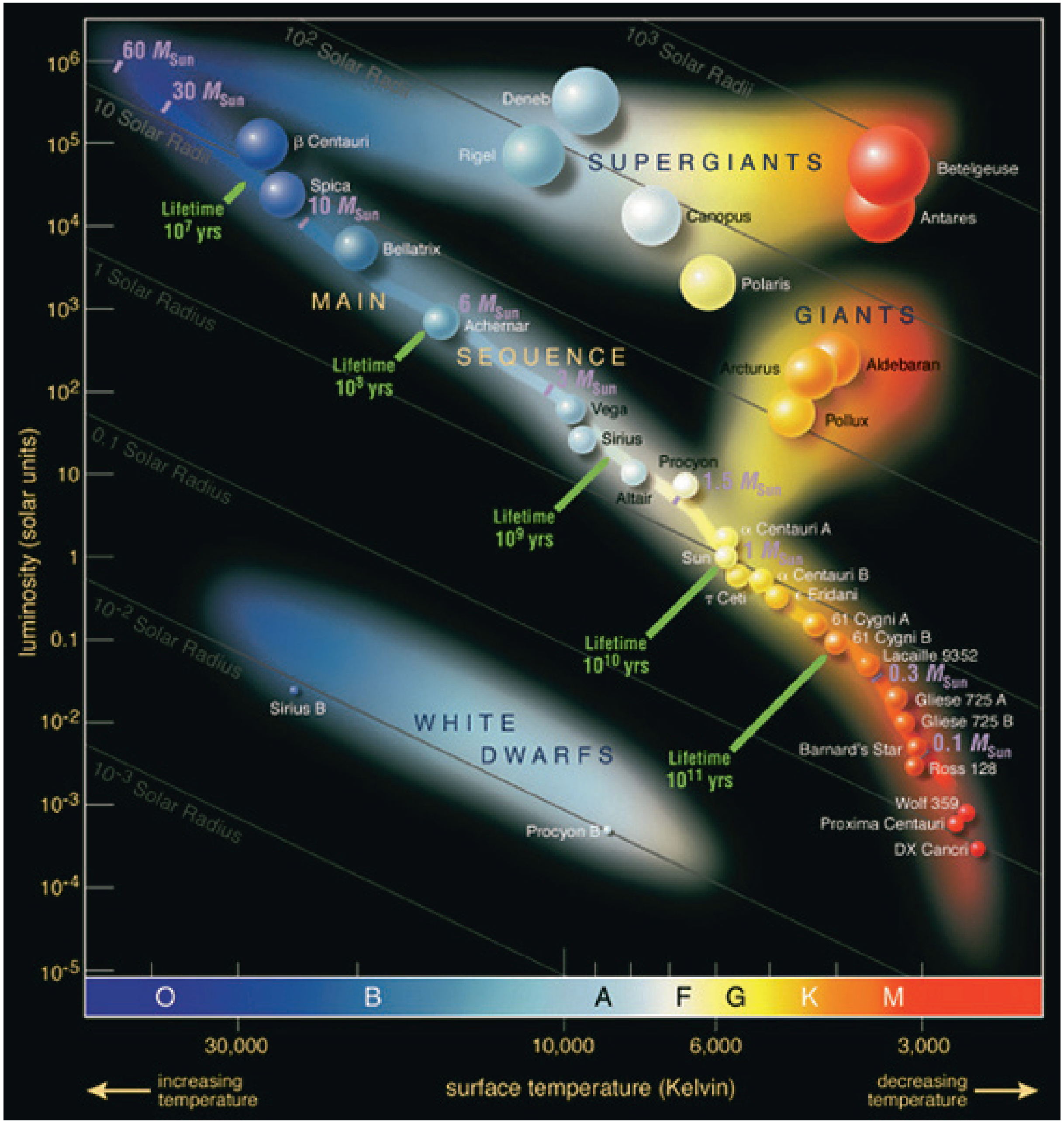
Essential Astrophysics: The HR Diagram

- Track/model stellar evolution
- Fundamental stellar properties
  - Luminosity
  - Radius
  - Temperature
- Examine properties of groups of stars
  - Clusters, associations



Calibrating the Cosmic Distance Scale

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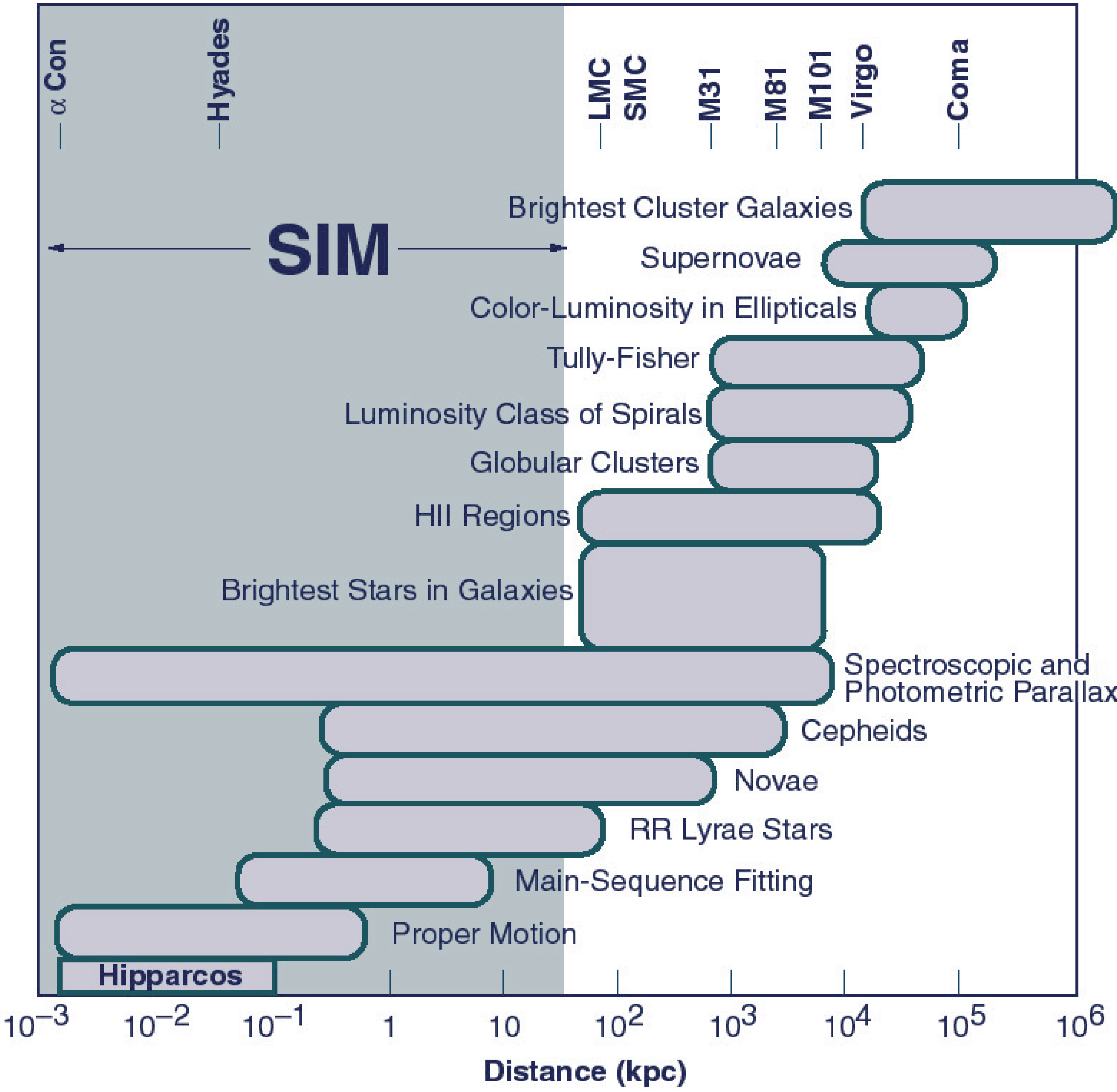
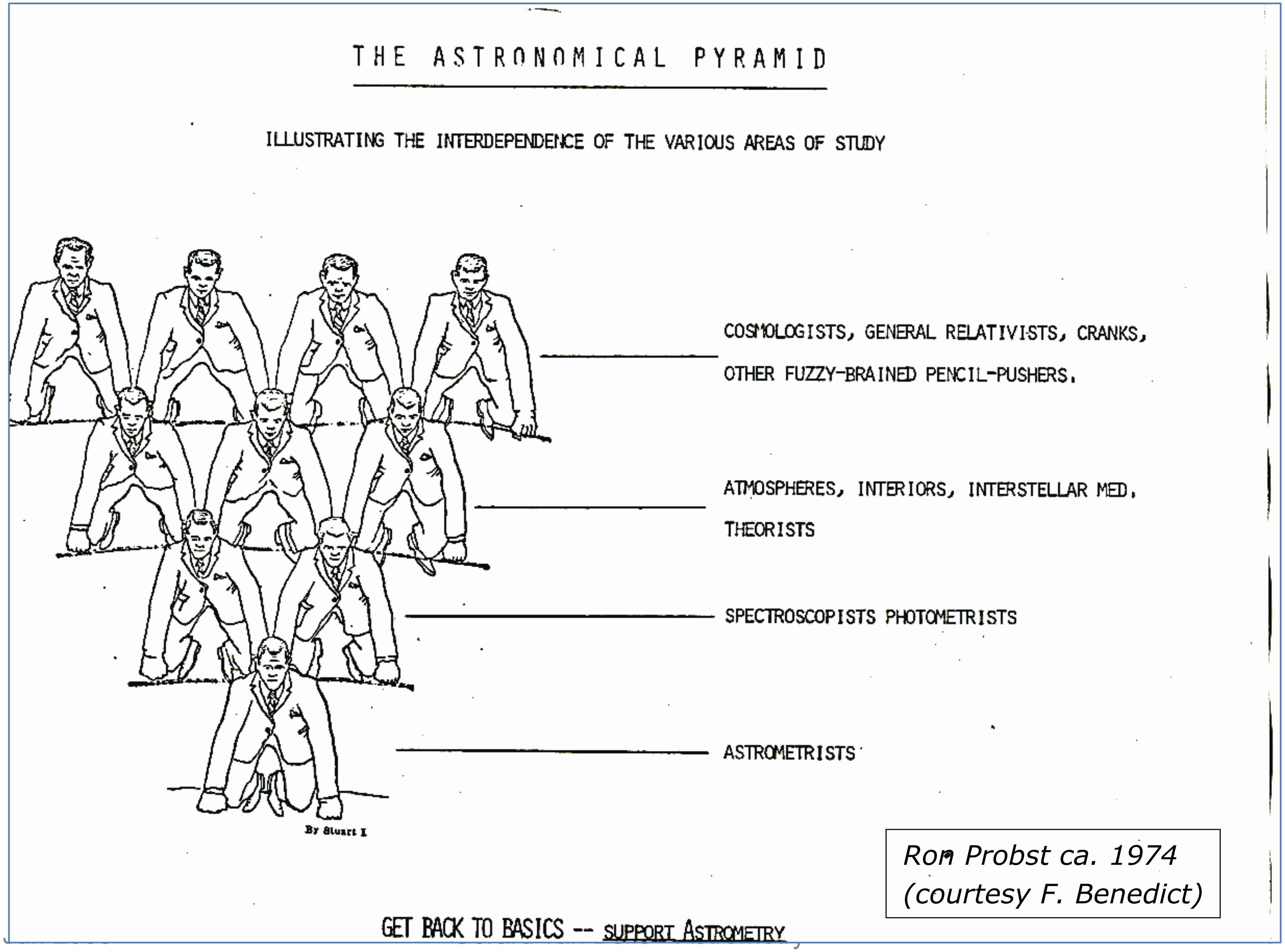
- Current parallax measurements reach only to about 100 pc
- Distances are derived from a staggered set of rungs, each relying on the previous step.
- SIM will calibrate the rungs of the distance ladder throughout the Galaxy (10% to 25,000 pc, 1% to 2,500 pc)



Why Astrometry?



THE ASTRONOMICAL PYRAMID

ILLUSTRATING THE INTERDEPENDENCE OF THE VARIOUS AREAS OF STUDY

COSMOLOGISTS, GENERAL RELATIVISTS, CRANKS, OTHER FUZZY-BRAINED PENCIL-PUSHERS.

ATMOSPHERES, INTERIORS, INTERSTELLAR MED. THEORISTS

SPECTROSCOPISTS PHOTOMETRISTS

ASTROMETRISTS

GET BACK TO BASICS -- SUPPORT ASTROMETRY

Ron Probst ca. 1974
(courtesy F. Benedict)

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Regimes of Interest

I. Accuracy (Precision)

- Arcseconds
  - Proper motions of the “fastest” stars
  - General relativity (42” for ☿)
- Milliarcseconds
  - Parallaxes of the nearest stars (α Cen 0.7”)
- Microarcseconds
  - Planet detection (500μas for ♃ @ 10pc ☉)
- Nanoarcseconds
  - Earth detection (300nas for ⊕ @ 10pc ☉)

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Regimes of Interest

II. Position and its Derivatives

- Position
  - Cosmic structure (How are things put together?)
- Motion
  - Cosmic dynamics (How will things be put together?)
- Acceleration
  - Cosmic interaction (What are the forces acting on things?)
- Higher order derivatives..?
  - Cosmic events? (Do I need to sell short my Caribbean resort stock for the impact of asteroid 99942 Apophis in the north Atlantic in the year 2036?)

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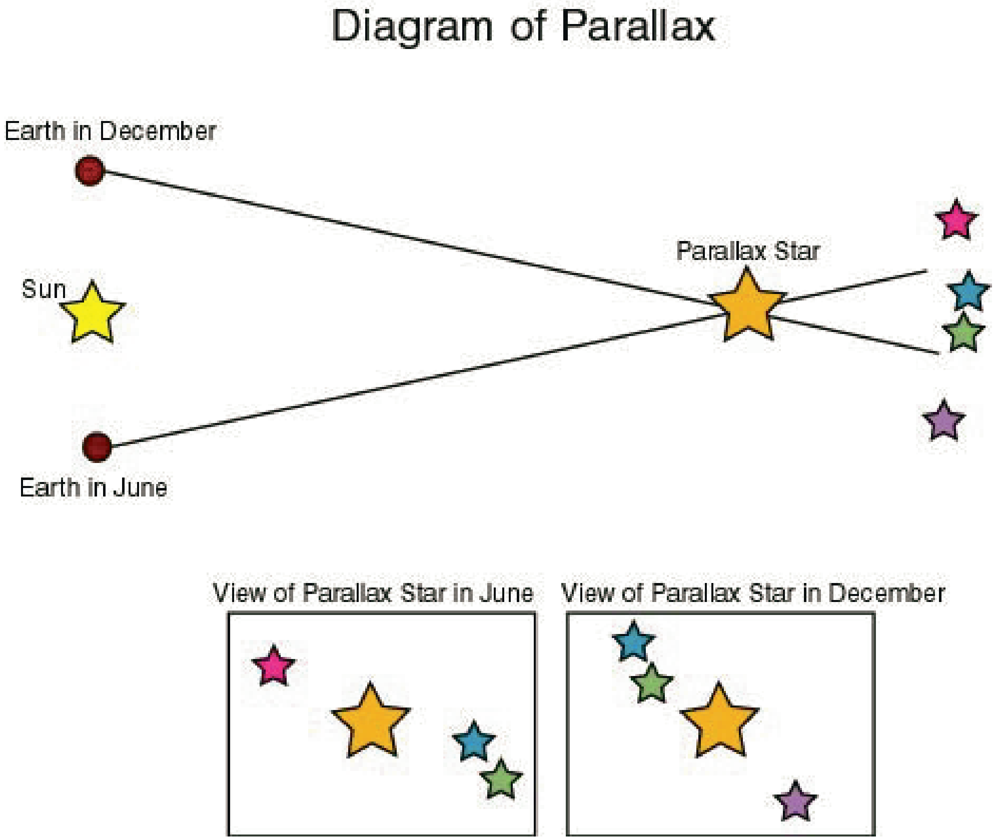
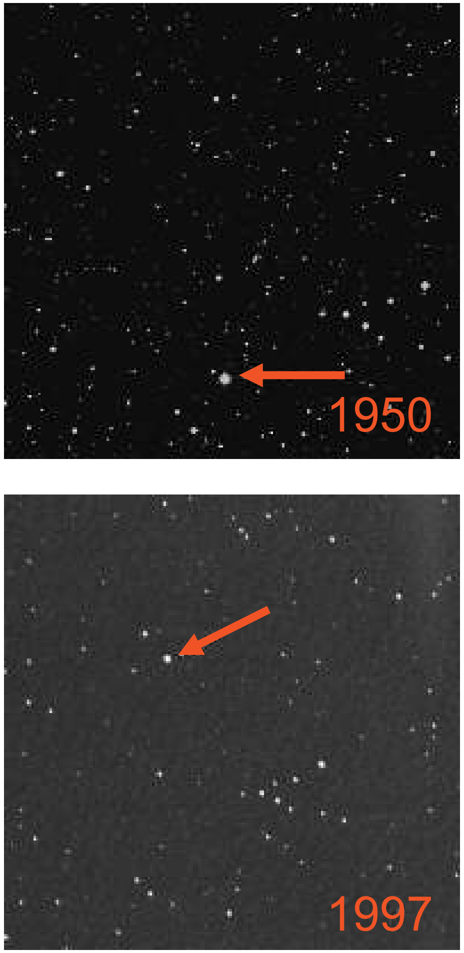
Stellar Parallax

- Basic principles of observing parallax
  - The Earth moves
  - The stars don't move
  - Some stars are nearer than other
  - (Some) astronomers are patient



Stellar Proper Motion

- Basic principles of observing proper motion
  - The stars move
  - The Earth doesn’t
  - Some stars are nearer than other
  - (Some) astronomers are **really** patient



Barnard’s Star

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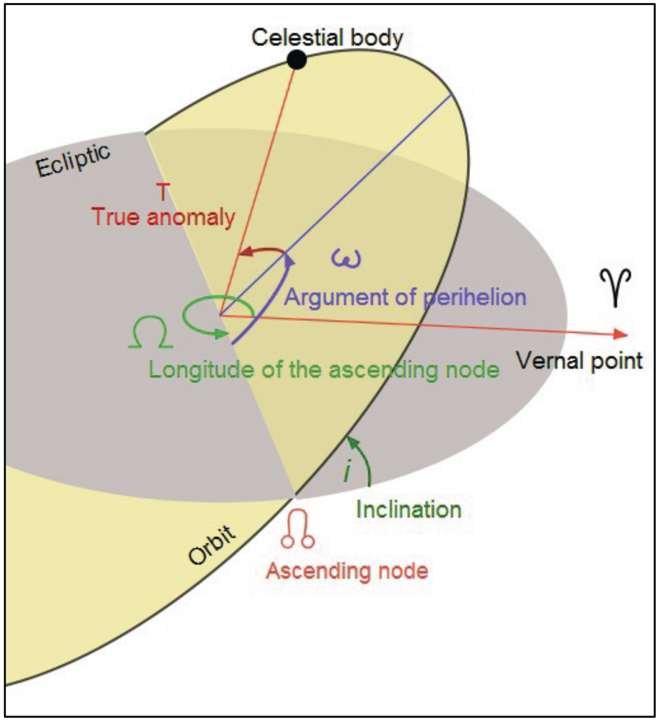
Astrometric Solutions

- Five terms
  - Position (α,δ), parallax (π), proper motion ($\Delta\alpha$, $\Delta\delta$)
- Looking for a planet or other companion?
  - 7 Keplerian orbital terms (i, Ω, ω, e, a, M_0, T_0)
- Keep in mind that at least N>12 independent data points needed to solve for orbits
  - Potentially additional terms (eg. RV) as well



Limits of Astrometry

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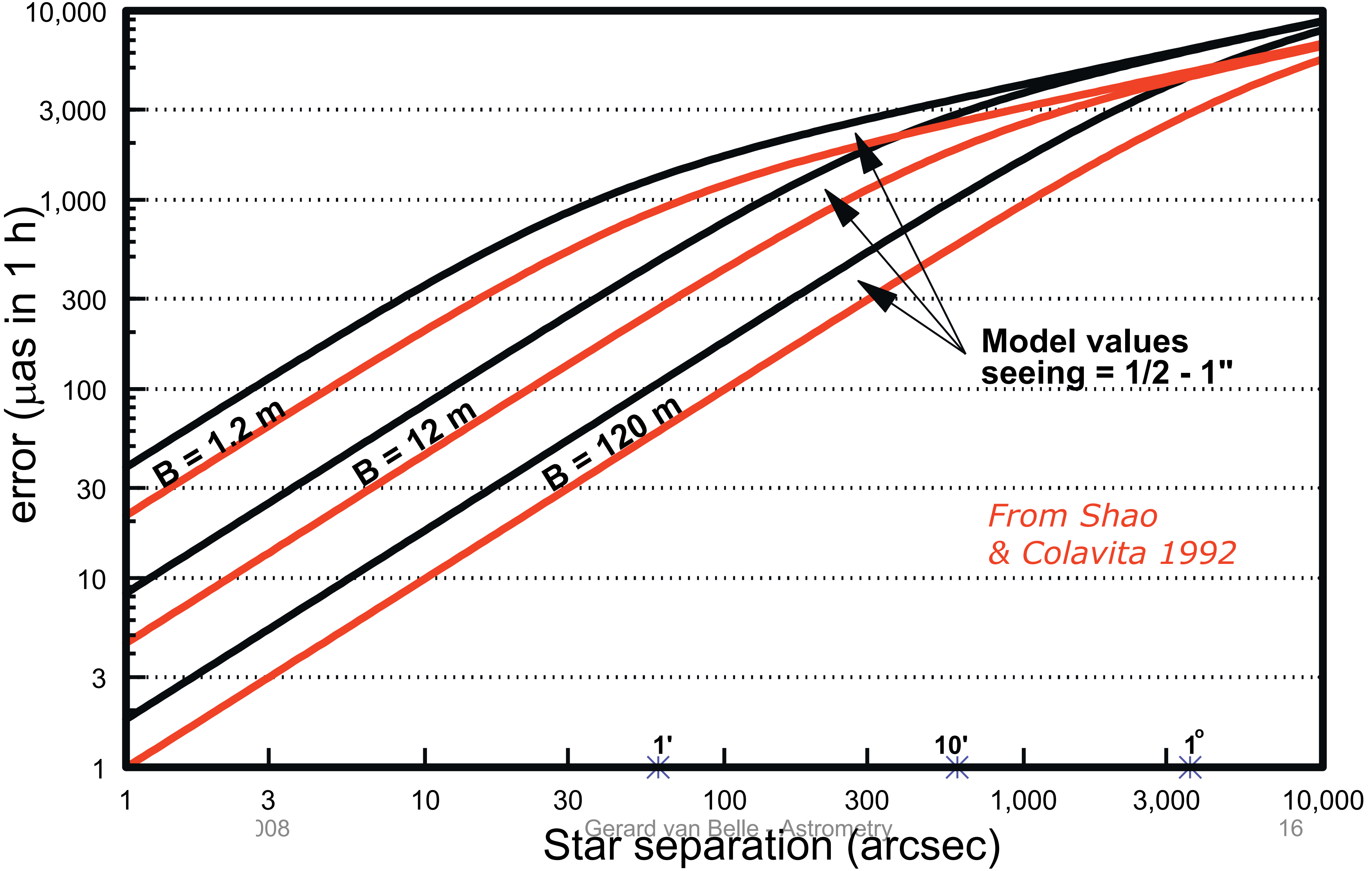
"The Universe and Man" - Camille Flammarion, 1888

Atmospheric limits to a narrow-angle measurement



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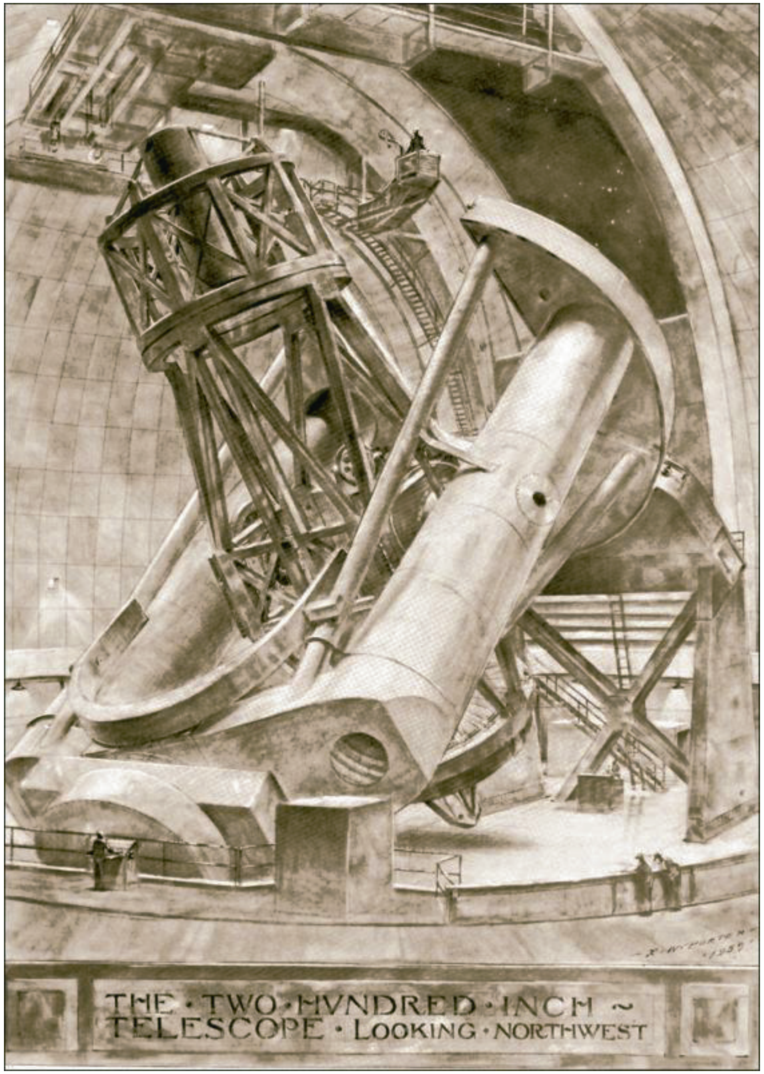
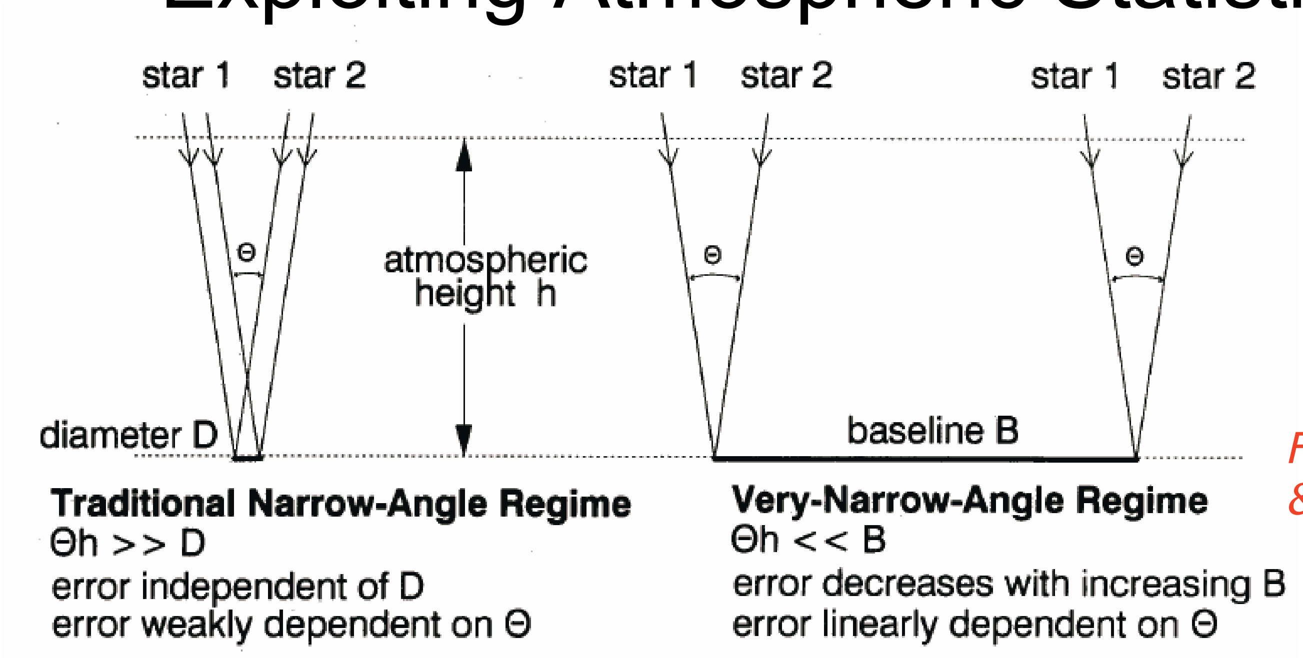
Single-Aperture Astrometry

- Recent results from VLT (Lazorenko et al 2007)
  - 200-300µas per measurement for stars B=18-19
  - Limit of 30-40µas per hour?
- Palomar (Cameron, Britton & Kulkarni 2008)
  - Imaging behind an AO system
  - <100µas in 2^{min}
  - Accurate to 100µas with $\Delta t=2^{\text{months}}$



Long-Baseline Astrometry: Exploiting Atmospheric Statistics



From Shao & Colavita 1992

- Single-aperture versus long-baseline interferometry
  - Operational regime of LBI superior to single-aperture: bigger is better
- Atmospheric Noise Dominated By Low-Frequency Component
- Longer-Baselines Increase the *Correlation* of Atmospheric Turbulence
- This Correlation is What We Exploit Differentially

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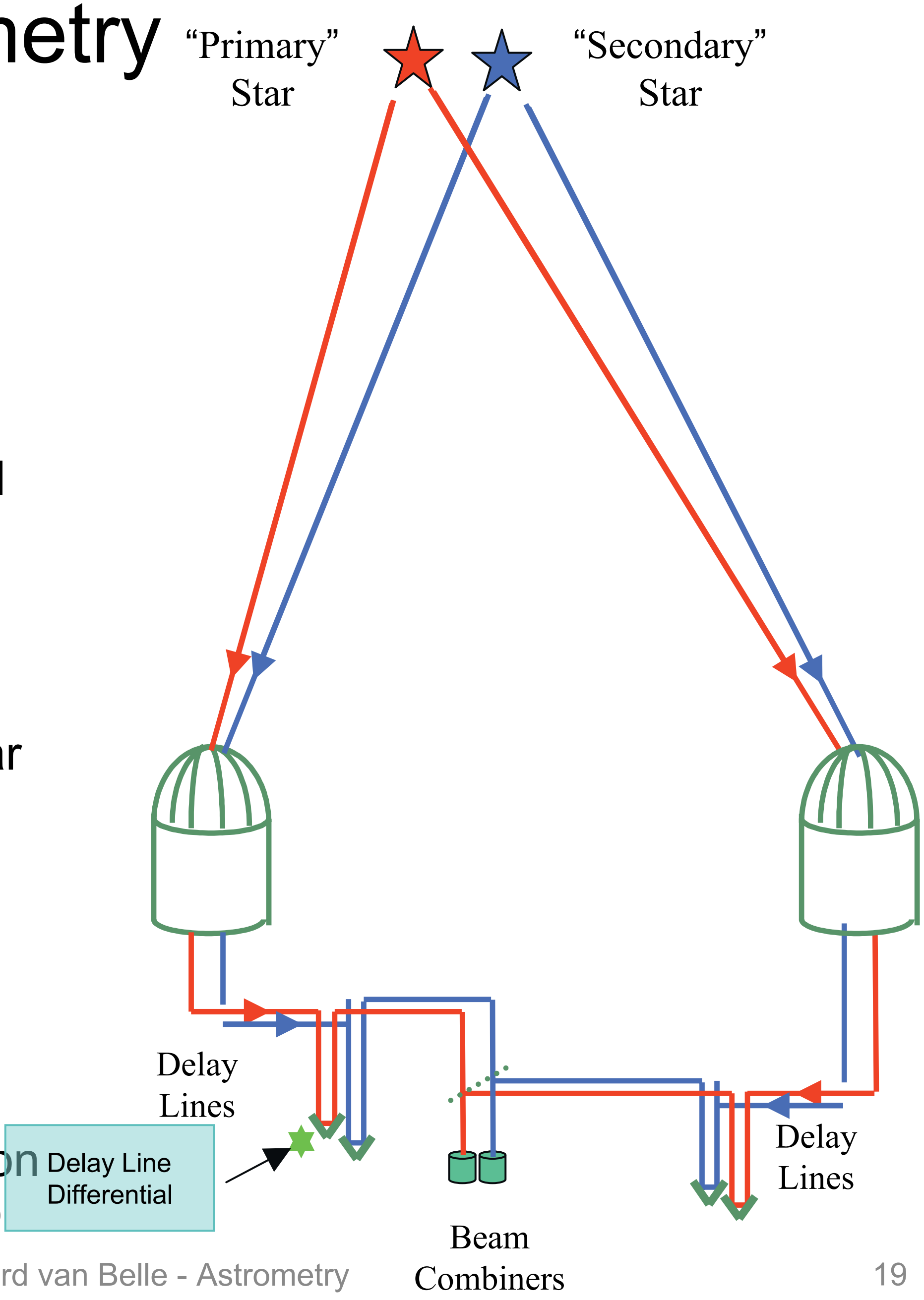
Dual Star Astrometry

Objective: ground-based astrometric detection of exo-planets

~ 10 - 50 μas @ VLTI

- Primary star
  - Used to phase individual apertures
  - Used to co-phase the interferometer
- Secondary star
  - Used as positional reference for primary star
- Delay line difference
  - Observable proxy for angular separation between stars
  - Angular separation reflects periodic reflex motion of stars due to planetary companions
- For exo-planet reflex detection
  - 10s of μas ($O(10^{-11}$ rad))



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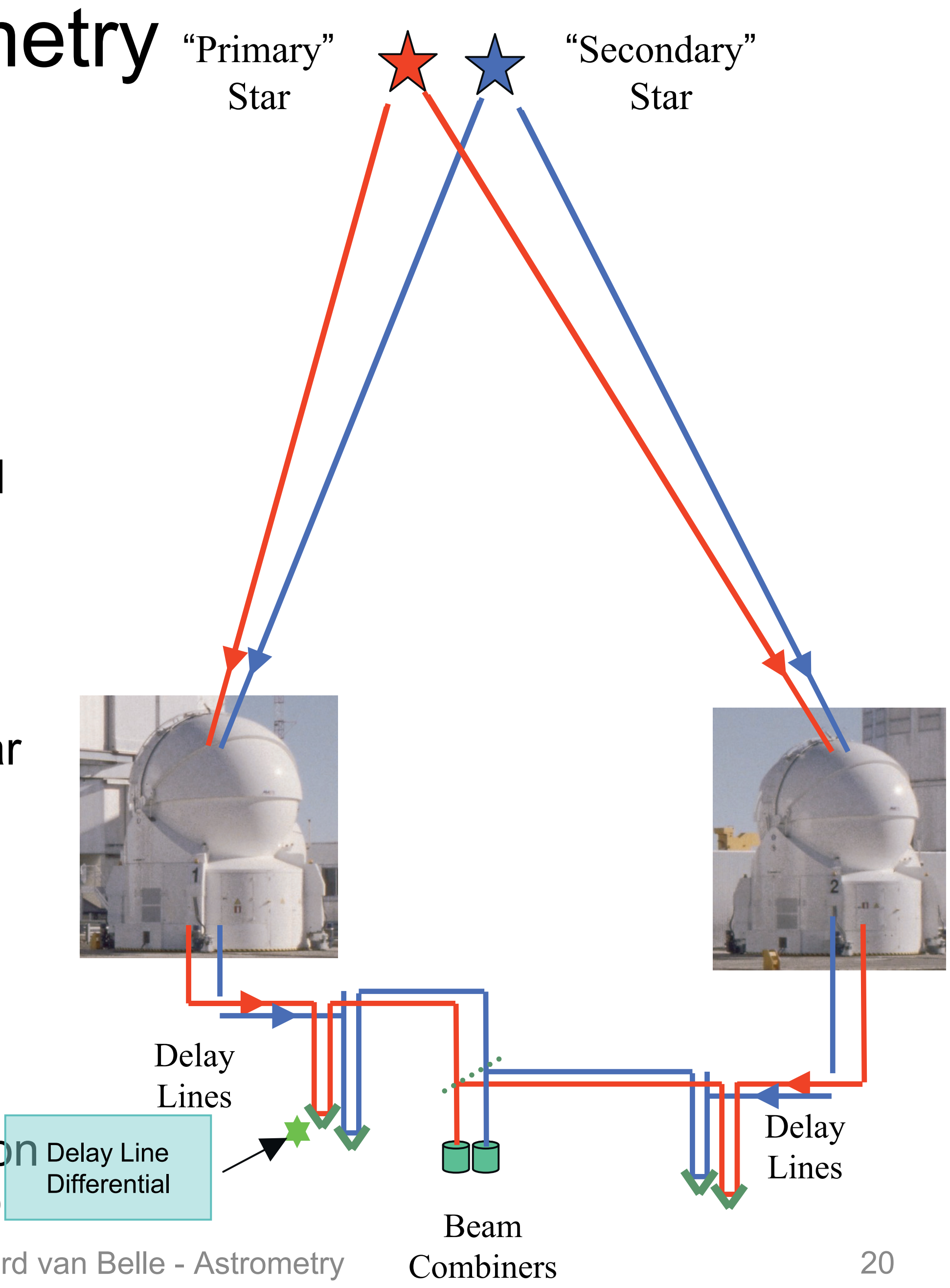

Differential Interferometric Astrometry

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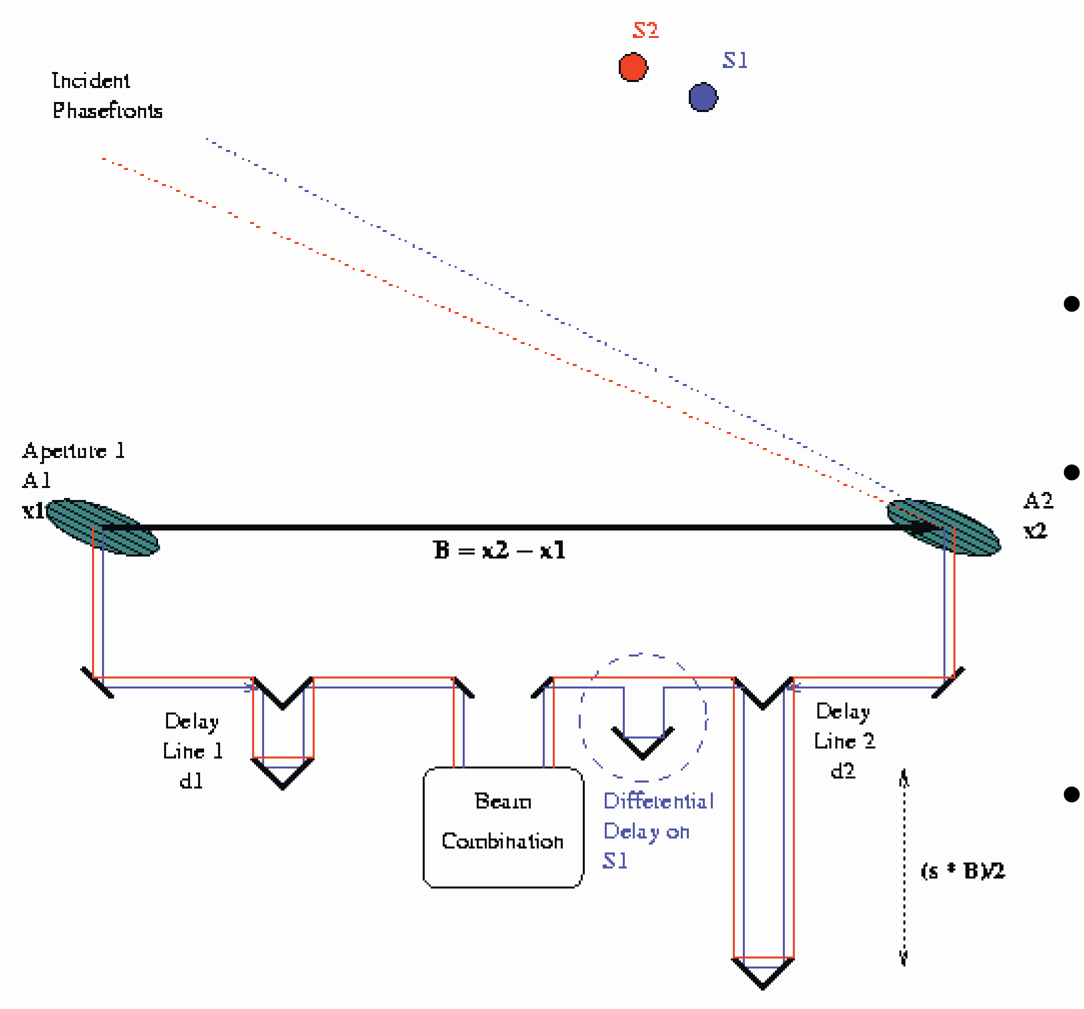

- Two Simultaneous Beam Combiners, Independently Tracking Two Stellar Sources
- Differential Delay Mechanism
- Metrology In Each Interferometer Measuring the Relative Delay
- Relative Delay Difference is the Observable

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Differential Interferometric Astrometry II.

$$d_2 - d_1 = (\hat{s}_2 \bullet \underline{B} + C_2) - (\hat{s}_1 \bullet \underline{B} + C_1)$$

$$= (\hat{s}_2 - \hat{s}_1) \bullet \underline{B} + (C_2 - C_1)$$

$$\Delta d = \underline{\Delta s} \bullet \underline{B} + \Delta C$$

- Delay Difference (Δd) is Observable Proxy for Sky Separation (<u>Δs</u>)
- Differential Delay Contains Instrumental Signature (ΔC) That Must Be Calibrated

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Interferometric Tolerances for Differential Astrometry

$$\Delta s \approx \frac{\Delta d}{B}$$

$$\delta\Delta s \approx \frac{\delta\Delta d}{B} + \frac{\Delta d}{B^2}\delta B = \frac{\delta\Delta d}{B} + \Delta s\,\frac{\delta B}{B}$$

Homework: calculate delay and baseline knowledge requirements for a 1 μas relative measurement over a 1 deg field with SIM

- $\sigma_d \sim \sigma_s * B$; $\sigma_B / B \sim \sigma_s / s$
- Take B ~ 100 m, Δs ~ 20” (10^{-4} rad)
- To Make a 10 μas ($5*10^{-11}$ rad) measurement:
  - Must measure Δd to ~ $2.5*10^{-9}$ m (2.5 nm)
  - Must measure B to 2.5 parts in 10^7 (25 μm)

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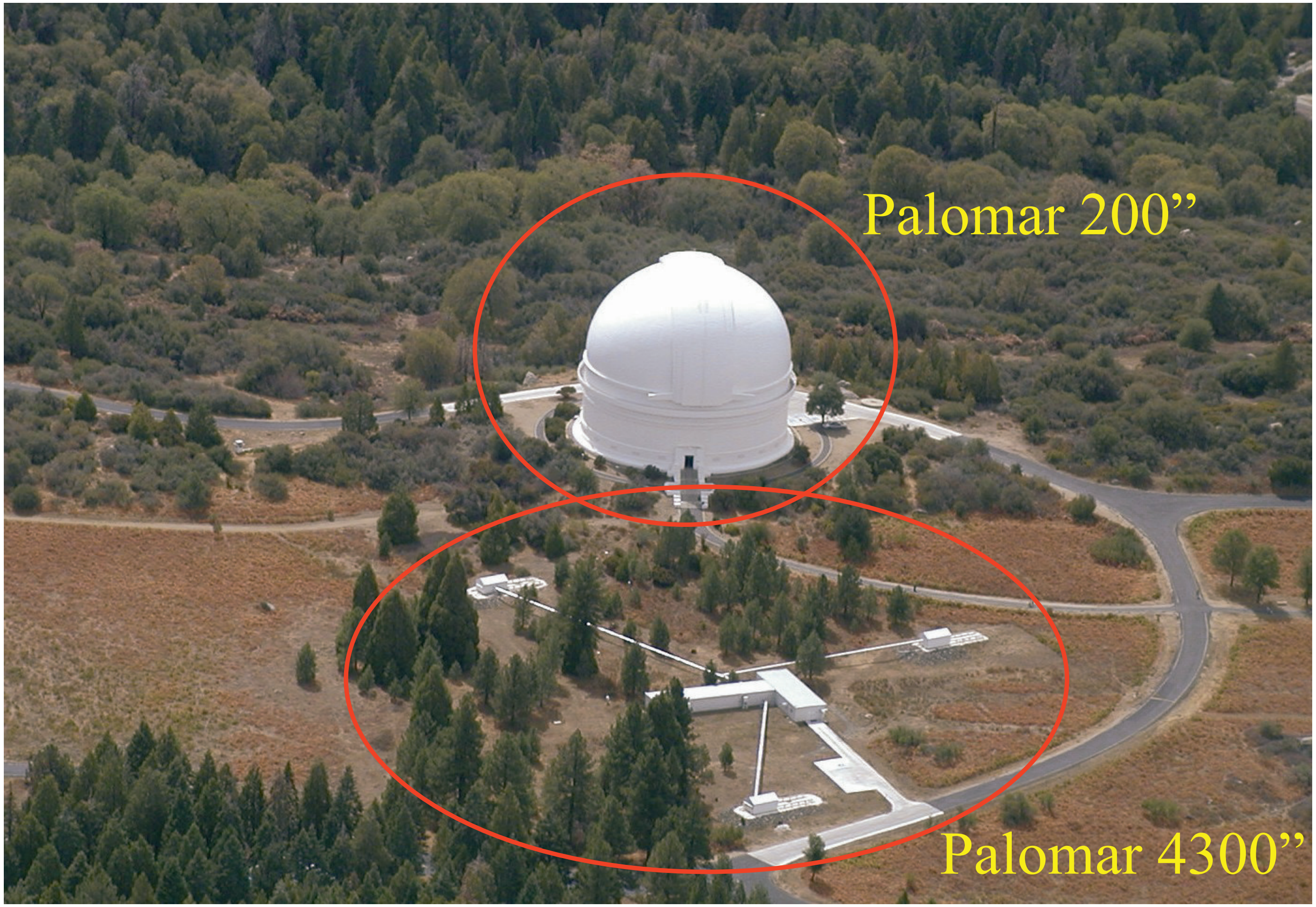
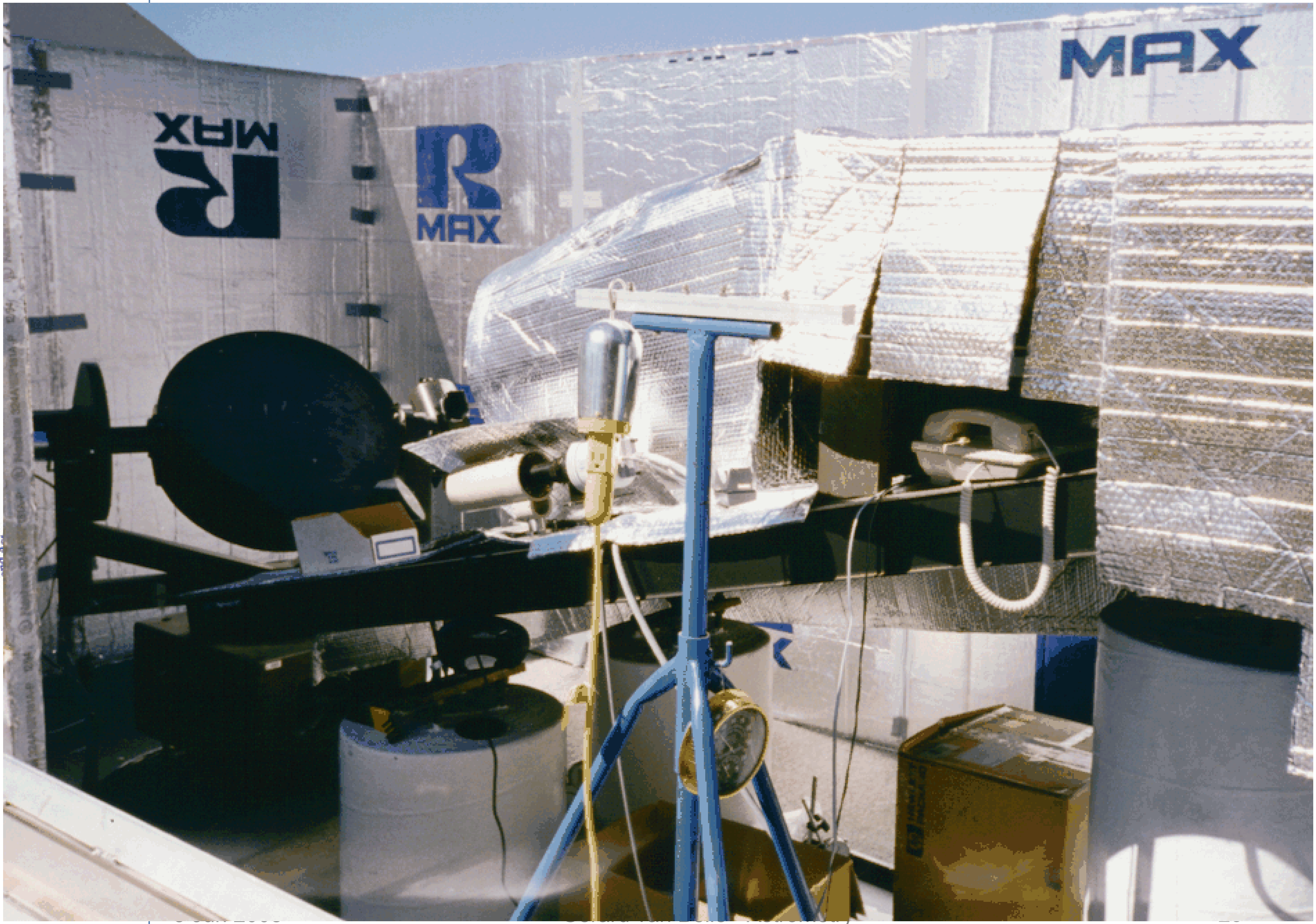
Dual Star Demo: Palomar Testbed Interferometer





MAX
R MAX
R MAX
MAX

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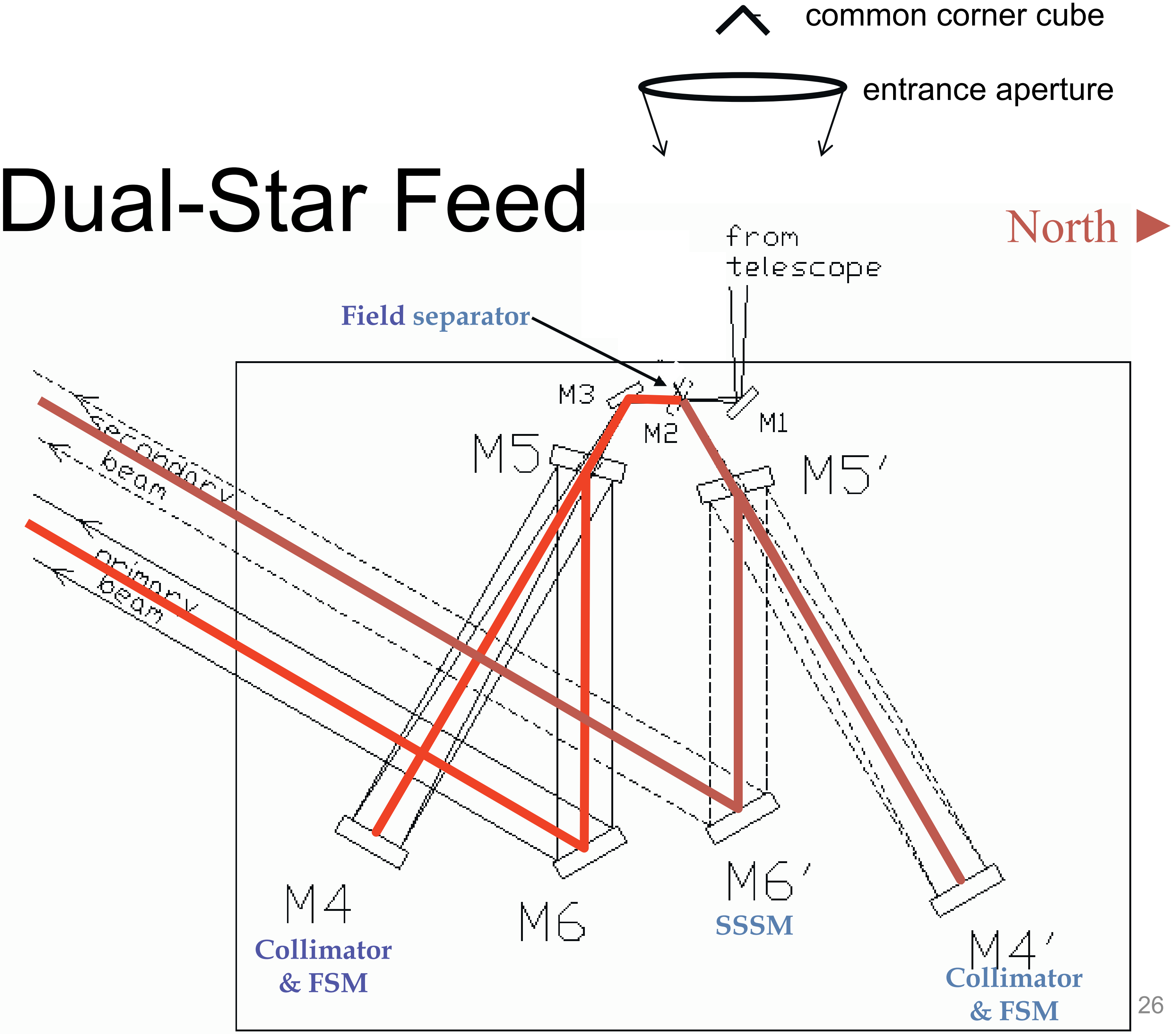
Dual-Star Feed



common corner cube

entrance aperture

North ▶

Field separator

Collimator & FSM

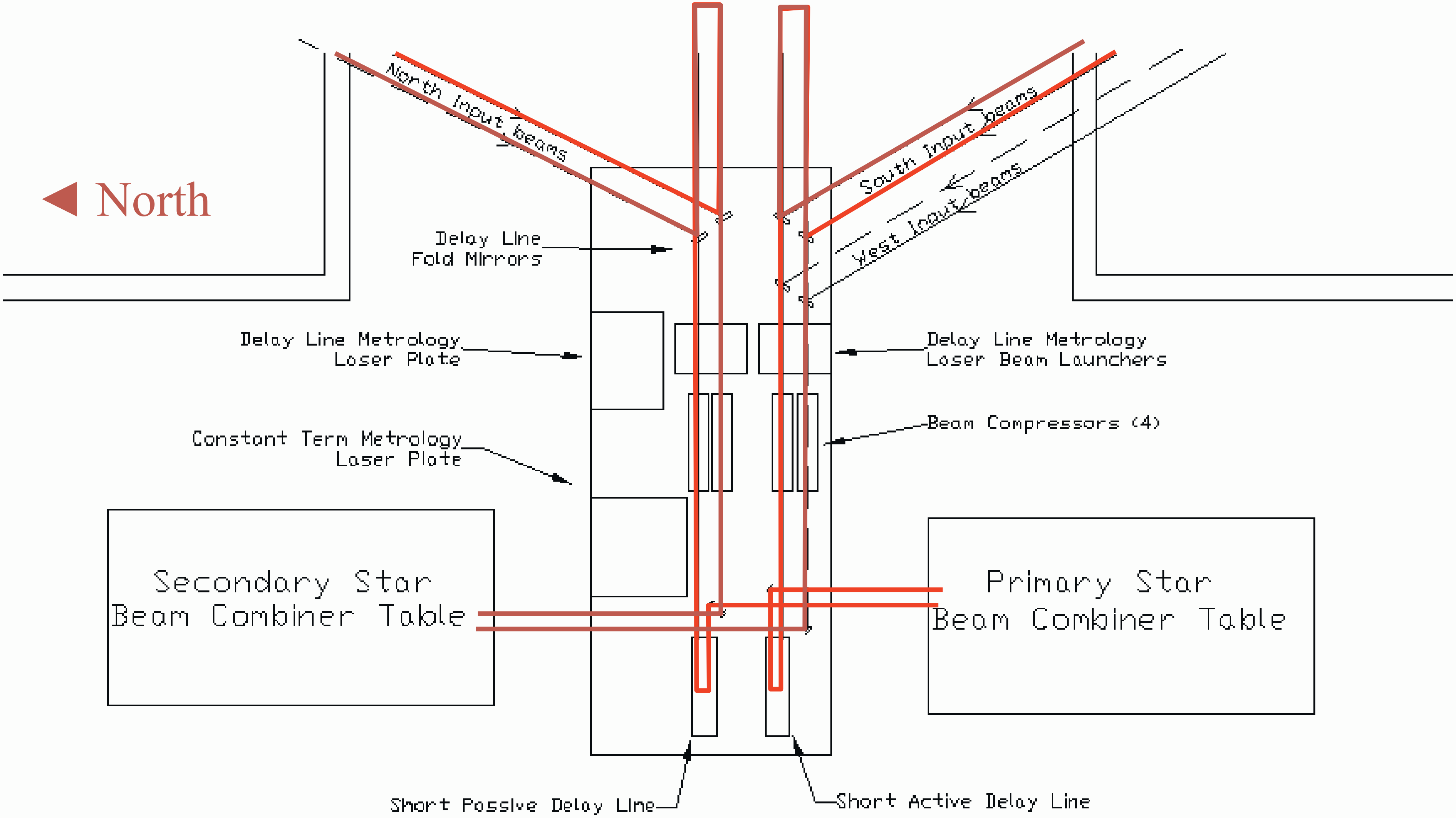
SSSM

Collimator & FSM

Delay Lines

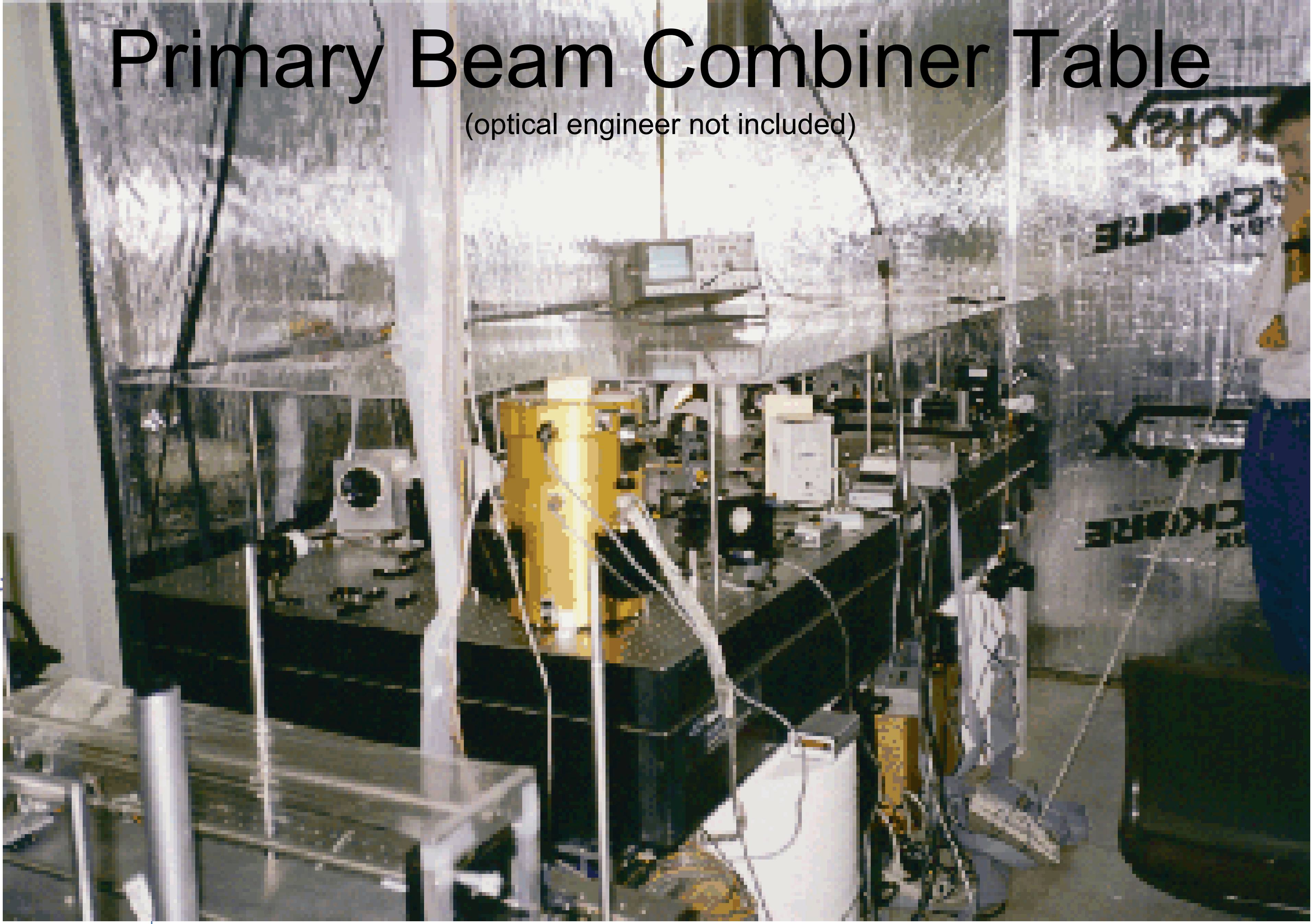

Thermax BLACKORE Celotex
Thermax BLACKORE Celotex
Thermax BLACKORE Celotex
Therm BLA C
Therm
herm AA

Central Optics

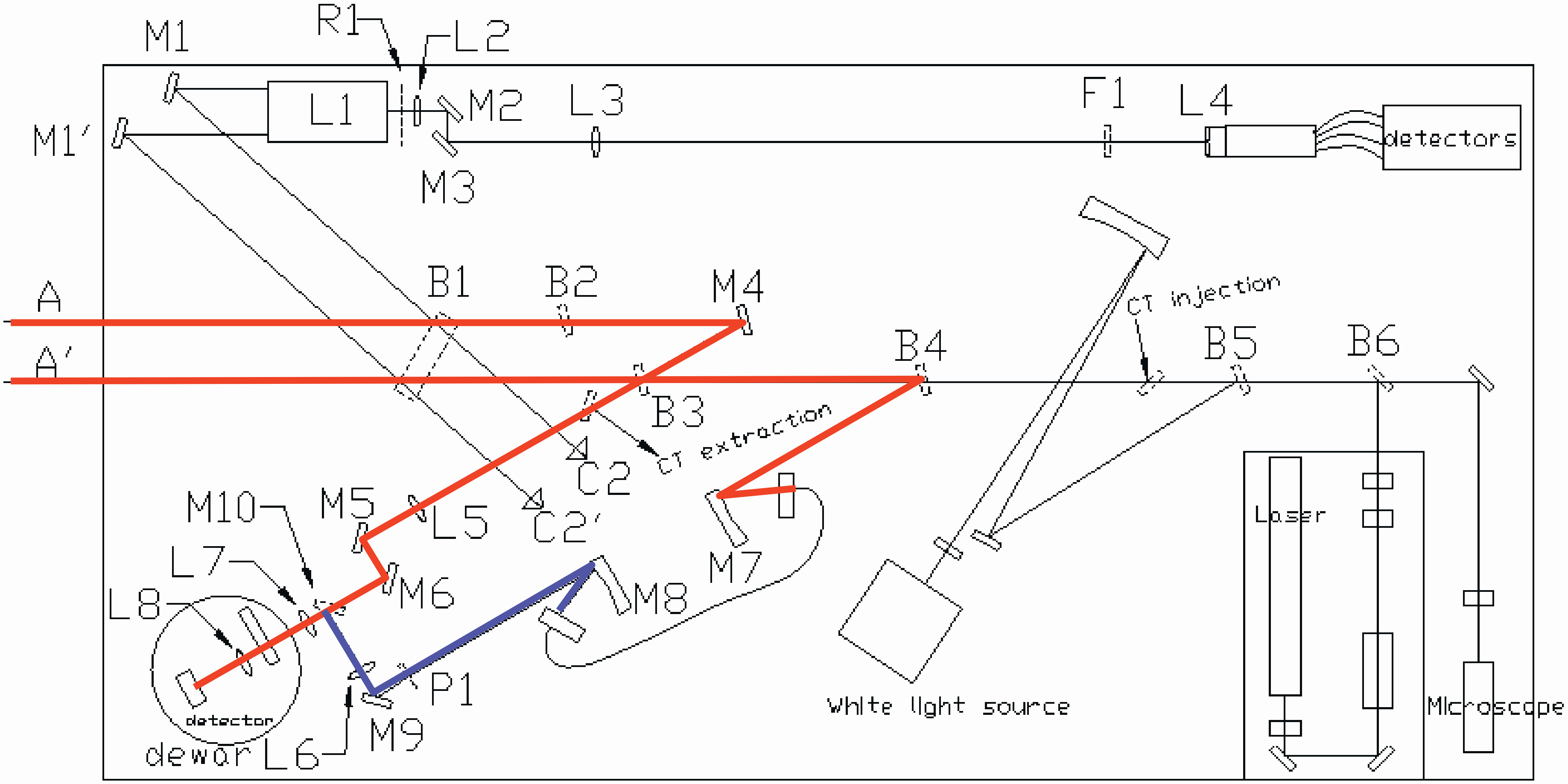


Primary Beam Combiner Table

(optical engineer not included)



Fringe Tracker Optics



Constant-Term Metrology

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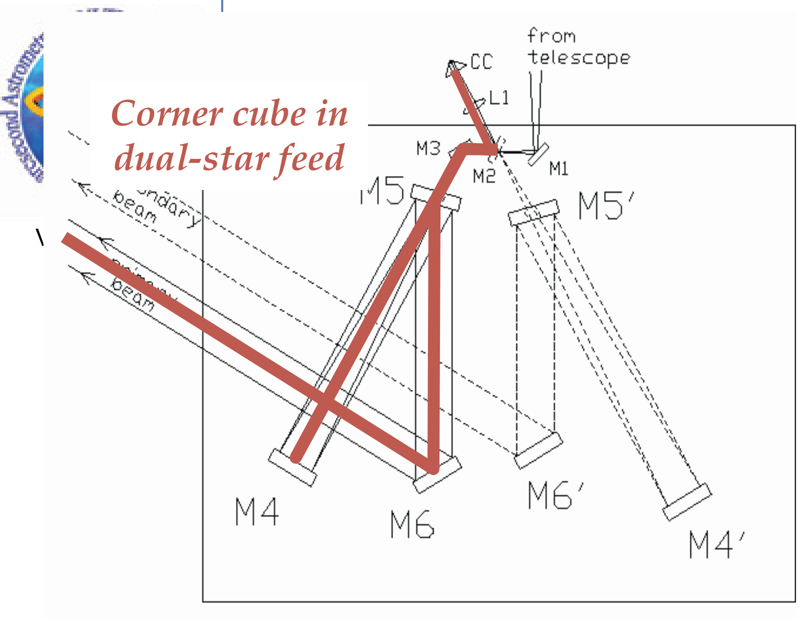
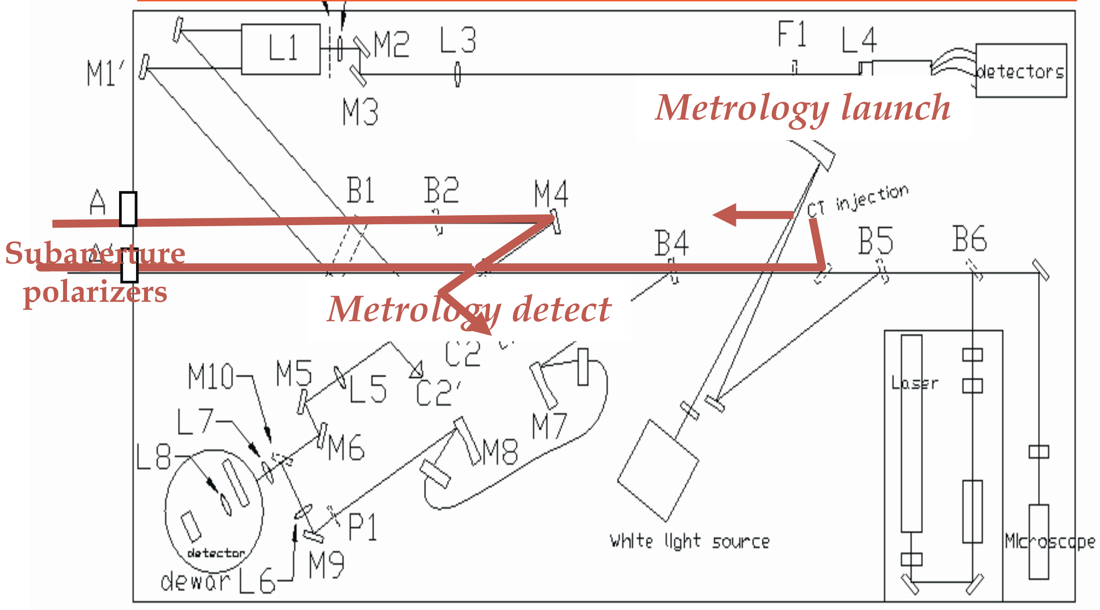
- Measures difference in optical path between the two arms for each beam combiner
  - Difference in metrology measurements between the beam combiners, plus fringe phase, gives star separation
- Heterodyne metrology starting at main beamsplitter to corner cubes at the dual star feed
  - Subaperture polarizers send and *s* and *p* polarizations to different arms
  - Heterodyne at separate carriers to avoid interference between primary and secondary metrology systems

$$\Delta d \equiv d_2' - d_1' = (d_2 - d_1) + (OPD_2 - OPD_1)$$


Corner cube in dual-star feed


Metrology launch

Subaperture polarizers

Metrology detect

Astrometry Systematics Error Budget

			nm per arm	**nm total**	**uas total**	
unmodeled pivot noise	25.0	um	1.9	2.7	5.5	
pivot beacon to pivot transfer	25.0	um	1.9	2.7	5.5	
DSM CC to beacon transfer	25.0	um	1.9	2.7	5.5	
baseline solution	35.0	um		2.6	5.4	
DCR					5.0	
beamwalk of secondary over field			2.5	3.5	7.3	
alignment of metrology to starlight	0.5	arc sec	1.8	2.5	5.2	
alignment drift	0.5	arc sec	1.8	2.5	5.2	
metrology stability	1.00E-08	fractional	0.1	0.1	0.2	
metrology polarizer mount gradient	0.04	K	2.0	2.8	5.8	
fringe-measurement accuracy	0.005	rads	1.8	2.5	5.1	
beamwalk stability in propagation	1.5	mm	2.3	3.2	6.6	
				TOTAL:	**18.8**	**uas**

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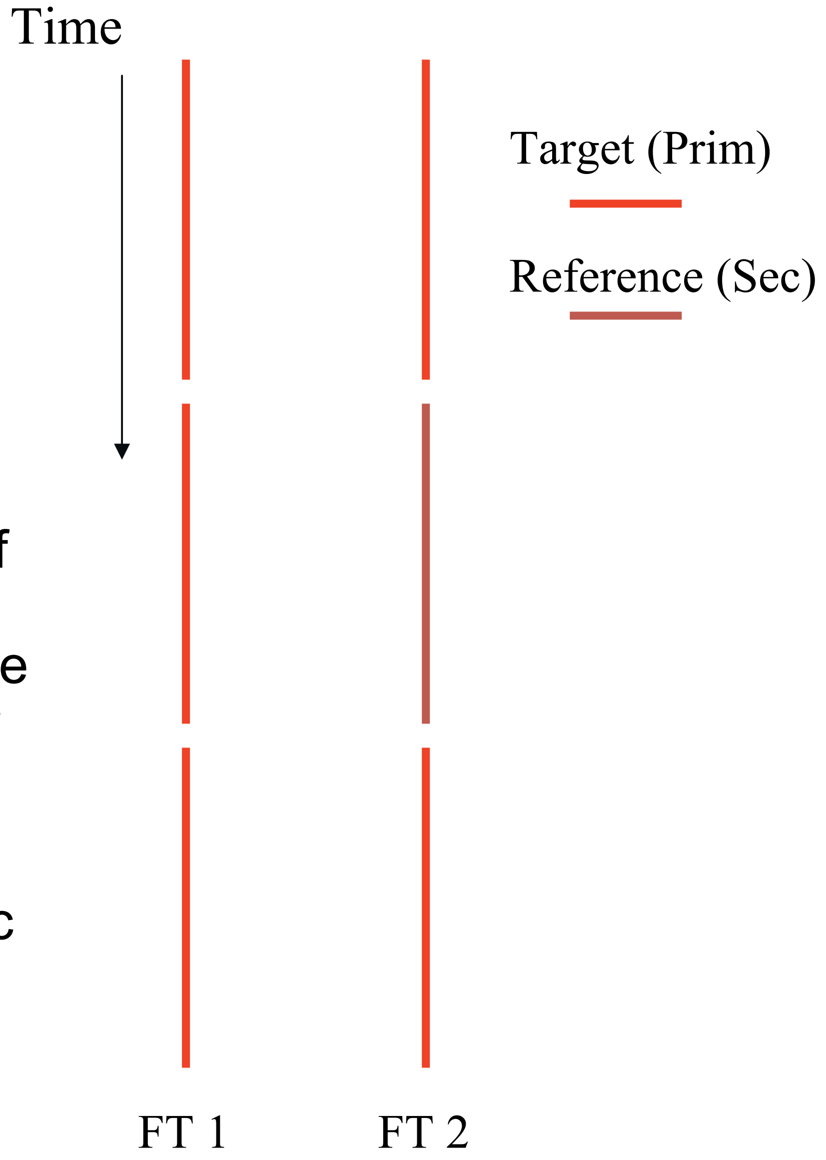
Bias Term Calibration Observing Sequence

$$\Delta d = \underline{\Delta s} \bullet \underline{B} + \Delta C$$

- Two Separate Interferometers >> Two Separate Bias Terms
- Simultaneous Measurement of the Same Star with Both Interferometers Yields Estimate of Relative Bias Difference ΔC
- Accomplished by “Astrometric Chop” Sequences (Astrometric Triplets)



One Night's Astrometric Data

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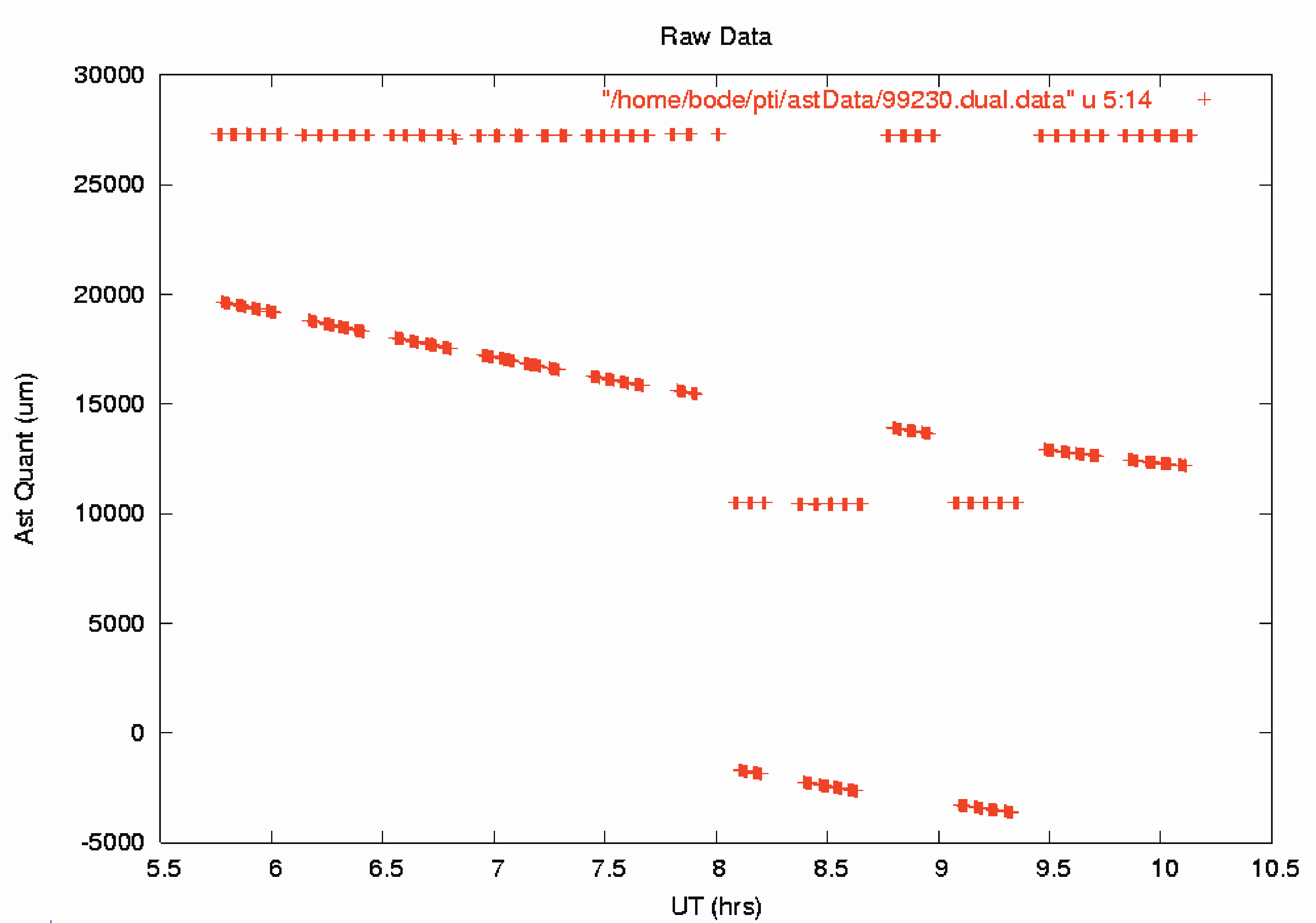

Bias Calibration – Example

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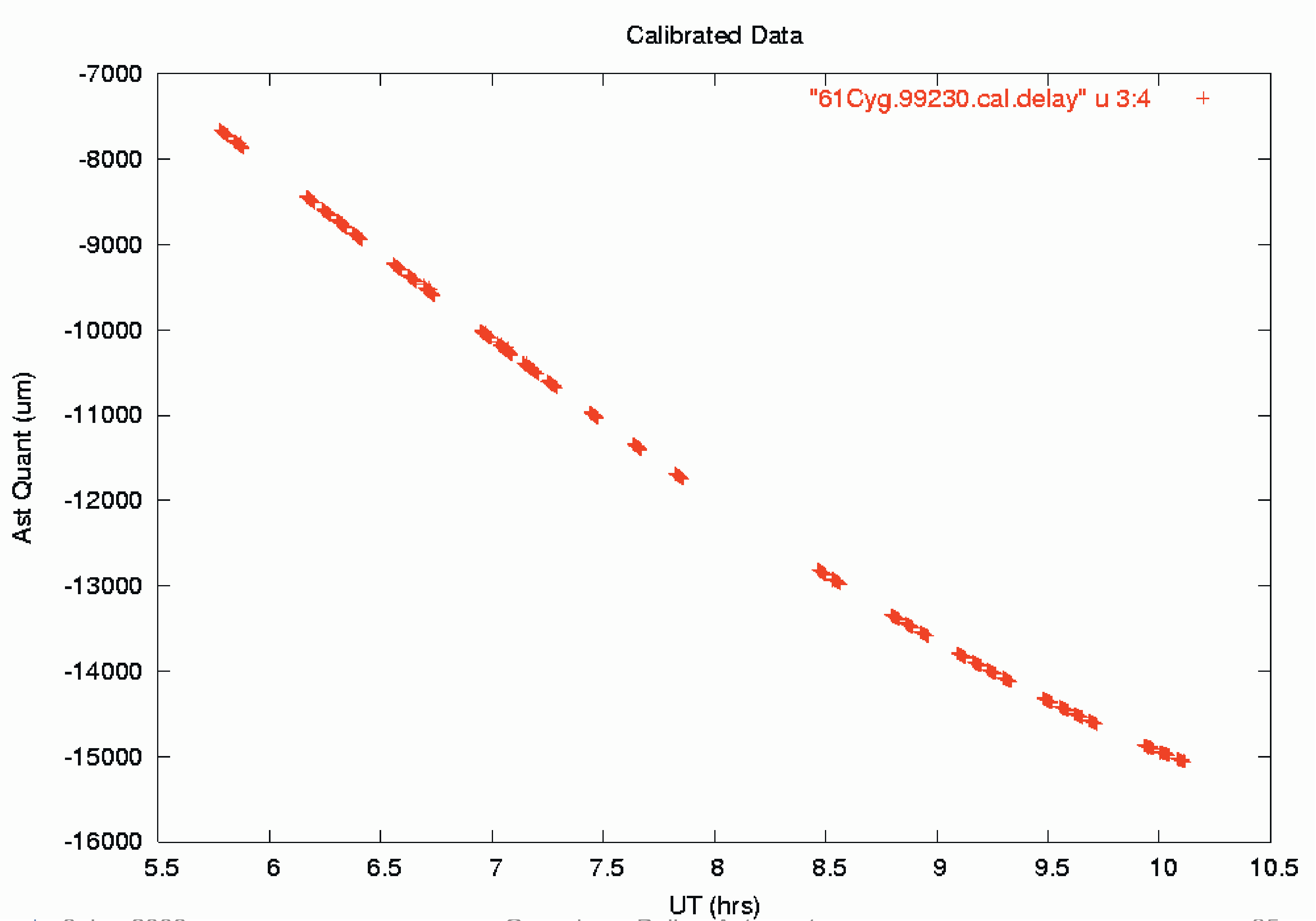

Bias Calibration – Example

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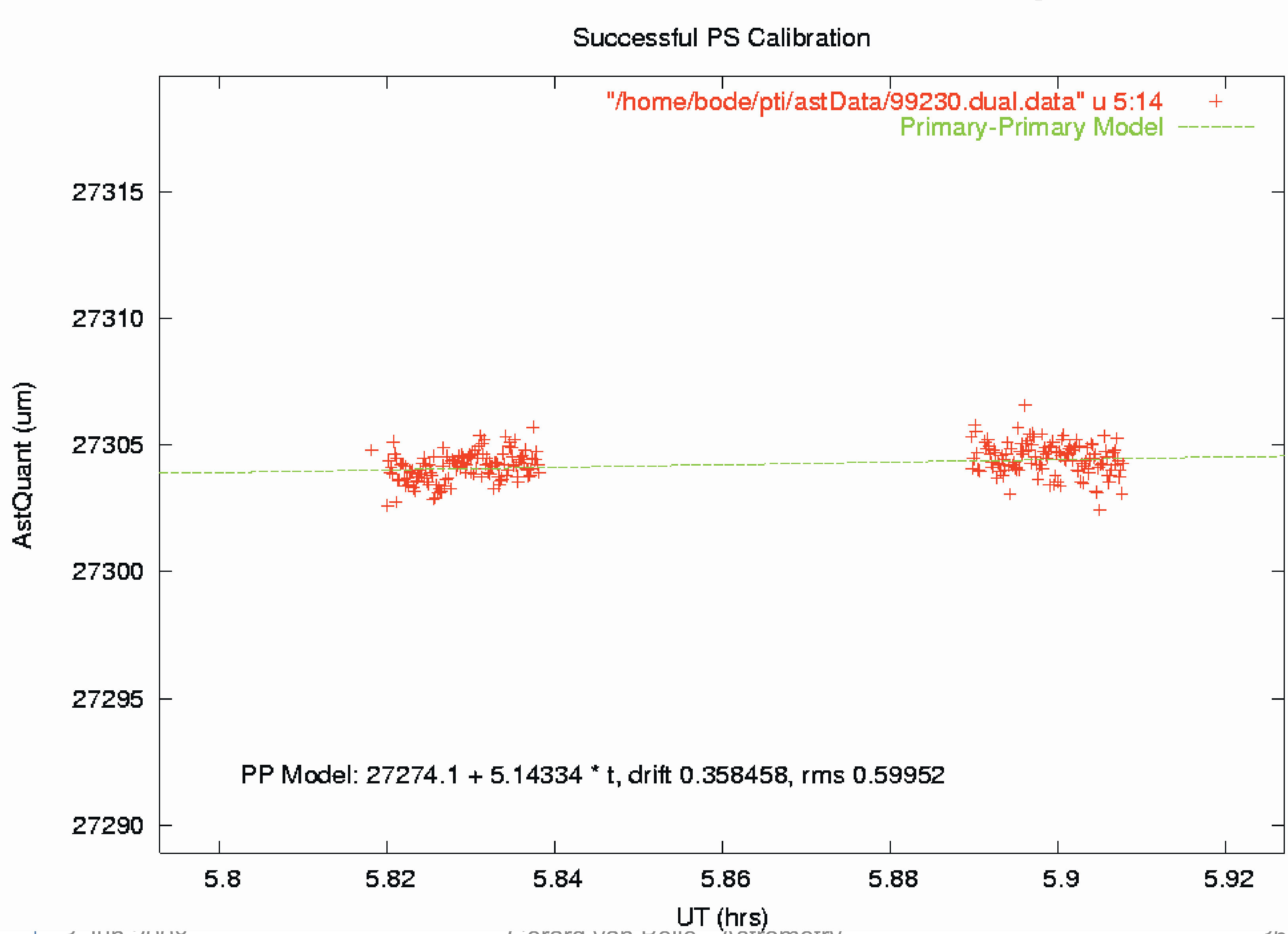

Bias Calibration – Example

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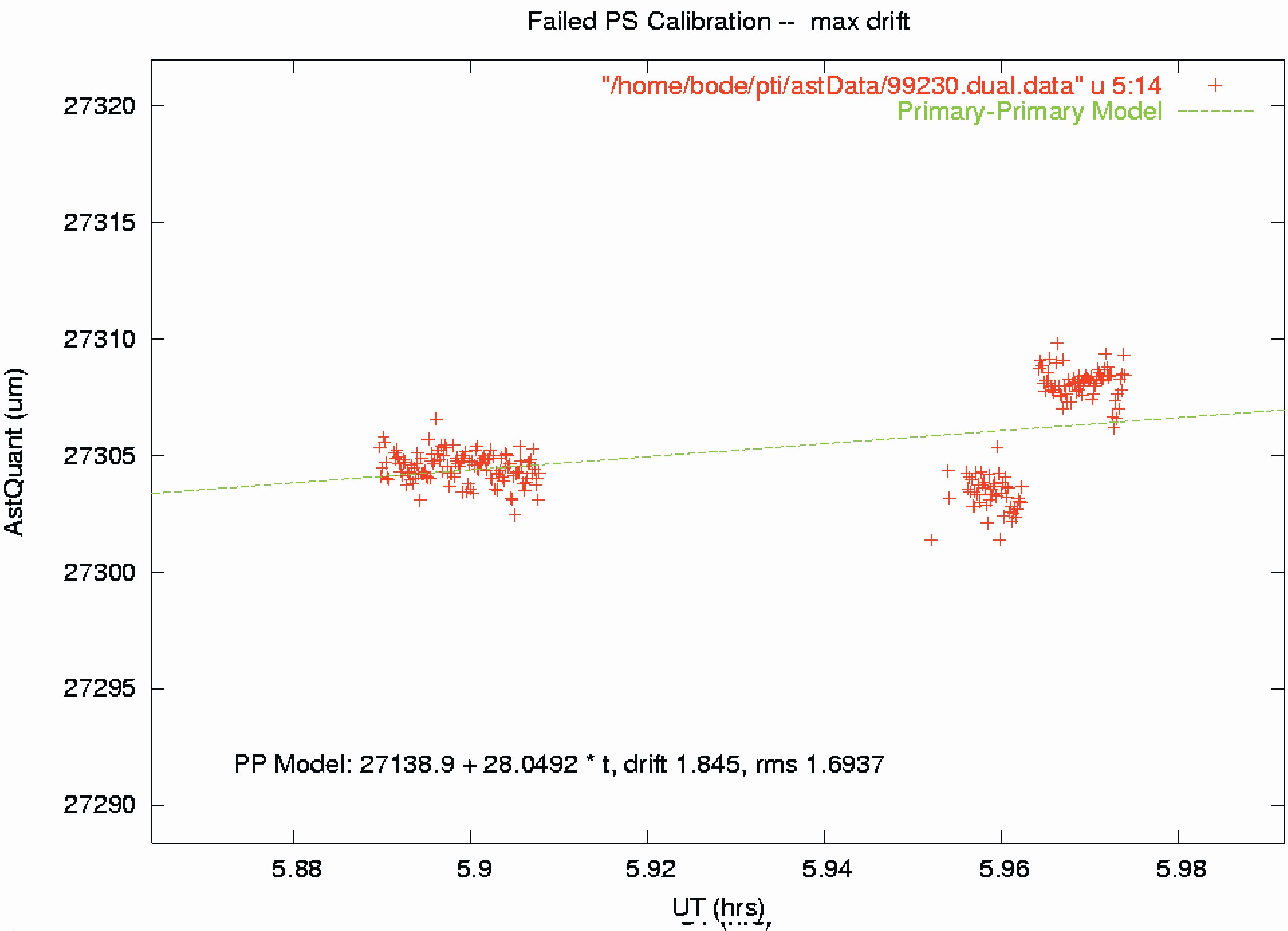

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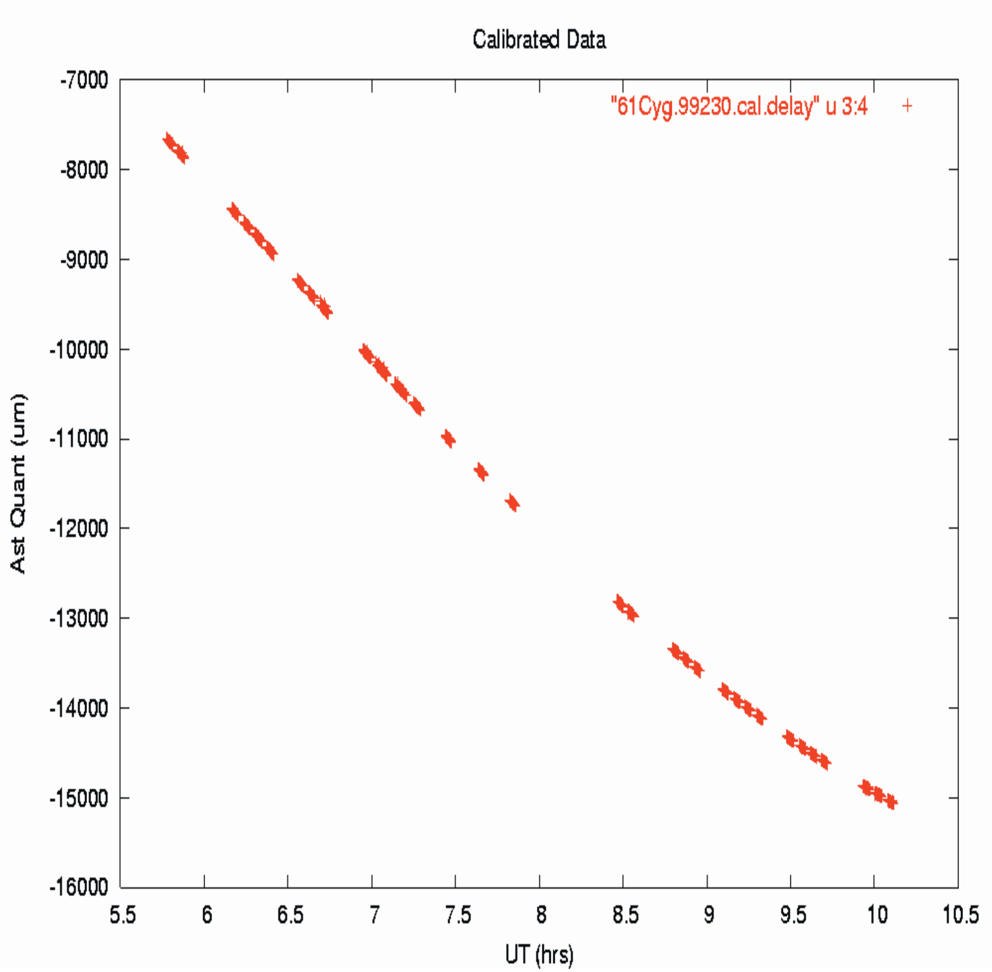
L-2 Processing: Separation Estimation

- Having Calibrated and Removed the Differential Bias Term, One is Left With:

$$\Delta d = \underline{\Delta s} \bullet \underline{B}$$

- If we Know $\underline{B}$, Estimating $\underline{\Delta s}$ is Straightforward...



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(External) Baseline Knowledge

- O(25 μm) Baseline Knowledge Requirement
- Canonical Model: Observations of Known (e.g. Hipparcos) Stars Over a Wide (~ 1 rad) Angle
- Again Delay is the Observable:

$$d_i = \hat{s}_i(t) \bullet \underline{B} + C$$

$$\begin{pmatrix} d_i \\ . \\ . \\ d_n \end{pmatrix} = \begin{pmatrix} s_{i-x} s_{i-y} s_{i-z} 1 \\ . \\ . \\ s_{n-x} s_{n-y} s_{n-z} 1 \end{pmatrix} \bullet \begin{pmatrix} B_x \\ B_y \\ B_z \\ C \end{pmatrix}$$

- Problem is Linear if Star Positions are Known (Hipparcos)

“Typical” PTI Baseline Fit

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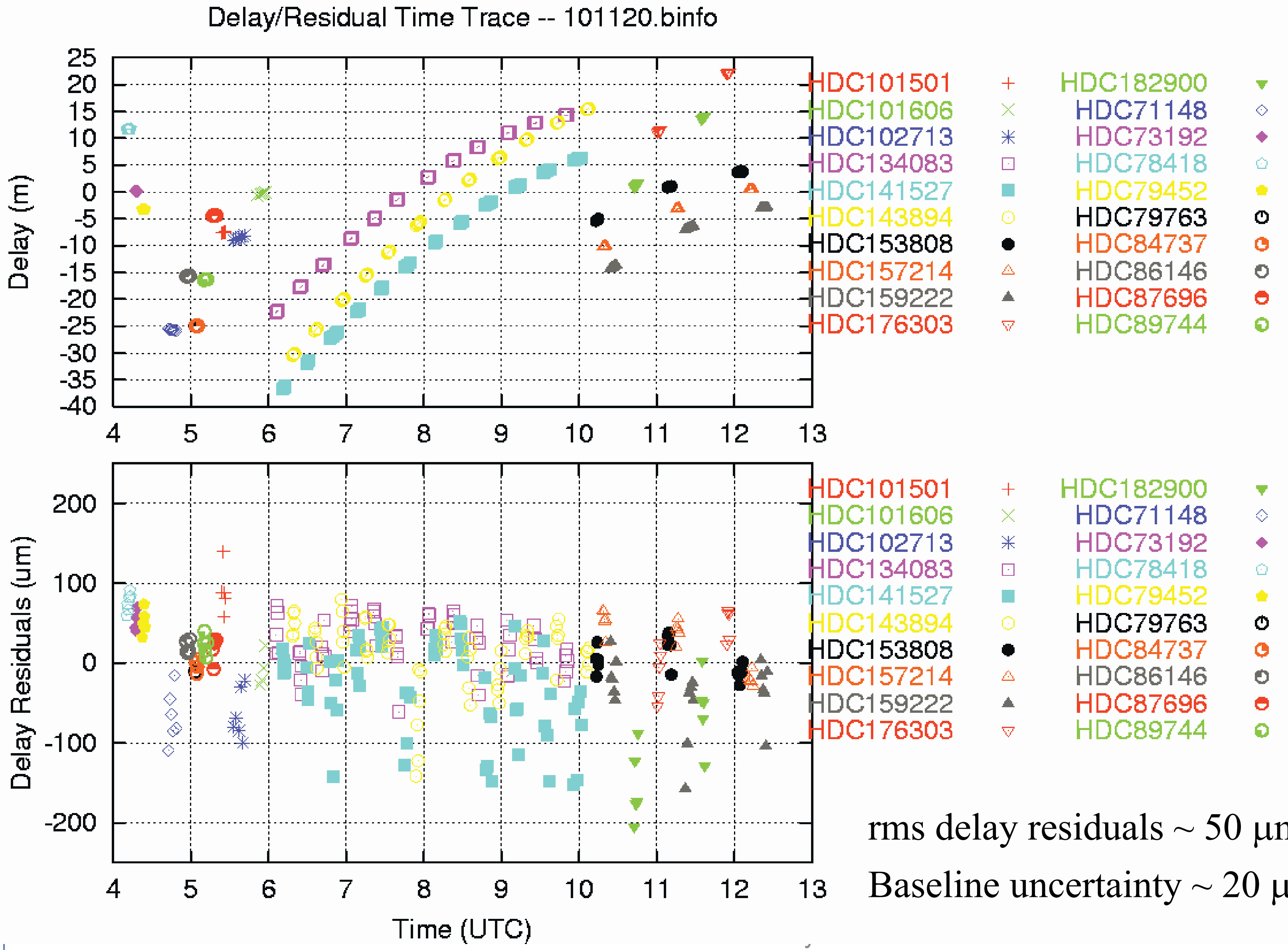

rms delay residuals ~ 50 µm

Baseline uncertainty ~ 20 µm

Astrometry Limits: Reference Stars

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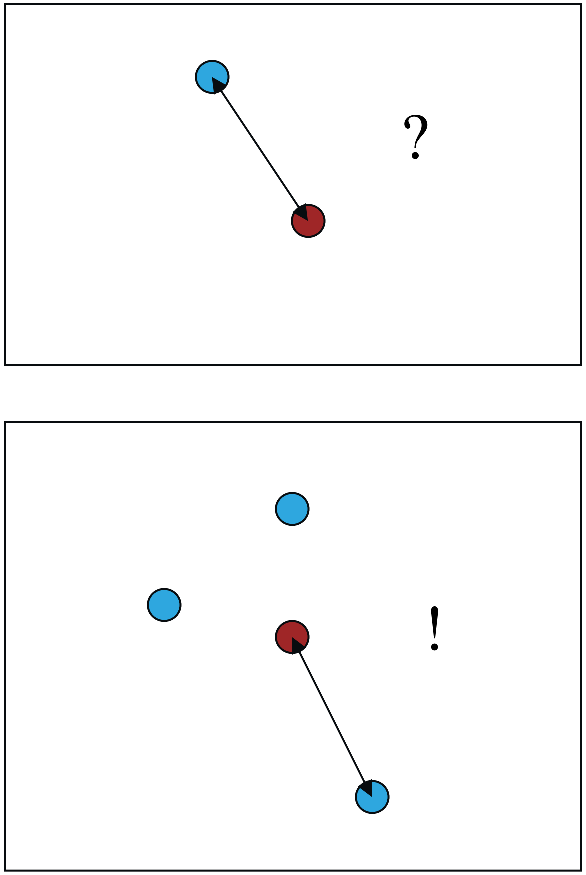
- If Target Exhibits Periodic Signal Against One Reference Star -- Unable to Determine Who is Doing the Wobbling
- With Two (Or More) Reference Objects, Target Motion Shows Up as Common Periodicity in Multiple Target-Reference Periodograms
  - Two+ reference star requirement limits number of targets on sky
    - Radial velocity vetting difficult for these objects
  - Eg. van Belle et al (1998) discusses need for 1.8-m telescopes → ~30-50% sky coverage at mean galactic latitudes
    - K5V @ 2kpc → m_K=16.0; 20 M_J companion → 65 μas wobble
- Other means of isolating reflex motion
  - Radial velocity



Experimental Verification

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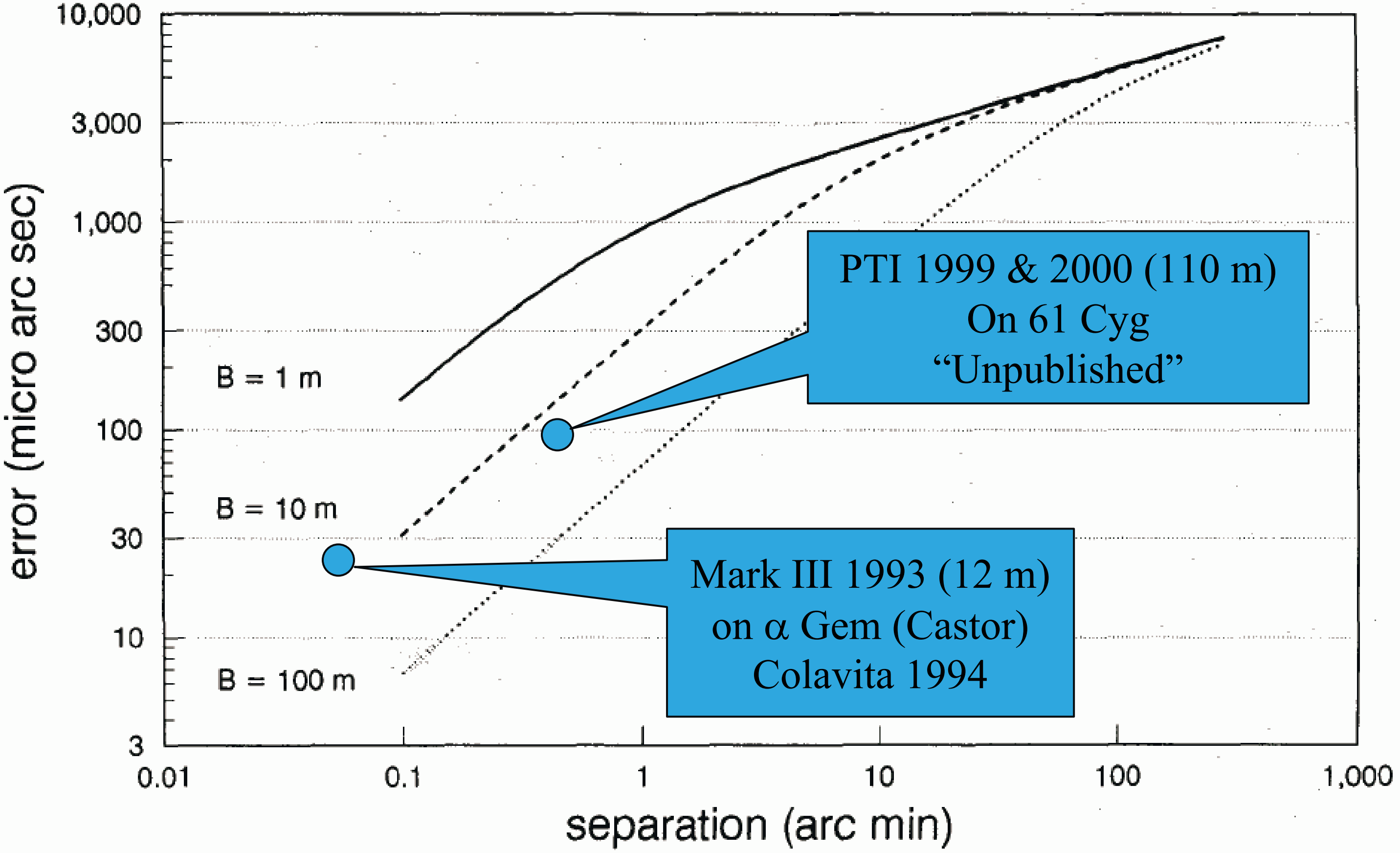

PTI 1999 & 2000 (110 m)
On 61 Cyg
“Unpublished”

Mark III 1993 (12 m)
on α Gem (Castor)
Colavita 1994

Fig. 2. Narrow- and very-narrow-angle astrometric error for several baseline lengths using measured Mauna Kea turbulence profiles and an integration time of 1 h

again, from Shao & Colavita 1992

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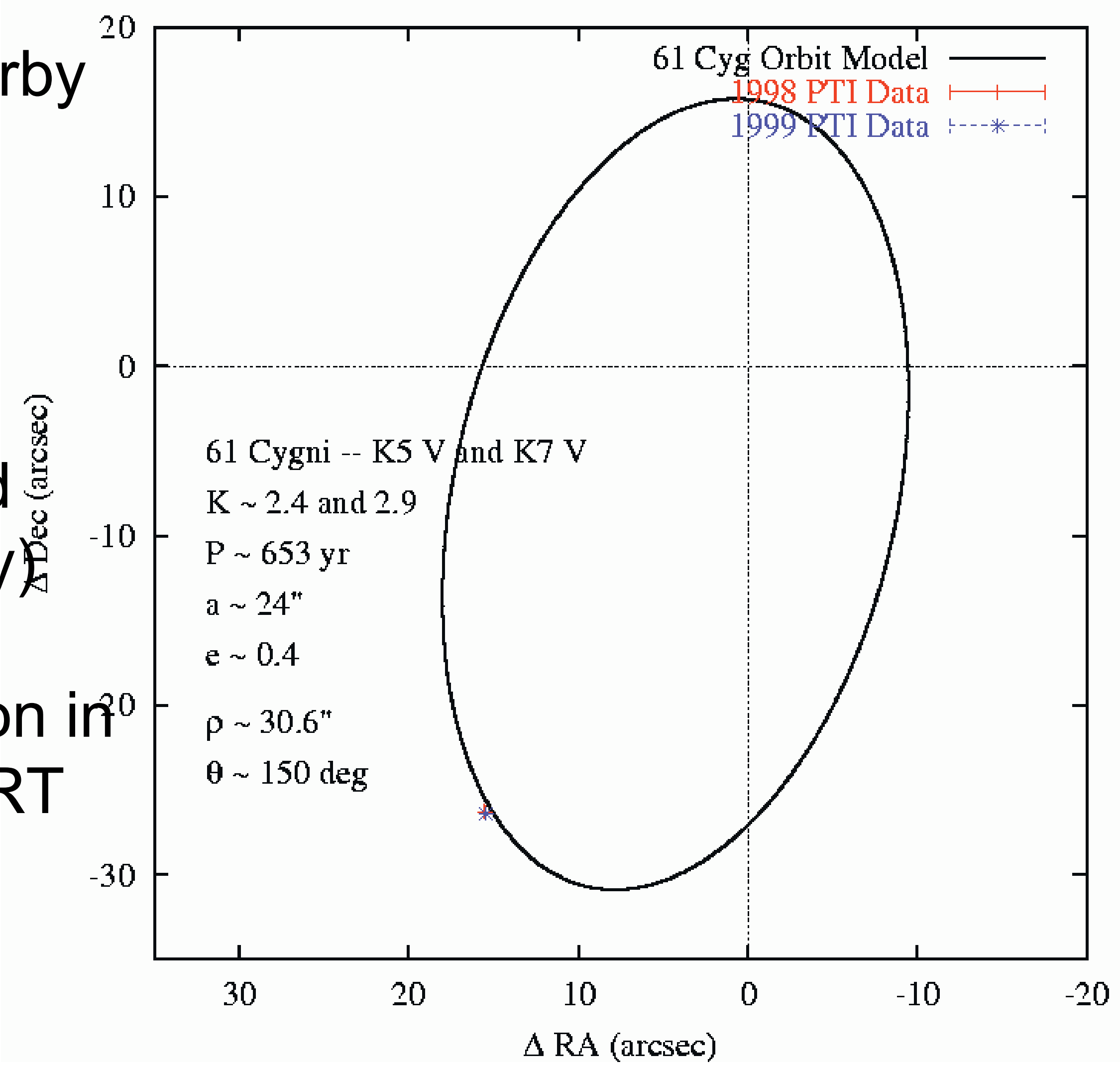
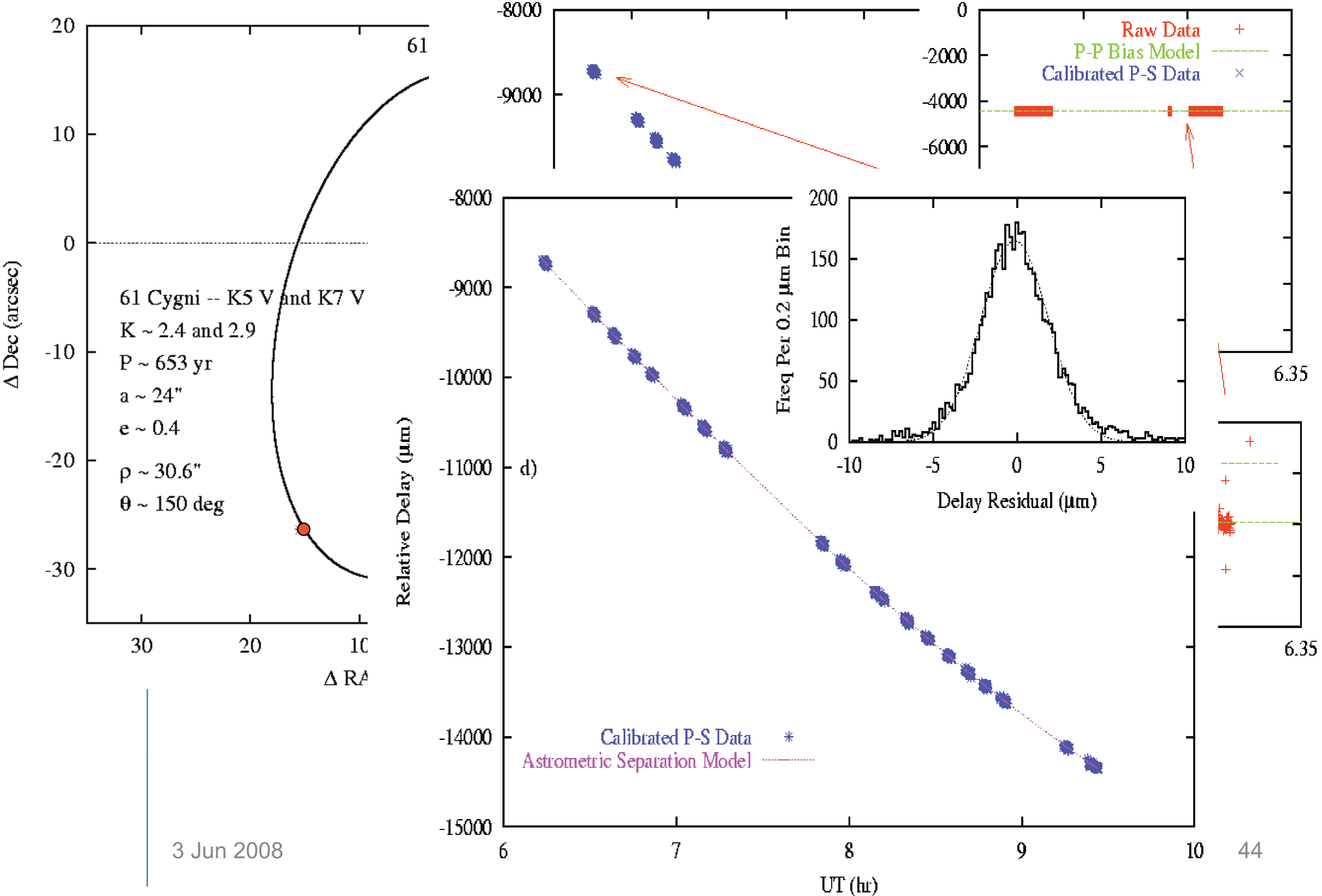
PTI Demonstration: 61 Cygni

- 61 Cygni -- Nearby K-dwarf Visual Binary (*K*~2.5)
- ~ 650 yr Period Eccentric Orbit
- Have it on Good Authority (Marcy) that There is *Nothing* Going on in This System WRT Planets



PTI Astrometry 61 Cygni I.



PTI Astrometry on 61 Cygni II.

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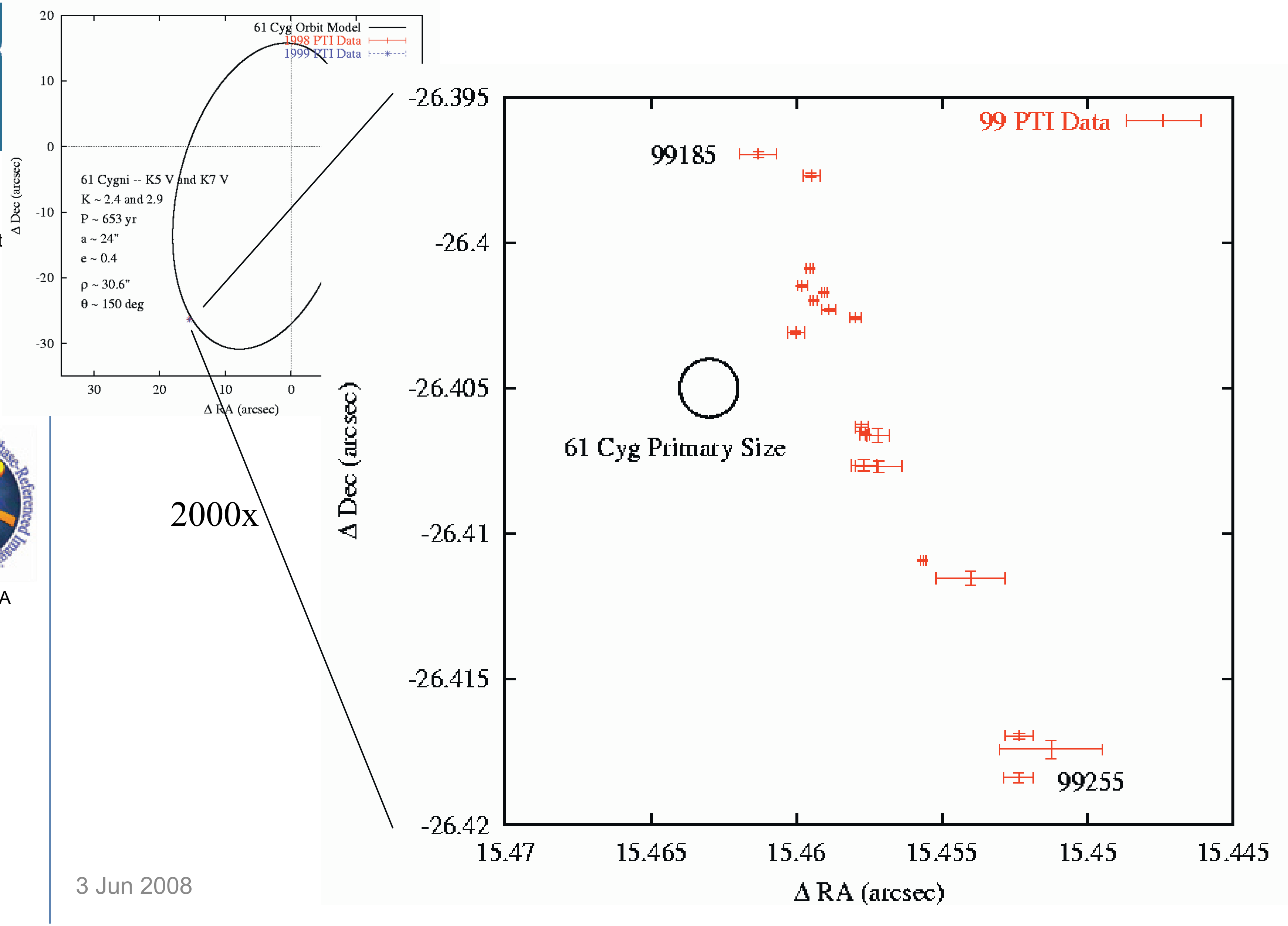

61 Cyg 1999 Declination-Only Data

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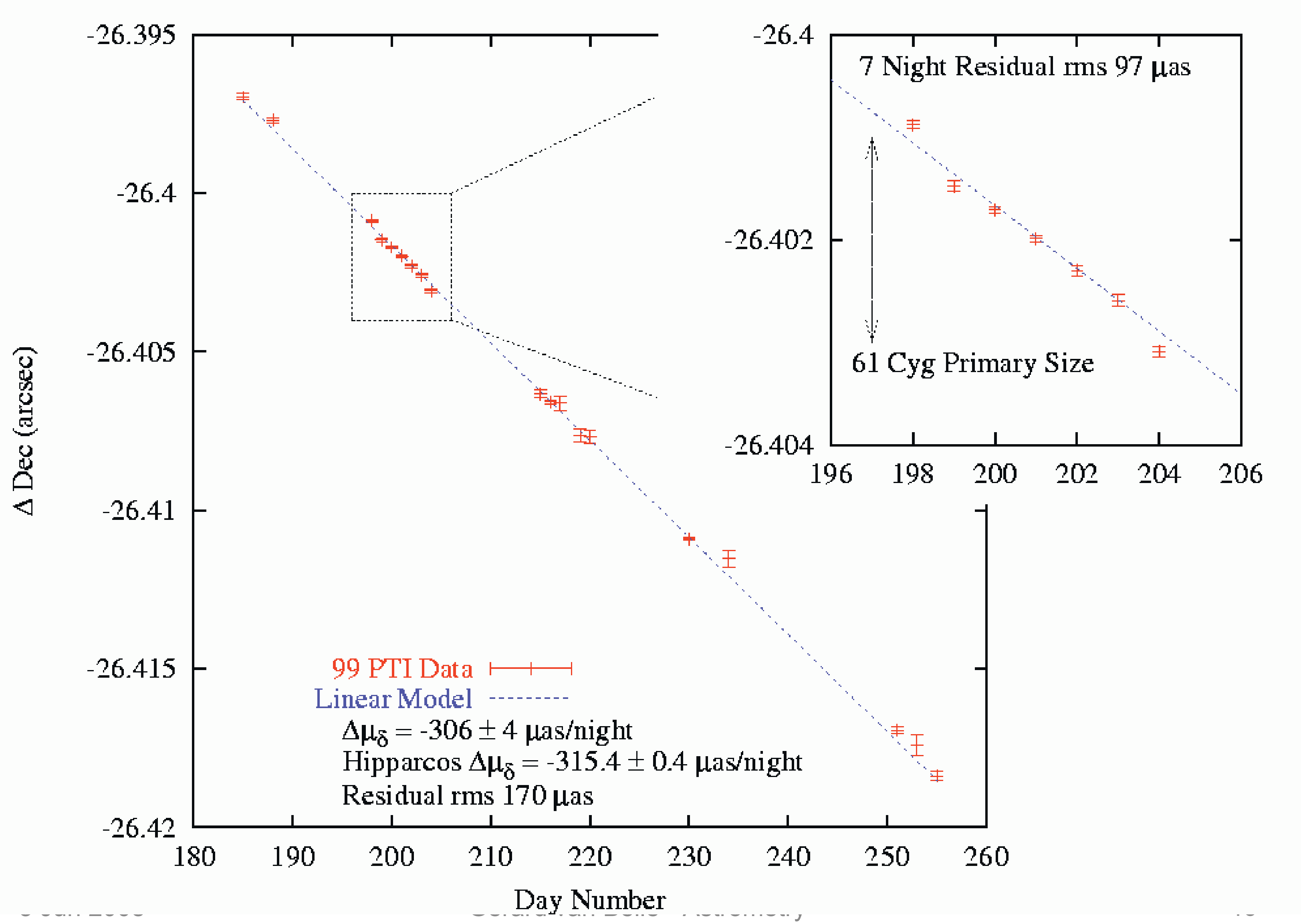

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Future History of Astrometry I.

- VLTI-PRIMA (2008)
  - Facility production-mode dual-star astrometry at the ~10s of μas level
  - Primary aim is extrasolar planet detection with true mass determinations, down to ~20 M_E

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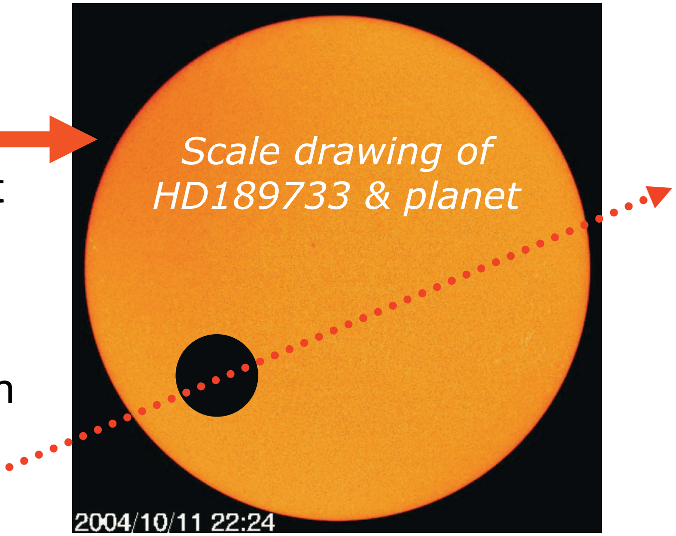
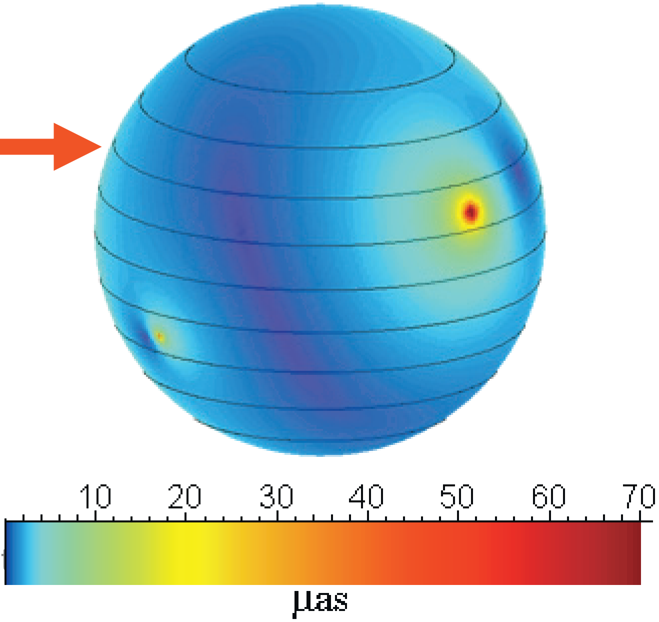
Novel Ideas for PRIMA Observing I.

- Planet transit host stars
  - Transit event induces a photocenter shift on the star
  - Effectively a perfectly black ‘starspot’
- Example case: HD189733
  - 0.376±0.031 mas (CHARA, Baines & van Belle et al. 2007)
  - Transiting planet diameter of ~60μas
  - Ratio of the areas indicates a shift of ~5uas on star centroid
    - This may be difficult


Scale drawing of HD189733 & planet

- Direct detection of GR effects
  - Measure astrometric shifts due to nearby passage of Jupiter, other large solar system bodies
- Weighing solar system objects
  - Precision astrometry of orbits



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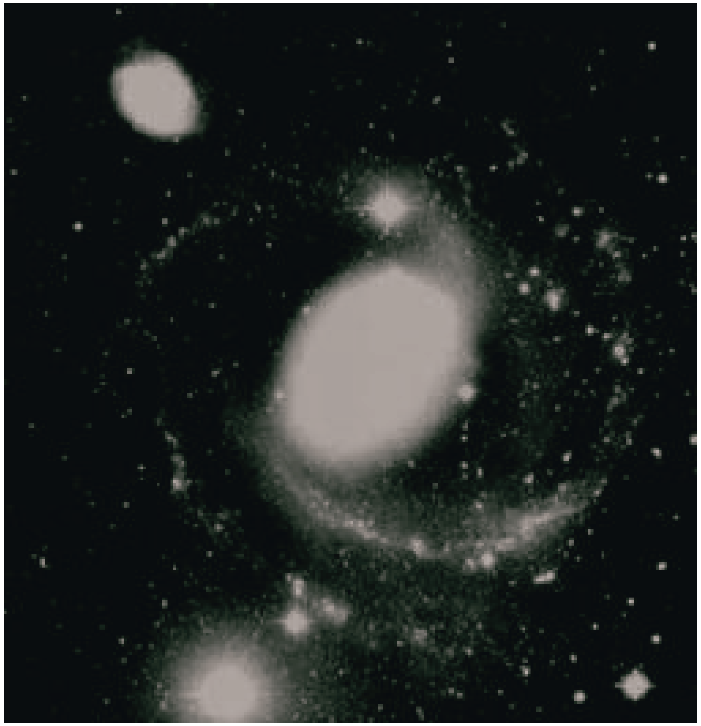
Novel Ideas for PRIMA Observing II.

- Distance determination
- Relative sense
  - Use dim (eg. distant) reference stars, correct for relative parallax
  - This is effectively how ~1 mas HST FGS parallaxes are done (eg. Benedict et al 2007)
- Absolute sense
  - Start with a sample of known, fixed(?) fiducials
    - eg. AGNs, particularly Seyfert 1s
  - Find any science targets that may lurk nearby them
    - Then proudly declare those targets are of course interesting



NGC 4151
Swain et al. 2003

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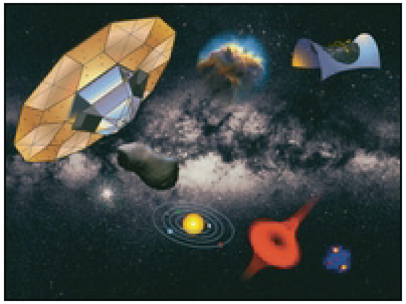
Future History of Astrometry II.

- GAIA (2011?)
  - Compile catalog of ~1Bn stars to mag. 20
  - Position, proper motion, distances to 20-200µas **end-of-mission** accuracy



- SIM, SIM-Planetquest, SIM-Lite (2015??)
  - Optical interferometer: 10 or 9 or 6 m baseline
  - Single-measurement accuracy of 1µas

Dual-Object Phase Referencing

Objective: long synthetic coherence time for faint-object detection –
Fundamentally enabled by dual-beam optical design

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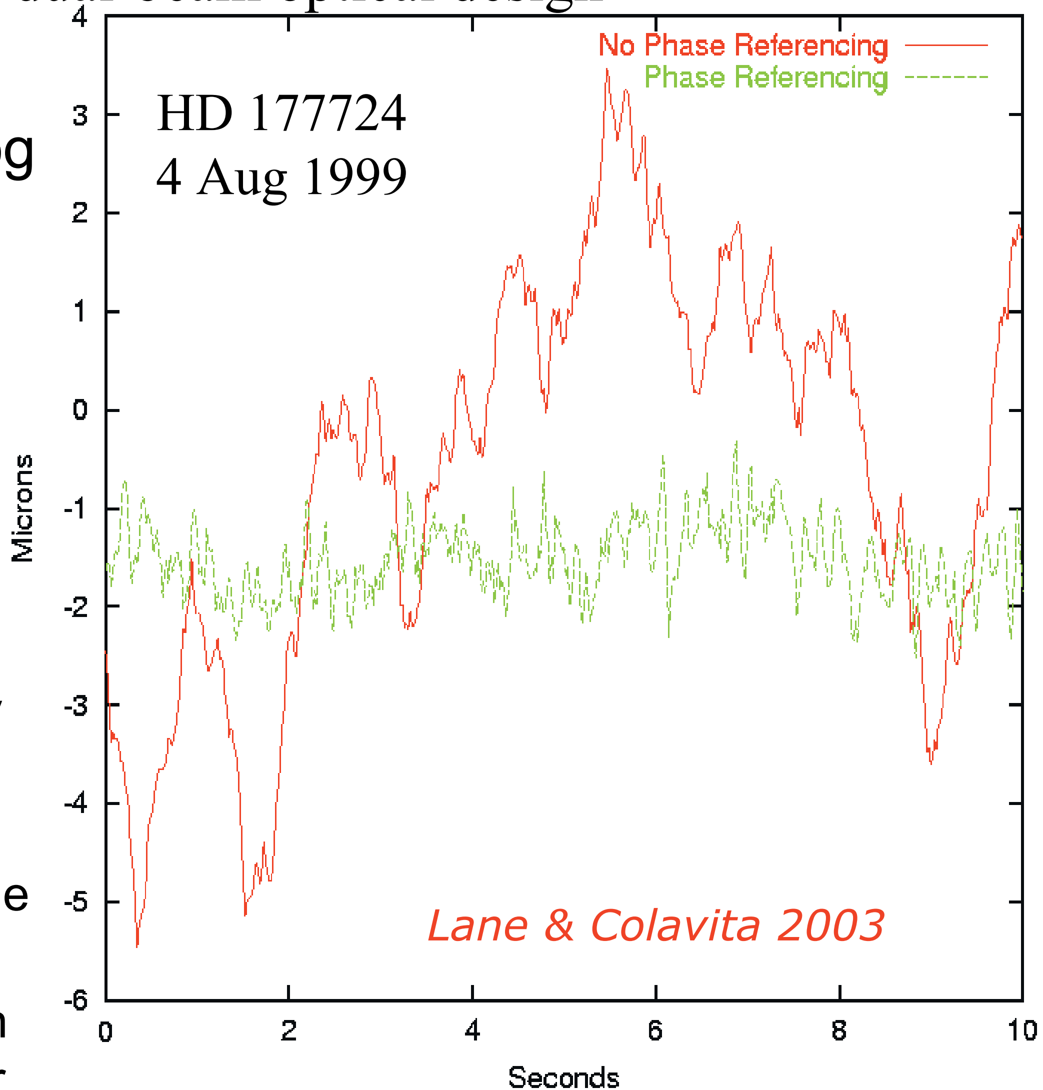
Phase referenced interferometry: the analog of single-aperture AO

- Fringe tracking piston correction signal on one object is used to correct the piston on a second, nearby (isoplanatic separation) object.
- Required for KI and VLTI faint-object interferometry
- Phase error with and without loop closed between the two PTI fringe trackers.
- Two data segments taken within 200 s of each other.



HD 177724
4 Aug 1999

Lane & Colavita 2003

Any Questions?

Evening at Paranal with AT1 and AT2

ESO PR Photo 07c/05 (14 March 2005)

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Baseline Slides

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Baseline Monitoring for Astrometric Interferometry

- These details are largely lifted from Hrynevych, Ligon & Colavita (2004 SPIE)

Astrometric Baseline

- To convert optical delay → angle on sky
  - Need to know interferometer baseline
- Metrology retroreflectors in DSM
  - Baseline is the projection of the retros into object space
  - Even if projection stable, still need to solve for this baseline
- Use high quality telescope pivot
  - Solve for baseline connecting true telescope pivots from wide-angle measurements
- Use pivot monitor to reference narrow-angle baseline to wide-angle baseline

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Establishing Baseline for Narrow-Angle Astrometry

1. Determine the wide-angle baseline (WAB)
2. Locate the telescope fiducial with respect to the telescope pivot
3. Co-locate the narrow-angle (NAB) and wide-angle baseline (WAB)

Steps in detail (next slides)

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1. Determine the WAB

- Use stars with *a priori* positions
  - Hipparcos catalog stars
  - *Tolerance on positions? separations?*
- Measure delays in interferometer
- WAB is determined with respect to true telescope pivot point

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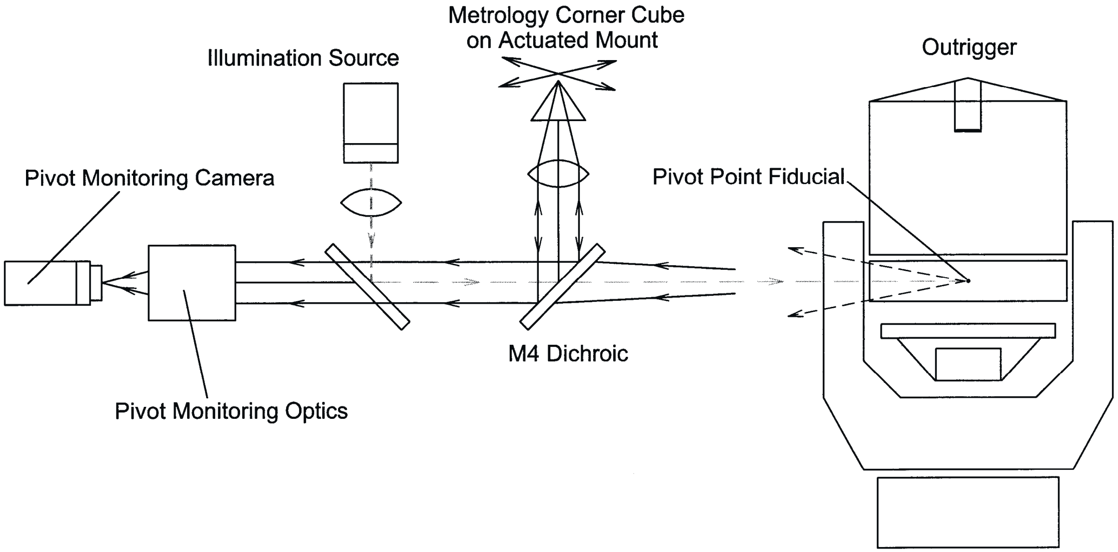
2. Locate the Telescope Fiducial with respect to the telescope pivot

- Pivot point monitor
- Fiducial is a laser fiber source
  - Inserted in a hole in the tertiary in primary space
  - At a known distance from the pivot point



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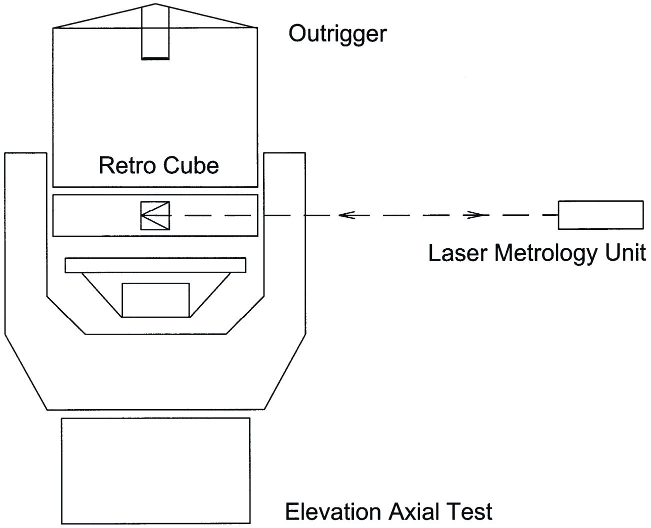
Aside: Telescope Pivot Point Measurements

- *Separate* baseline monitor
- Elevation axis runout: axial, radial
- Azimuth axis runout: axial, radial
- Requirements
  - – Pivot point motion < 700um
  - – Modelable to 25um rms



Axial runout measurement setup for elevation axis

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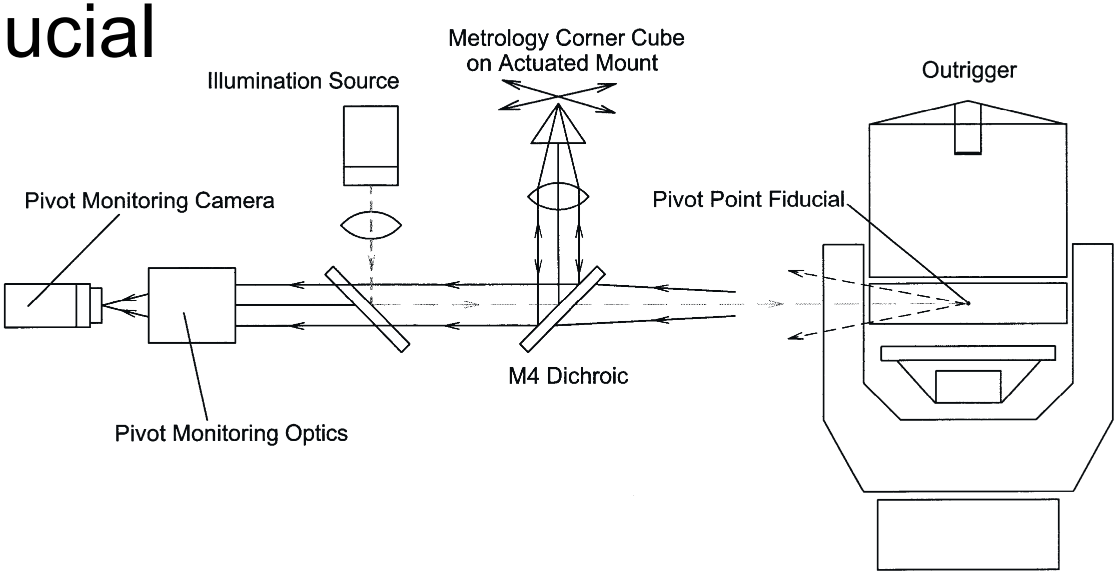
3. Co-locate the NAB and WAB

- NAB is projection of DSM retroreflector into the pupil containing the telescope fiducial
- Pivot point camera is used to view DSM retro and fiducial simultaneously
- DSM retro translated to be coincident with telescope fiducial



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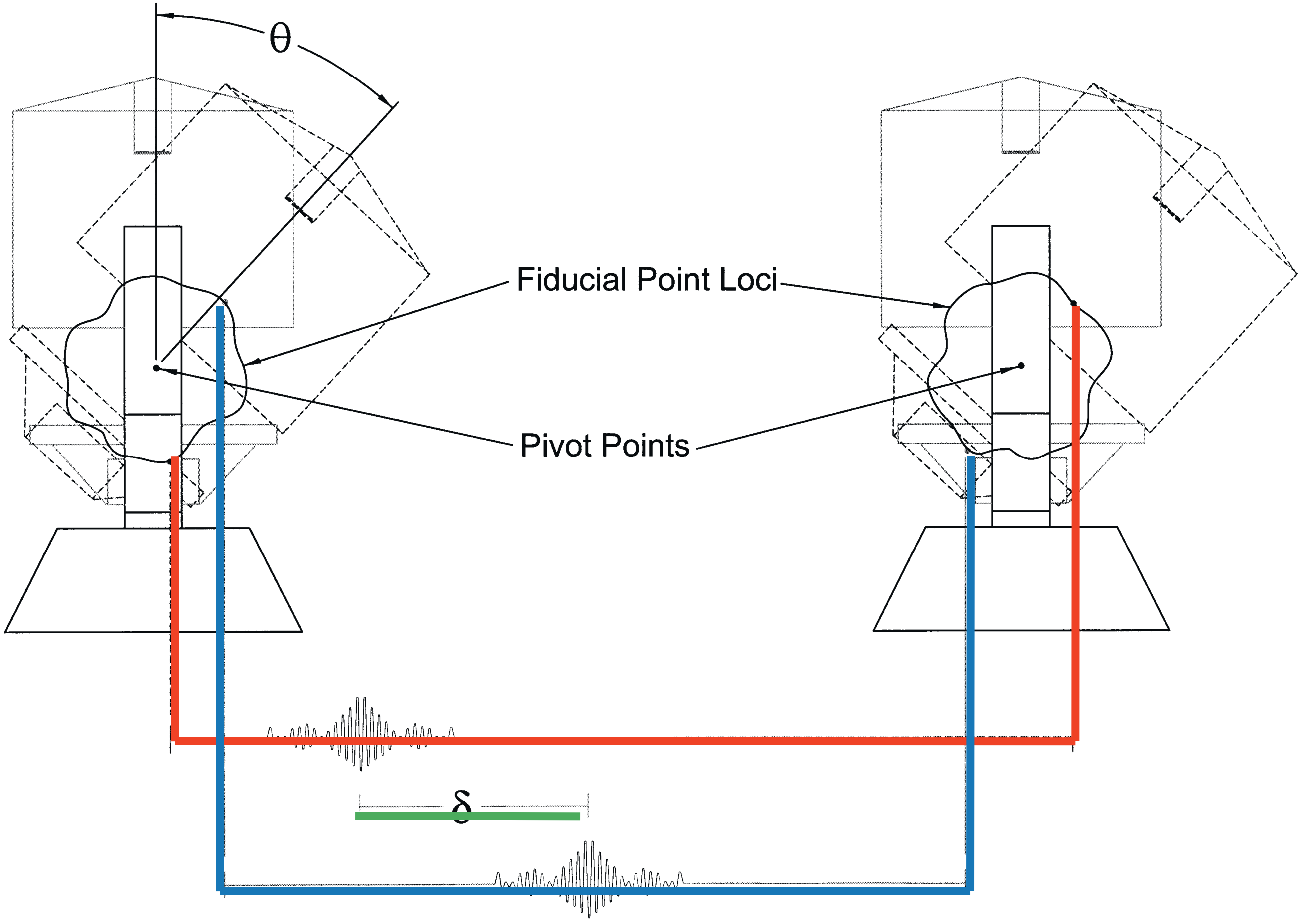
Relationship between WAB and NAB



WAB: From difference in fringe position (δ) of two widely separated stars (θ)

Fiducial point loci can be used to locate both pivots and NAB for all orientations

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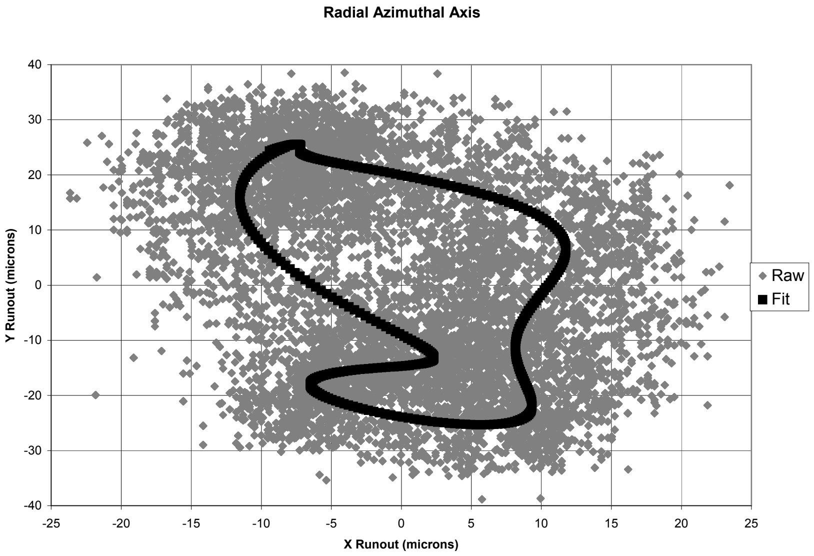
Results from Outrigger Testing

- Elevation, Azimuth modelable pivot motion < 130um *{Specification: 700um}*
- Elevation, Azimuth random pivot motion < 11um *{Specification:*



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Implications for ATs?

- No provision for pivot/baseline monitoring in place
  - No provision for pivot monitoring camera
  - Lines of sight for baseline monitor needed to be cut into Outrigger domes – not possible for ATs if desired?
- Outrigger bearings specifically manufactured for precision repeatability
  - No such similar requirement for ATs?
  - Not modelable by FEM
- Keep in mind dissimilar designs
  - Coudé trains highly different
  - DSM / STS differences
  - No outrigger derotator
  - Metrology differences
- Differential wind loading not specifically considered in this analysis
  - Though probably accounted for with outriggers due to active nature of monitors

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- Ground-based
  - Wide-field
  - Narrow-field
- Space-based

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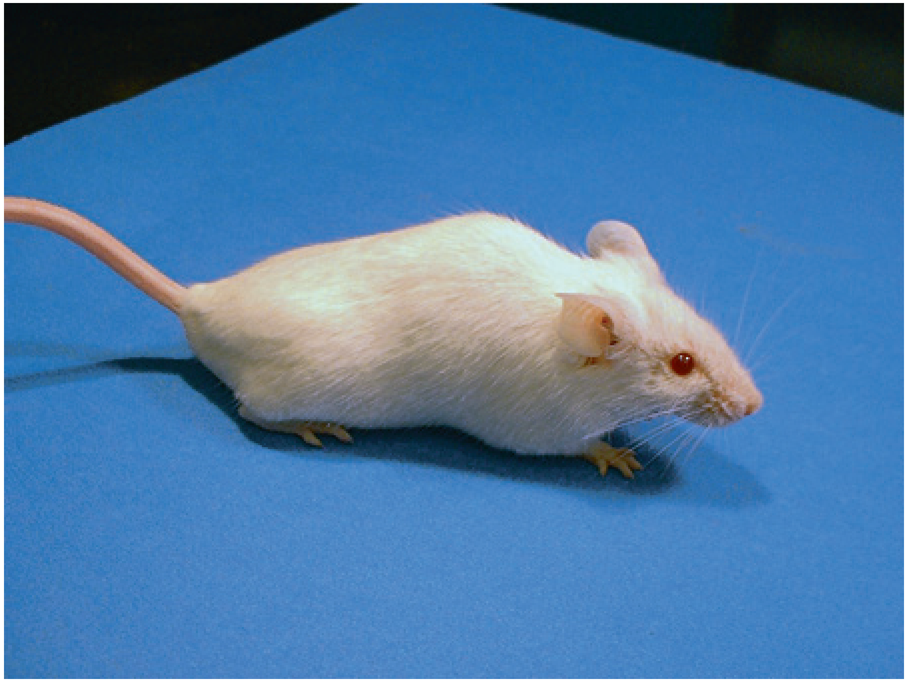
> "The best-laid plans of mice and men go oft awry."
>
> *Robert Burns, 1785*



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BACKUP SLIDES (currently none)

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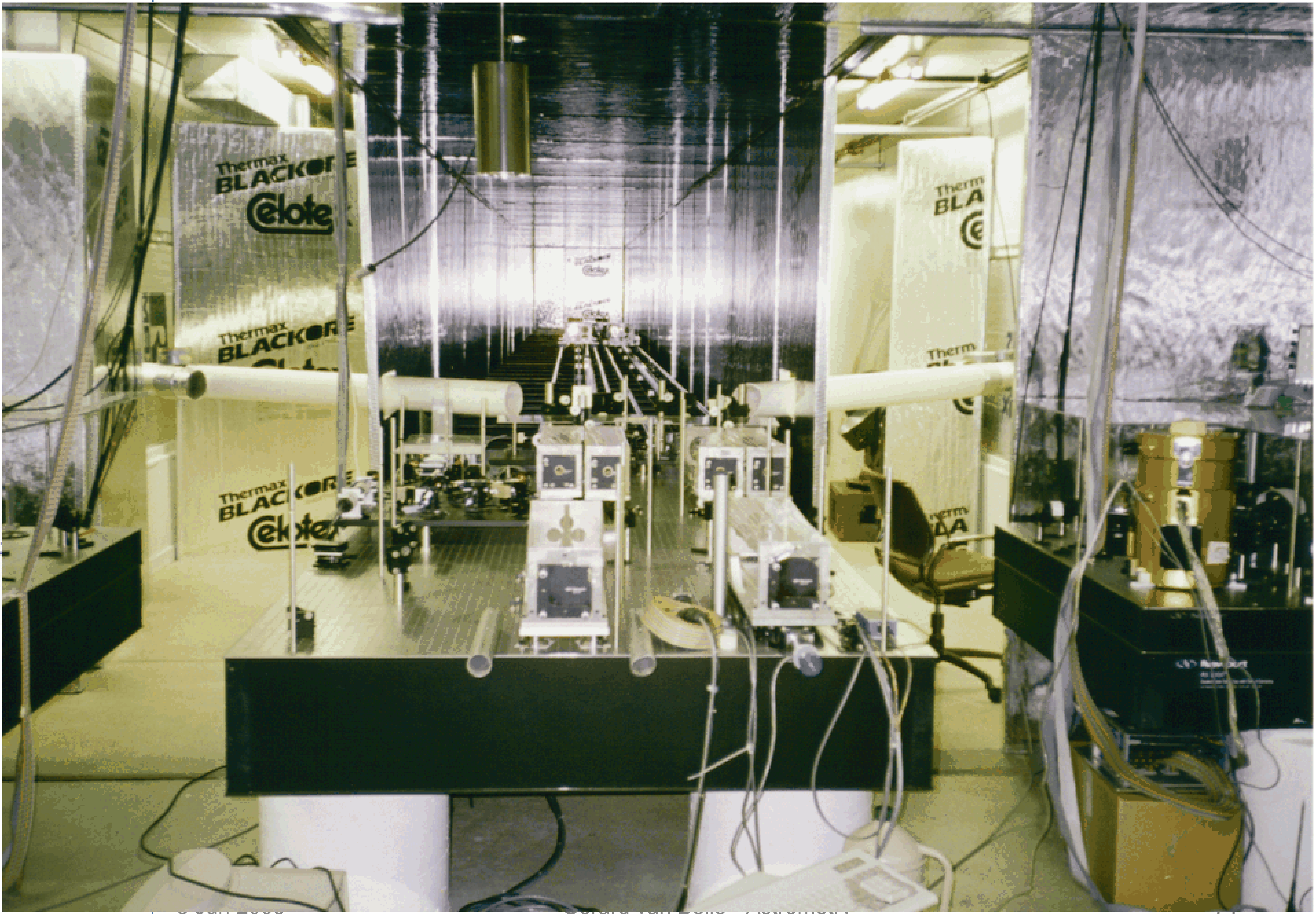
Astrometry systematics error budget

			nm per arm	nm total	uas total	
unmodeled pivot noise	25.0	um	1.9	2.7	5.5	
pivot beacon to pivot transfer	25.0	um	1.9	2.7	5.5	
DSM CC to beacon transfer	25.0	um	1.9	2.7	5.5	
baseline solution	35.0	um		2.6	5.4	
DCR					5.0	
beamwalk of secondary over field			2.5	3.5	7.3	
alignment of metrology to starlight	0.5	arc sec	1.8	2.5	5.2	
alignment drift	0.5	arc sec	1.8	2.5	5.2	
metrology stability	1.00E-08	fractional	0.1	0.1	0.2	
metrology polarizer mount gradient	0.04	K	2.0	2.8	5.8	
fringe-measurement accuracy	0.005	rads	1.8	2.5	5.1	
beamwalk stability in propagation	1.5	mm	2.3	3.2	6.6	
				TOTAL:	**18.8**	**uas**

Palomar Testbed Interferometer

- NASA funded, tech development for Keck and other interferometers
- 2-way system, 110 m max baseline
- 40 cm collecting apertures
- Active broadband fringe tracking at K (2-2.4 μm) or H (1.5-1.8 μm)
- Spectrometer resolution of R = 25 – 50
- Angle tracking at R+I (0.7 – 1.0 μm)
- Dual-star capability for narrow-angle astrometry

More detail:
ApJ 510, 505 (1999)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BLACKORE
Celotex

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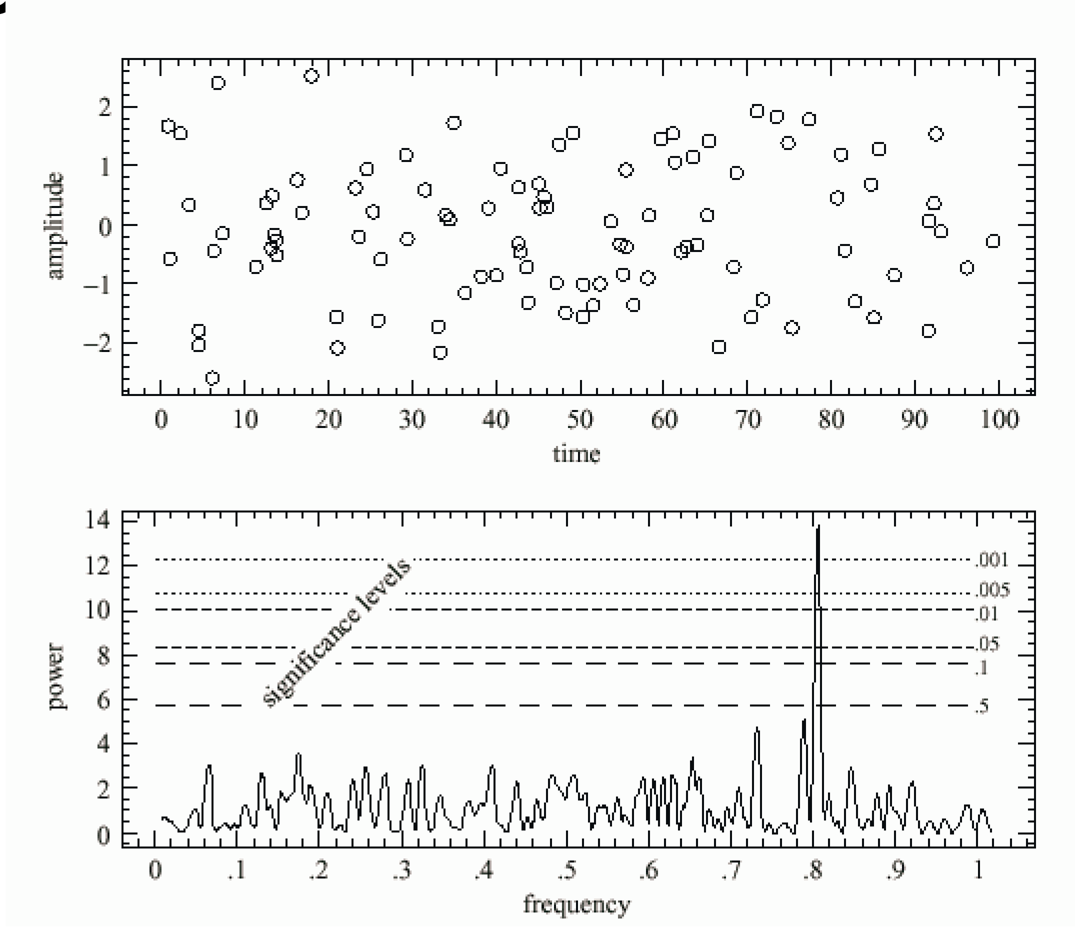
Harmonic Detection

- The Common Detection Algorithm for Harmonic Signals is the Lomb-Scargle Periodogram -- Least Squares Fit of sin Function



Numerical Recipes, 2nd Ed

- Performs Well for Data That

Astrometric Reference Star Measurement Noise

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- Astrometric error given by

$$\Theta = \frac{\lambda}{2\pi B}\frac{\sqrt{2}}{\mathrm{SNR}},$$

where

$$\mathrm{SNR}^2{}_{\mathrm{BLIP}} = 0.81 \times \frac{4N_1N_2V^2}{B_1 + B_2}\ (\mathrm{Total\ SNR})$$

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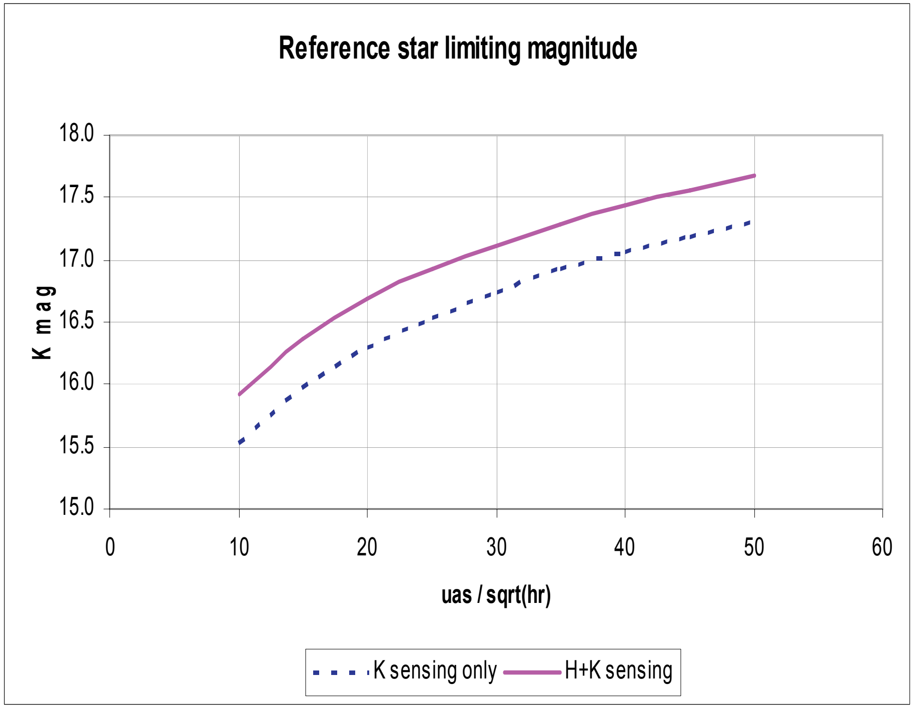

- Measurement noise < 30 uas / hr for K<17.1

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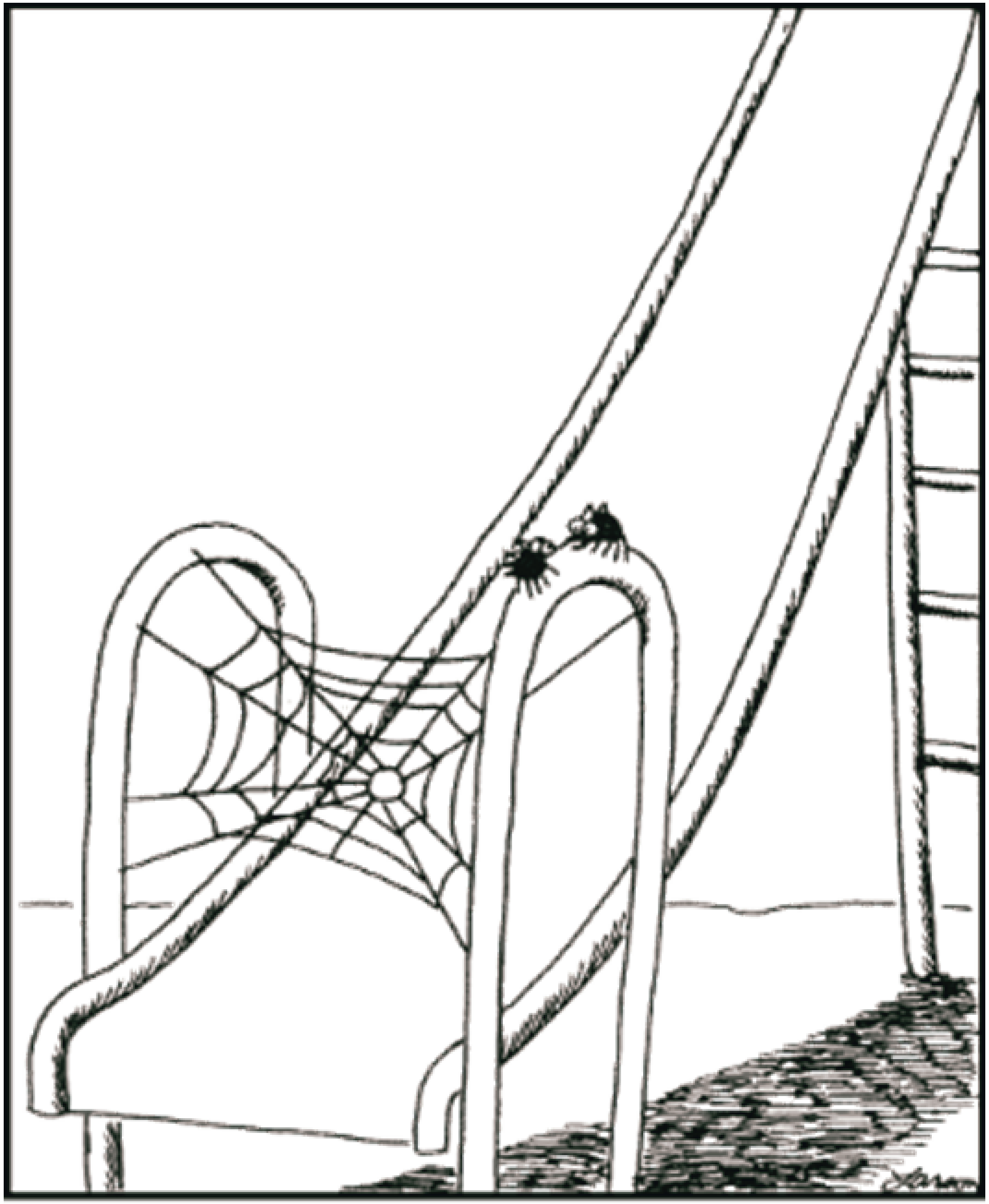

“If we pull this off, we’ll eat like kings.”

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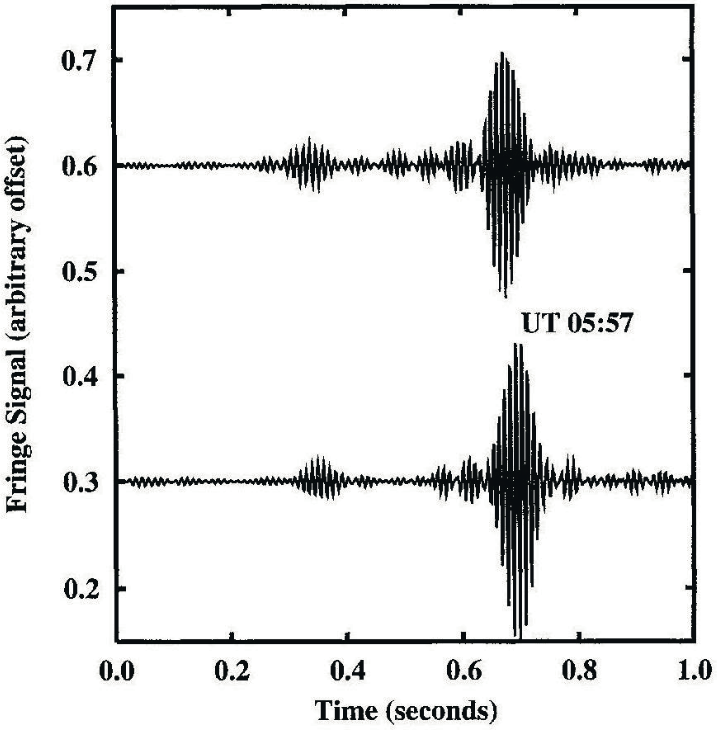
Very Narrow-Angle Astrometry

- Regime where no dual-beam feed necessary
  - FOV of single beam is sufficient
  - For PTI, corresponds to <<1”
- First demonstrated by Dyck, Benson & Schloerb (1995) at IOTA
  - ζ Her separation of



Dyck Benson & Schloerb 1995

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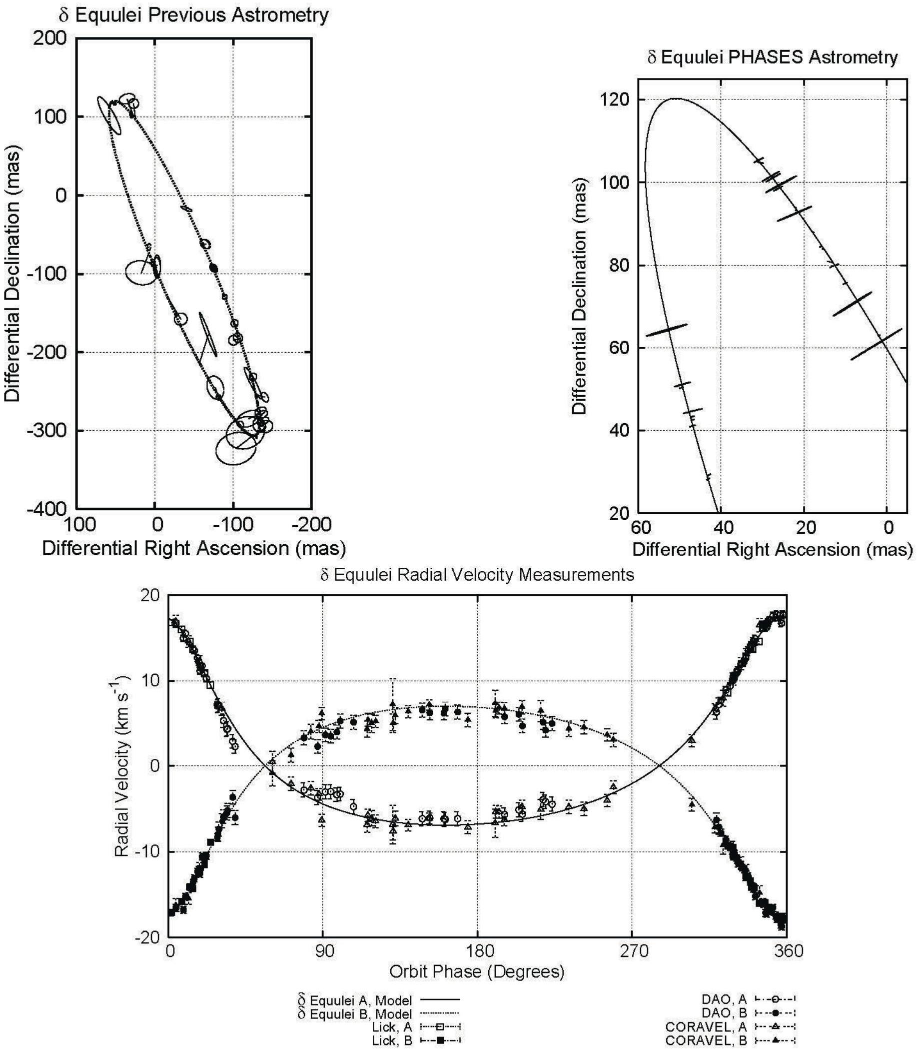
PHAS

- Fringe tracker phased on primar star
  - ‘Synthetic’ coherence time of ~1 second allows for delay line scanning
- Example target: δ Equ
  - ~120 mas separation, 5.7 yr orbit.



Muterspaugh et al. 2005

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Novel Ideas for PRIMA Observing (II)

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- Relative sense
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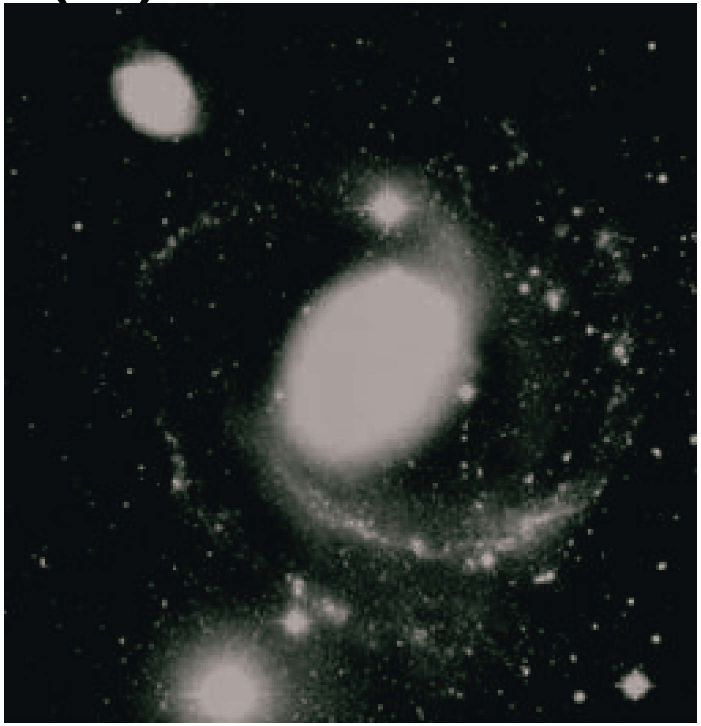

NGC 4151
Swain et al. 2003