Interferometry and astrometry

Andreas Quirrenbach

Abstract

Astrometric observables (delay, fringe phase, differential delay), metrology, baseline solutions, wide-angle astrometry, narrow-angle astrometry, atmospheric limits, astrometry from space.

Interferometry and Astrometry

Andreas Quirrenbach

(University of California, San Diego)

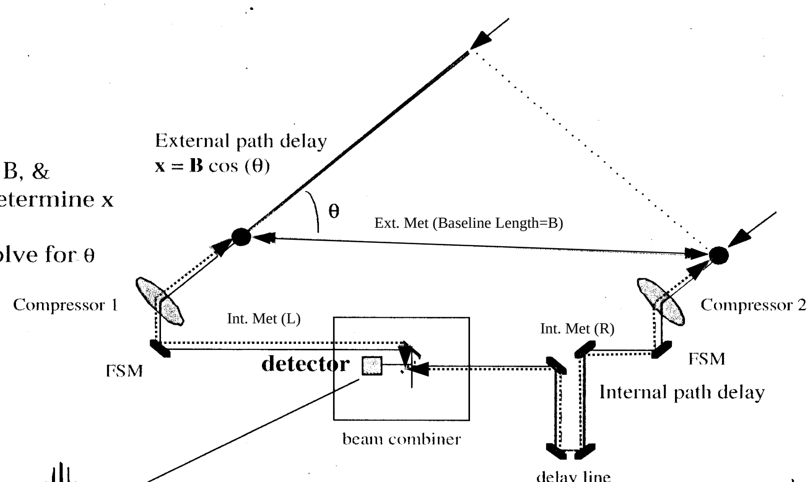
S I M

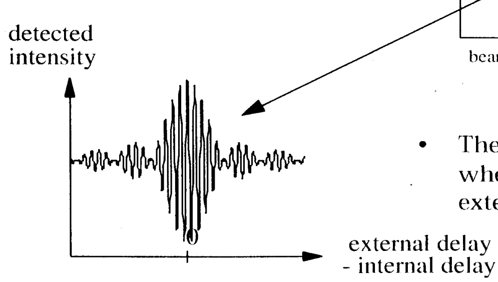
Space Interferometry Mission

SIM Astrometric Measurement

- If:
  - Know B, &
  - Can determine x

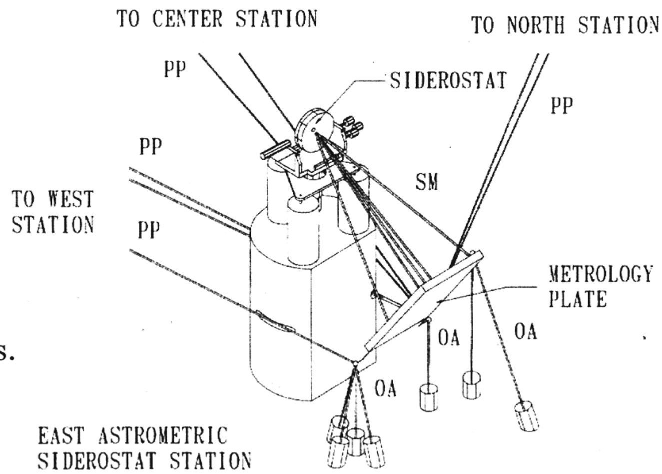
Then:
  - Can solve for θ





- The peak of the interference pattern occurs when the internal path delay equals the external path delay

Wide-Angle Astrometry



- Catalog of ~1000 Hipparcos stars with internal accuracy of 1 - 3 mas.
- Update and correct for rotation in Hipparcos reference frame.

Anisoplanatism

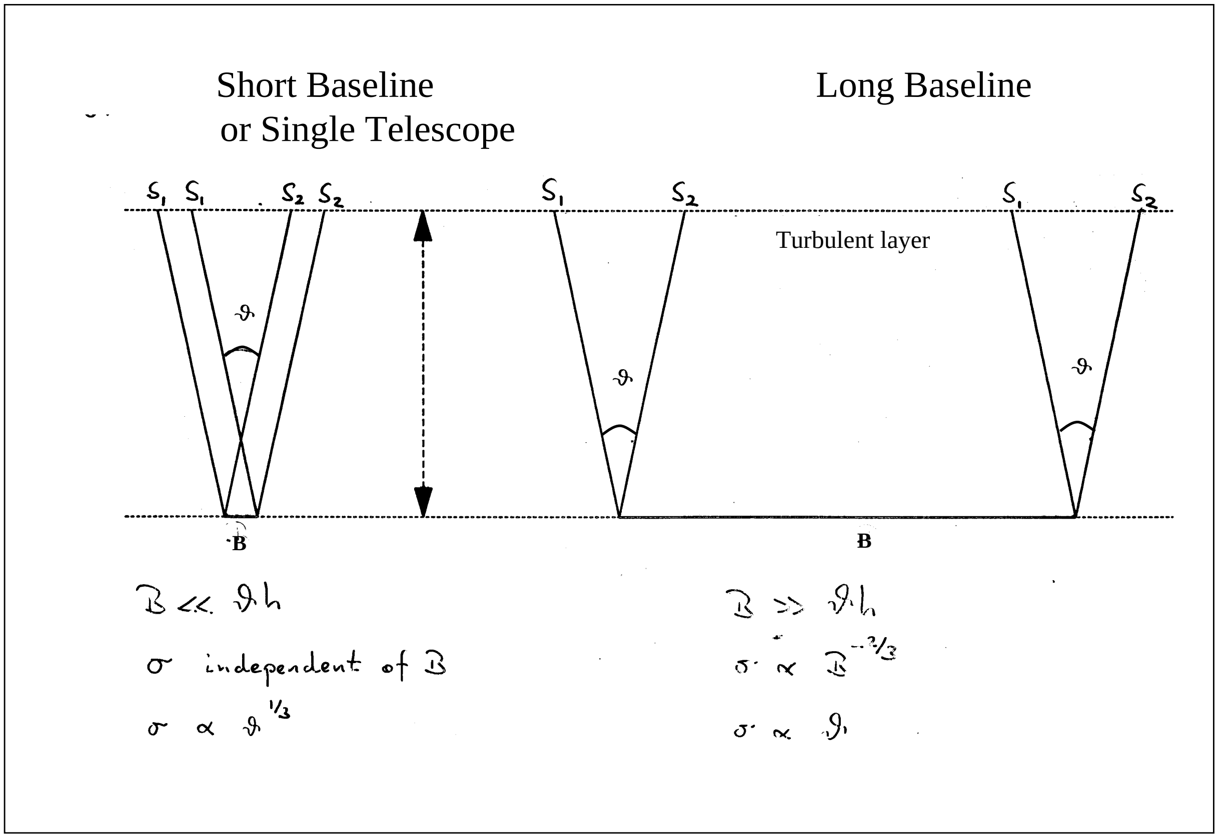
- **The light from two stars separated by an angle θ passes through different patches of the atmosphere and therefore experiences different phase variations.**
- **It can be shown that the variance of the phase difference between the two stars is given by:**

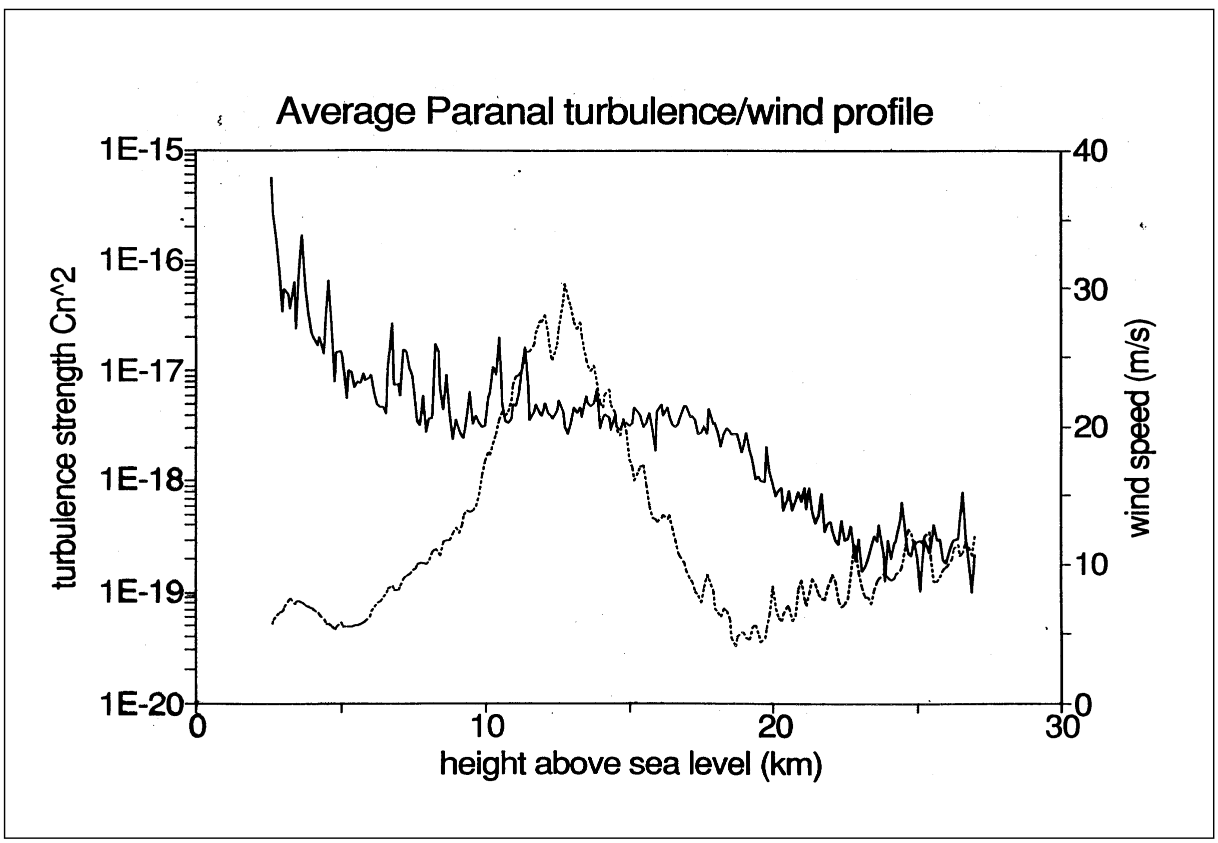
$$\langle \sigma_\theta^2 \rangle = \left(\frac{\theta}{\theta_0} \right)^{5/3}$$

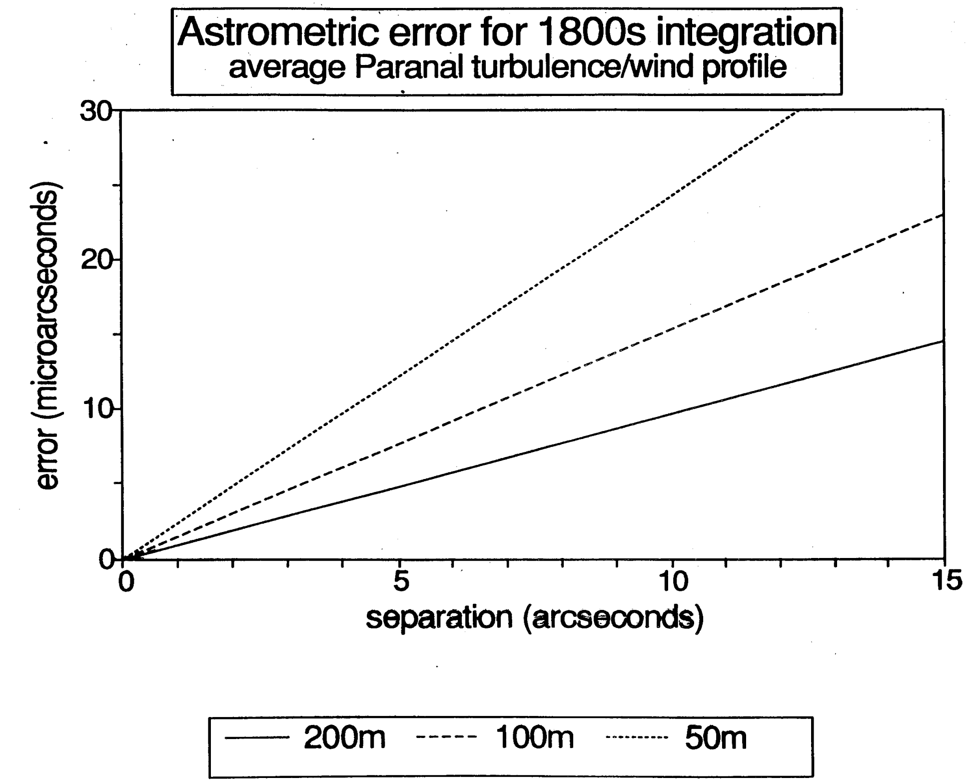
- **In this relation, the *isoplanatic angle* is given by:**

$$\theta_0 \equiv \left[2.914 k^2 (\sec z)^{8/3} \int dh\, C_N^2(h) h^{5/3} \right]^{-3/5}$$

- **Note: the short-exposure point spread functions for two stars separated by more than θ_0 are different, but the long-exposure psf's are (nearly) identical.**
- **Anisoplanatism is dominated by high-altitude turbulence.**


Short Baseline
or Single Telescope
Long Baseline
S1 S1 S2 S2
S1 S2
S1 S2
Turbulent layer
B
B
B << ϑh
σ independent of B
σ ∝ ϑ^1/3
B >> ϑh
σ ∝ B^-2/3
σ ∝ ϑ


Average Paranal turbulence/wind profile
turbulence strength Cn^2
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
wind speed (m/s)
40
30
20
10
0
0
10
20
30
height above sea level (km)



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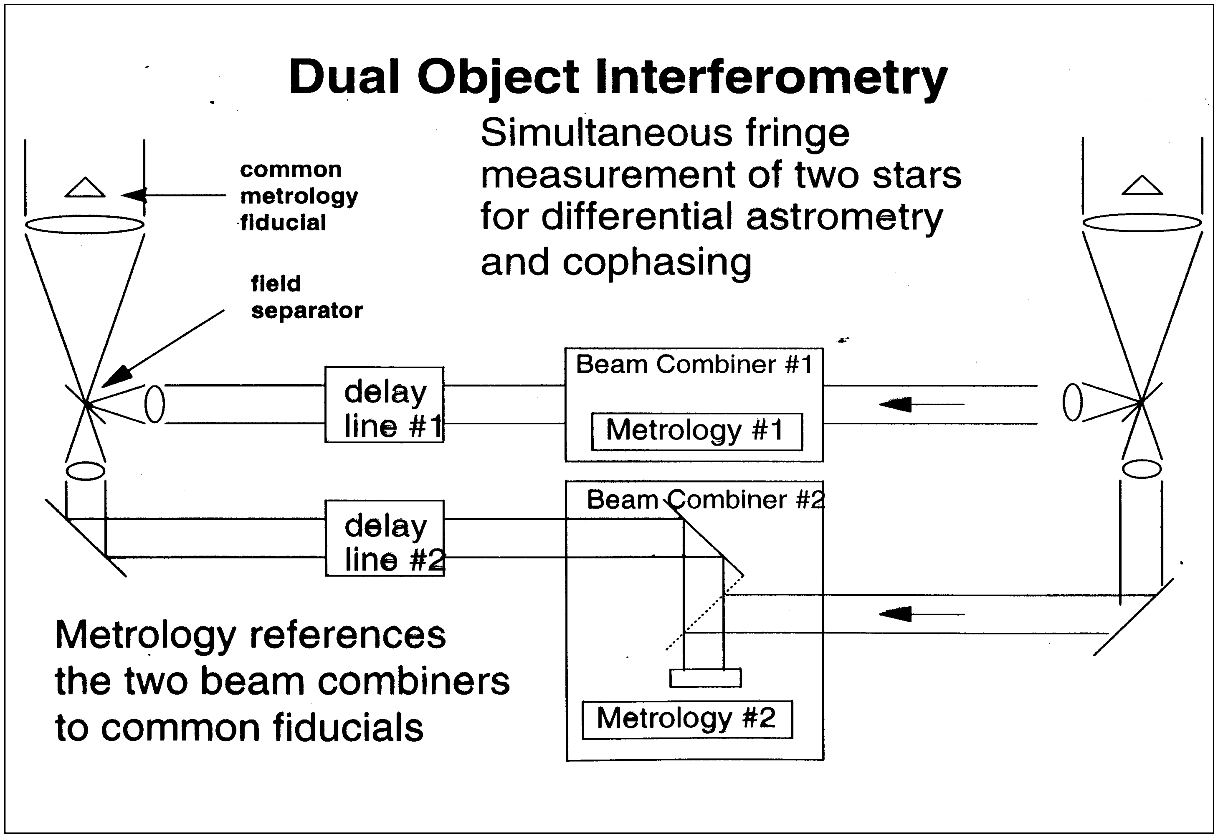
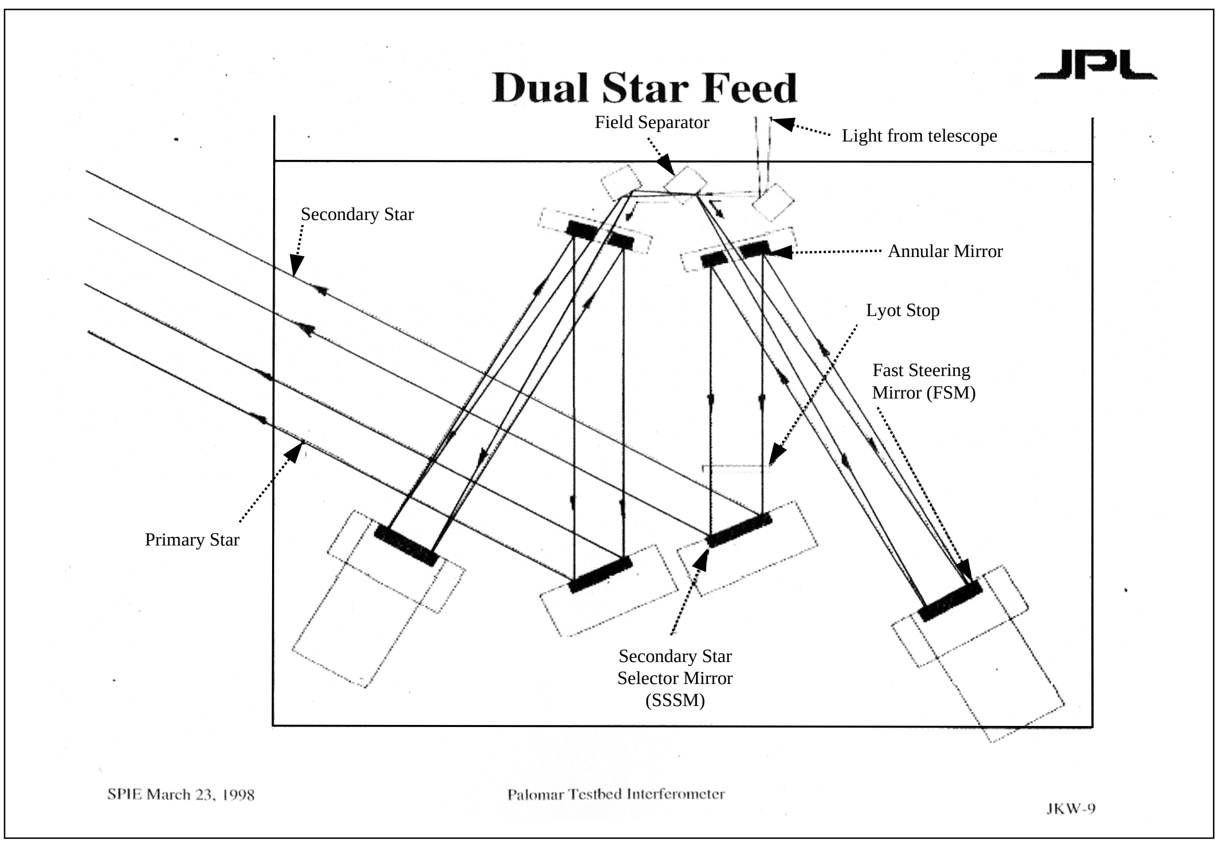
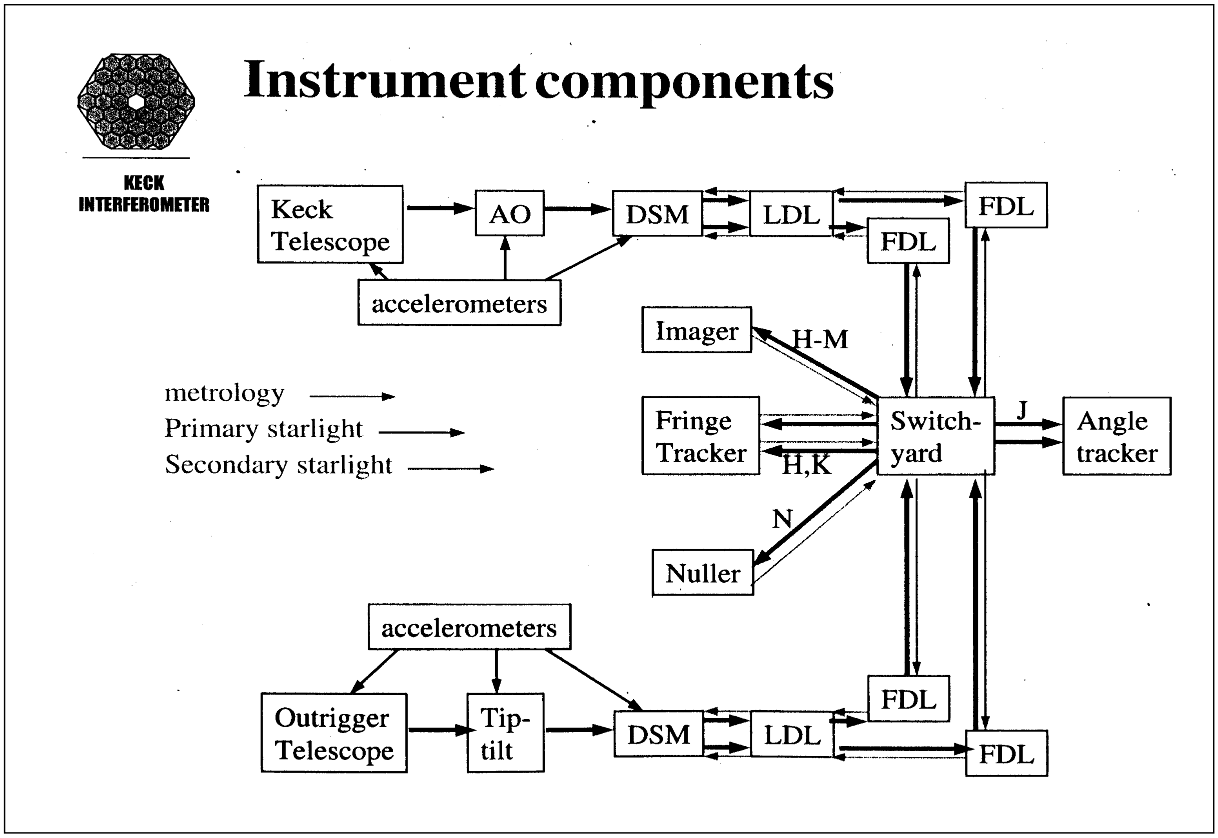
Astrometry Budget

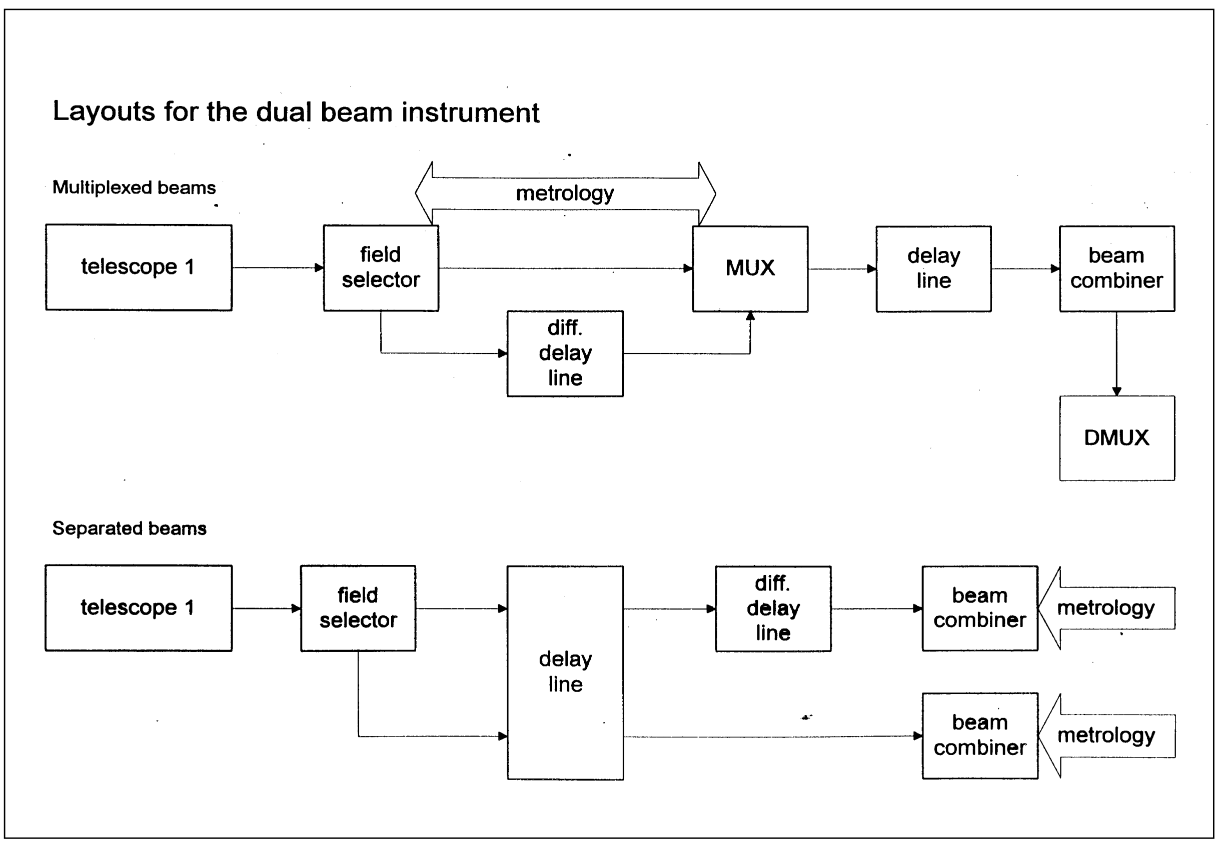
- Contributors to astrometry error budget
  - Measurement noise on reference star
    - » This will generally limit performance to ~30 uas / sqrt(hr)
  - Atmosphere
    - » With 100-m baseline, 15” mean star separation, 100 m outer scale, expect ~10 uas / sqrt(hr)
  - Instrument systematics
    - » Limit to 20 uas / sqrt(hr)

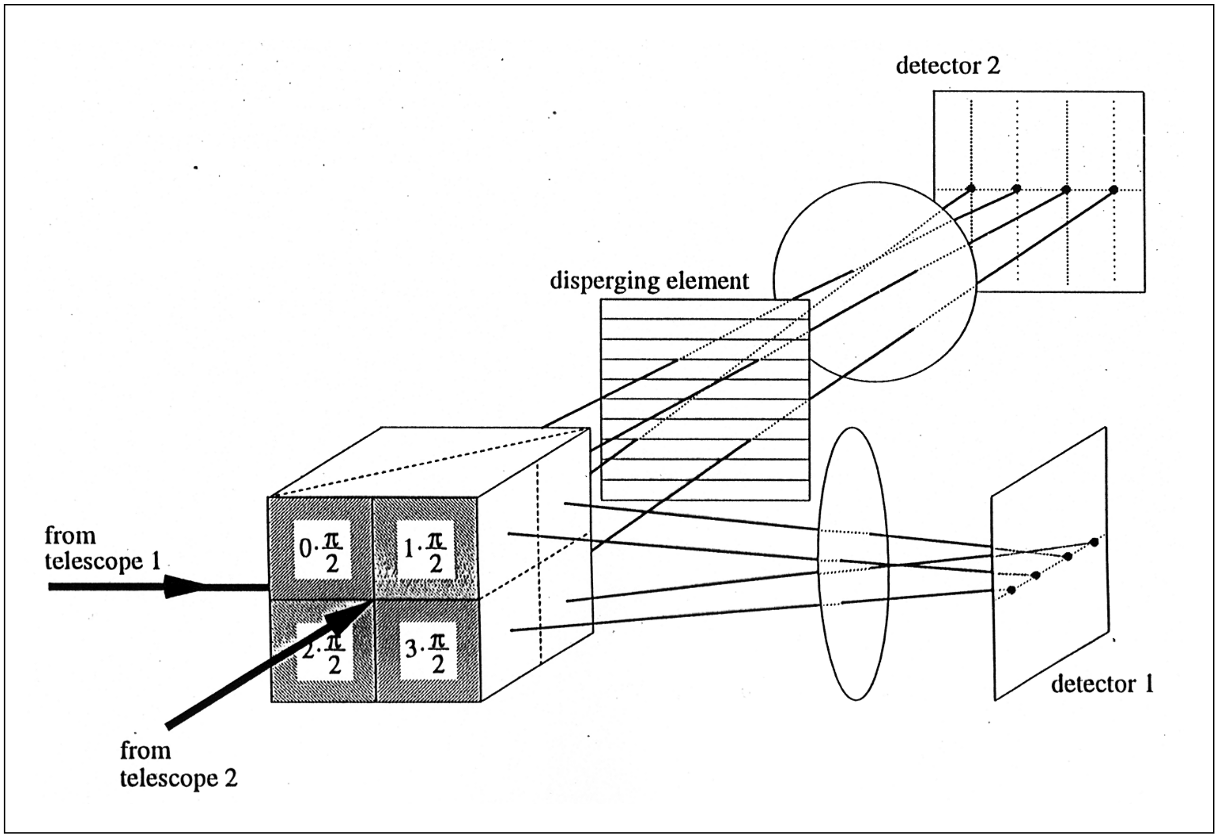
mmc 8/25/98 Error Budgets and Performance 26


Dual Object Interferometry
Simultaneous fringe measurement of two stars for differential astrometry and cophasing
common metrology fiducial
field separator
delay line #1
delay line #2
Beam Combiner #1
Metrology #1
Beam Combiner #2
Metrology #2
Metrology references the two beam combiners to common fiducials


Dual Star Feed
Field Separator
Light from telescope
Secondary Star
Annular Mirror
Lyot Stop
Fast Steering Mirror (FSM)
Primary Star
Secondary Star Selector Mirror (SSSM)
SPIE March 23, 1998
Palomar Testbed Interferometer
JKW-9


Instrument components
KECK INTERFEROMETER
Keck Telescope
AO
DSM
LDL
FDL
FDL
accelerometers
Imager
H-M
metrology
Primary starlight
Secondary starlight
Fringe Tracker
H,K
Switch-yard
J
Angle tracker
N
Nuller
accelerometers
Outrigger Telescope
Tip-tilt
DSM
LDL
FDL
FDL


Layouts for the dual beam instrument
Multiplexed beams
metrology
telescope 1
field selector
MUX
delay line
beam combiner
diff. delay line
DMUX
Separated beams
telescope 1
field selector
delay line
diff. delay line
beam combiner
metrology
beam combiner
metrology



Technical Requirements for Keck / VLTI

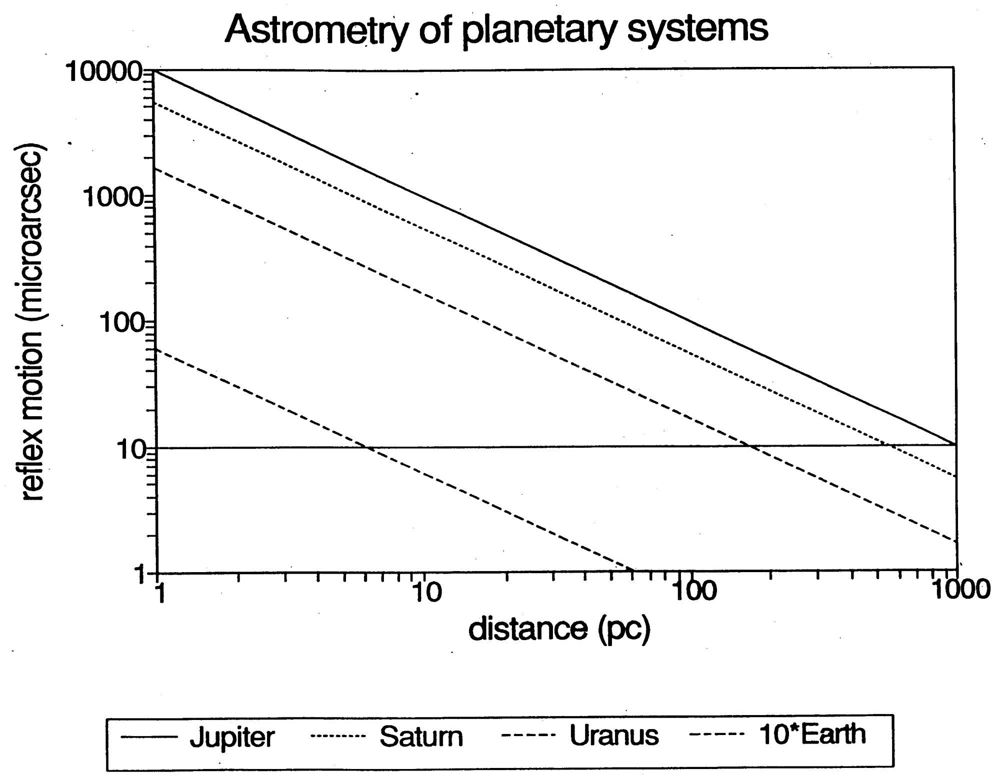
- Optimum wavelength: H and K band (1.6 μm and 2.2 μm)
- Target star (also used for fringe tracking): $m_K \lesssim 12$
- Astrometric reference: $m_K \lesssim 17$
- Maximum angle for reference star: $\sim$ 1 arc minute
- Baseline vector must be monitored with $\gtrsim$ 50 μm precision (will be determined from periodic astrometric solution)
- Differential delay has to be measured with 5 nm precision (will be done with laser interferometer)
- Can be implemented with outrigger (1.8 m) telescopes

Observing Strategy

- Use VISA (1.8 m) telescopes only
- Optimum wavelength is K band
- Three reference stars for each target
- 1800 s integration per star and night
- 20 to 30 observations for each target star
- Solve for parallax, proper motion; residuals give planets
- Start with 50 μas precision goal, more ambitious later
- Several hundred stars can be observed in Key Project

Field-of-View Requirements for PRIMA

- Astrometric search for exoplanets needs dual "zero" field
- Astrometry in Galactic Center is more efficient with $1''$ or $2''$ field
- Some imaging applications also require non-zero field
- Field distortions are important
- Non-zero field poses substantial technical challenges



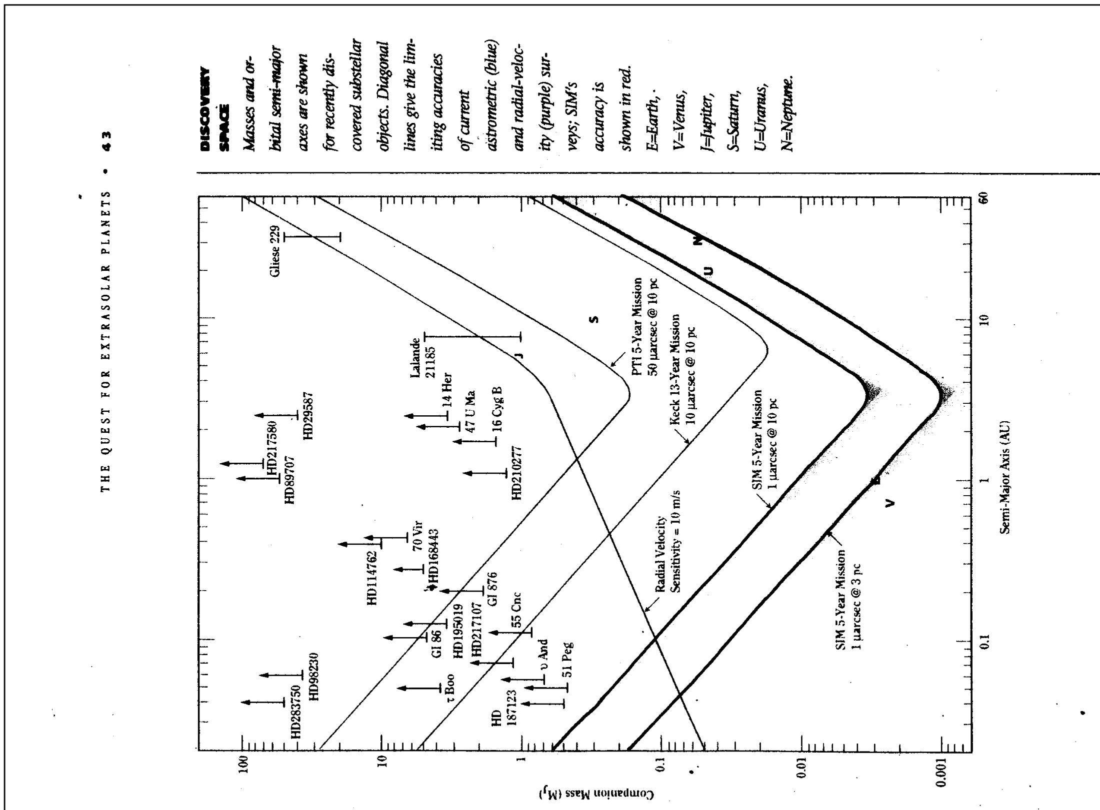
The Potential of Astrometry

- Search for Brown Dwarf companions to M-type stars
- Mass determination for planets detected in spectroscopic radial velocity surveys
- Inventory of planets around stars of various masses and spectral types (e.g., A to M)
- Gas giants around pre-main-sequence stars (→ phase of planet formation)
- Coplanarity of multiple companions (→ formation and dynamical evolution)
- Search for terrestrial planets in Solar neighborhood

Astrometry Compared with Radial Velocity Method

+ More sensitivity to planets at large distance from parent star
+ Mass determination without sin i problem
+ Applicable to all stellar types
+ Less susceptible to photospheric noise

– Less sensitivity to planets close-in
– Linear dependence of sensitivity on distance from Earth
– More complex and expensive technology



Astrometric Signature for Different Planets

Planet	Orbit [AU]	Star	Amplitude $\cdot\, d$ [μas $\cdot$ pc]
Earth	1	G2	3
Jupiter	5	G2	4 800
Uranus	20	G2	880
Jupiter	0.1	G2	96
Brown Dwarf	0.1	M5	7 500
Jupiter	5	A5	2 200
Jupiter	5	M5	24 000

What can be done with the VLTI?

- Require $4\,\sigma$ peak-to-peak variation for secure detection
- Case 1: VLTI with $50\,\mu$as precision (near-term)
- Case 2: VLTI with $10\,\mu$as precision (long-term)
- Case 3: Space interferometer with $1\,\mu$as precision

Science with 50μas Precision

Planet	Orbit [AU]	Star	maximum distance [pc]
Jupiter	5	G2	48
Uranus	20	G2	9
Brown Dwarf	0.1	M5	75
Jupiter	5	A5	22
Jupiter	5	M5	240

- Brown dwarfs around all M dwarfs to VLTI sensitivity limit
- Jupiter-like planets along the main sequence
- Multiplicity of gas giants around nearby G stars

Science with 10μas Precision

Planet	Orbit [AU]	Star	maximum distance [pc]
Jupiter	5	1 $M_\odot$	240
Uranus	20	G2	44
Jupiter	5	A5	110
10 Earths	1	G2	1.5

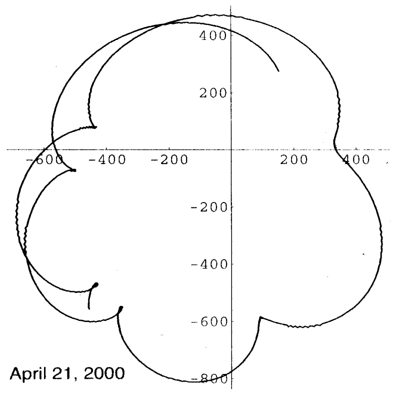
- Jupiter-like planets around pre-main-sequence stars
- Survey for multiple systems with better signal-to-noise
- Massive terrestrial planets around α Cen A and ε Eri

Astrometric Detection of Upsilon Andromedae

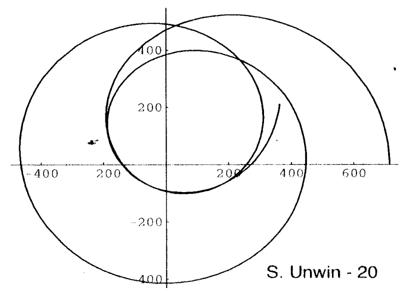
- Astrometric signature:
  - b: amplitude = 2.3 µas radial velocity 70 m/s
  - c: amplitude = 89.3 µas radial velocity 58 m/s
  - d: amplitude = 557.5 µas radial velocity 70 m/s
- Distance: 15 pc

SIM Space Interferometry Mission
A NASA Origins Mission

Upsilon Andromedae
viewed face on



Our Solar system
viewed from 15 pc, face-on



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Science with 1μas Precision (from Space)

Planet	Orbit [AU]	Star	maximum distance [pc]
Jupiter	0.1	G2	48
Earth	1	G2	1.5

- Jupiters in close orbits around G stars
- Survey for massive terrestrial planets in Solar neighborhood (a few to ~ 20 pc)
- Search for Earth twins around closest stars

Other Applications of Astrometry with the VLTI

- Mass determination of single-lined spectroscopic binaries
- Relative parallaxes (problem: conversion to absolute)
- Dynamics of globular clusters (problems: crowding, interferometric field-of-view)
- Orbits of stars in Galactic Center cluster, detection of infrared counterpart to Sgr A*

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Reference star measurement noise

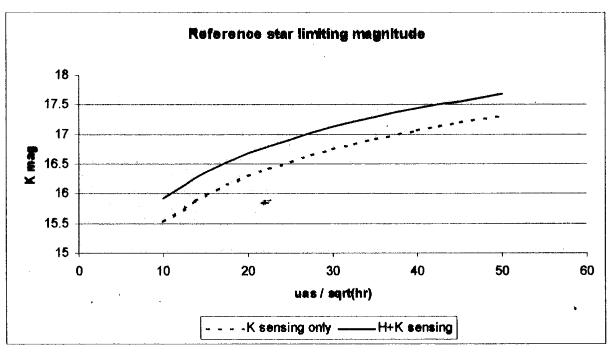
- Astrometric error given by

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

where

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

- Simultaneous H+K measurement required to achieve adequate SNR
- Measurement noise < 30 uas / hr for K<17.1



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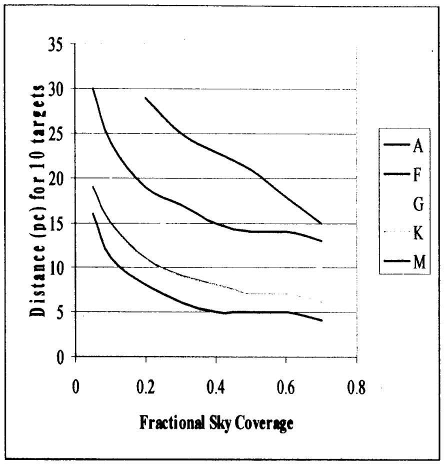
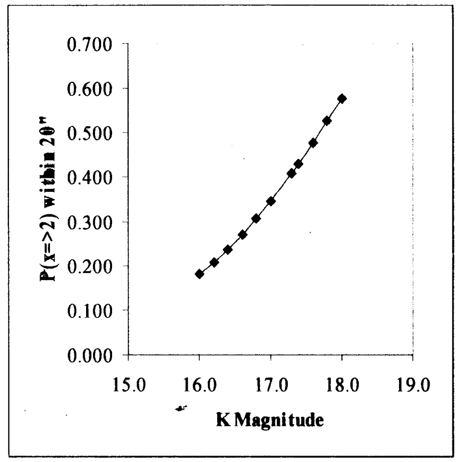
KECK

Star Availability, Counts





Keck Interferometer Astrometry

Are there Reference Stars?

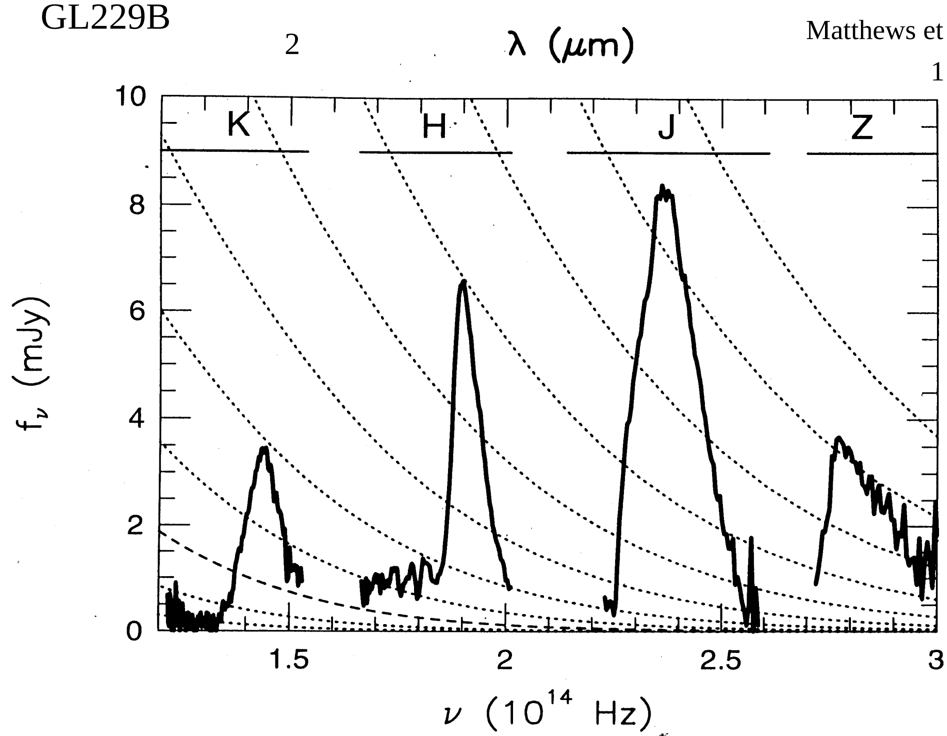
- Correlate catalogs with USNO-A1.0 to find reference stars
- Gives some false detections (target star itself, galaxies)
- Hipparcos Catalog ($\delta \leq 20°$):
  - 4760 stars with $\pi \geq 20\,\mathrm{mas}$
  - 1762 of these with 3 reference stars within $50''$
  - 734 of these with 3 reference stars within $30''$
  - 1018 stars with $\pi \geq 40\,\mathrm{mas}$
  - 130 stars with $\pi \geq 100\,\mathrm{mas}$
- Gliese Catalog ($\delta \leq 20°$):
  - 2381 stars
  - 874 of these with 3 reference stars within $50''$

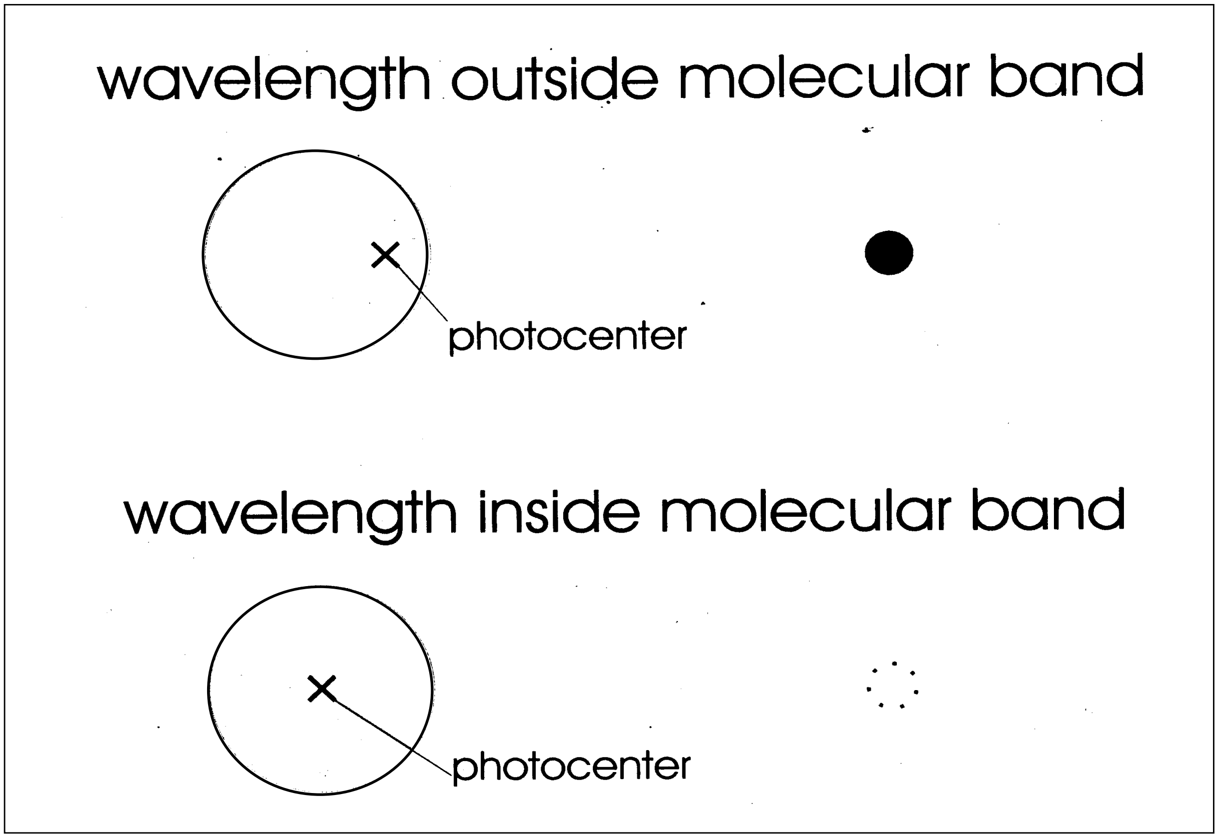
The Use of Double Stars

- Advantage: nearby reference, in most cases common proper motion (physical binary)
- Disadvantage: ambiguity of parent star for planets
- Washington Double Star Catalog ($\delta \leq 20°$):
  - 4566 stars with $20'' \leq d \leq 60''$
  - 6413 stars with $10'' \leq d \leq 20''$
  - 6518 stars with $5'' \leq d \leq 10''$
  - 745 FGK main sequence stars with $5'' \leq d \leq 20''$, $V \leq 10$
  - 23 G main sequence stars with $5'' \leq d \leq 20''$, $V \leq 7.5$

GL229B

Matthews et al. (1996)



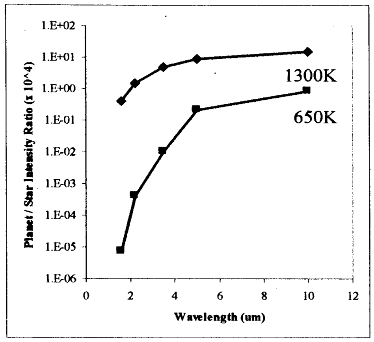


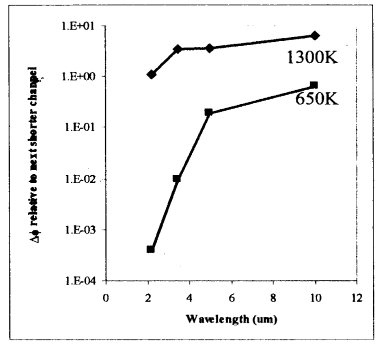
SNR Required for Direct Planet Detection

- For example 51 Peg B in the near-IR
- Contrast star – planet is $\sim 10^{-4}$
- Separation star – planet is ~ 10 mas
- Shift of photocenter is $\sim 1\,\mu$as
- Resolution of VLTI is 2 mas
- Precision required for differential phase measurements is ~ 0.5 mrad
- SNR required for phase measurements is ~ 3000

Signal-to-Noise Ratio for Detecting Warm Jupiters

- H-K Example
  - 1300K planet
  - $\Delta\varphi_K = 1.11\times10^{-4}$ rad
  - Requires SNR= 10^4
  - For m_K= 4.0, SNR = 2000 in 10 ms → 0.25 s
- M-N Example
  - 650K Planet
  - $\Delta\varphi_M = 0.63\times10^{-4}$ rad
  - Requires SNR=1.6×10^4
  - For m_M= 4.0, SNR = 700 in 10 ms → $t = 6$ s

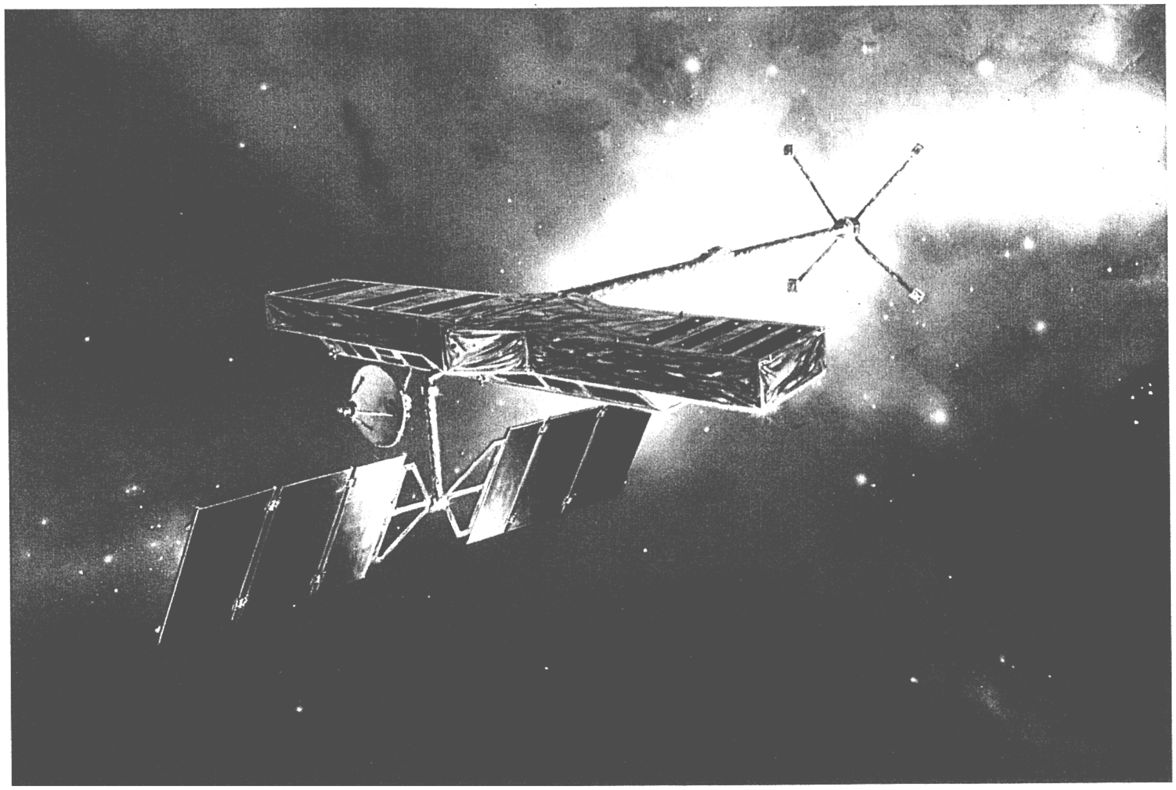


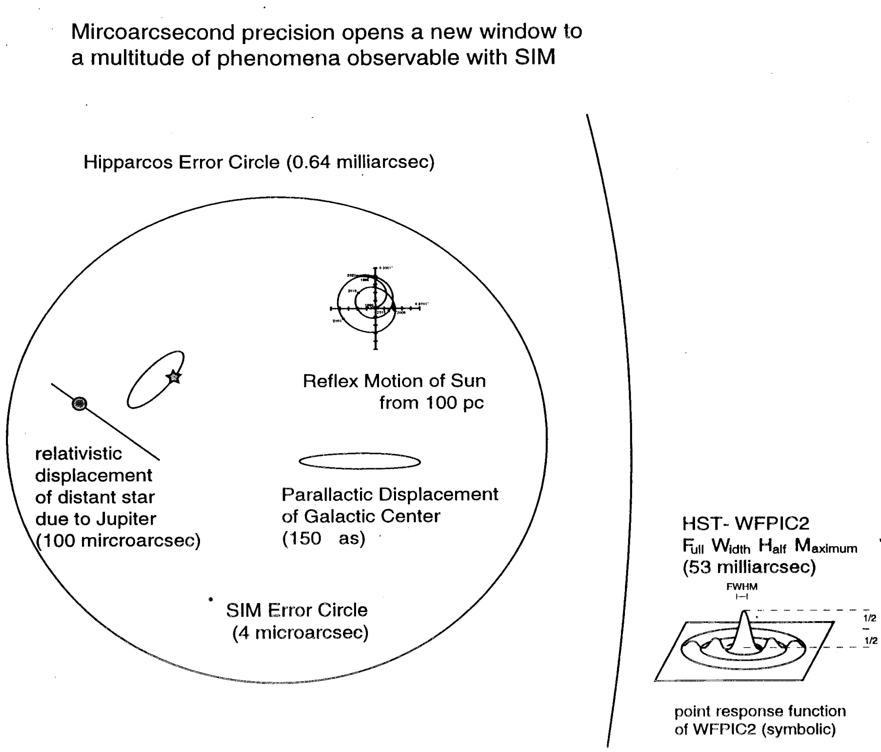


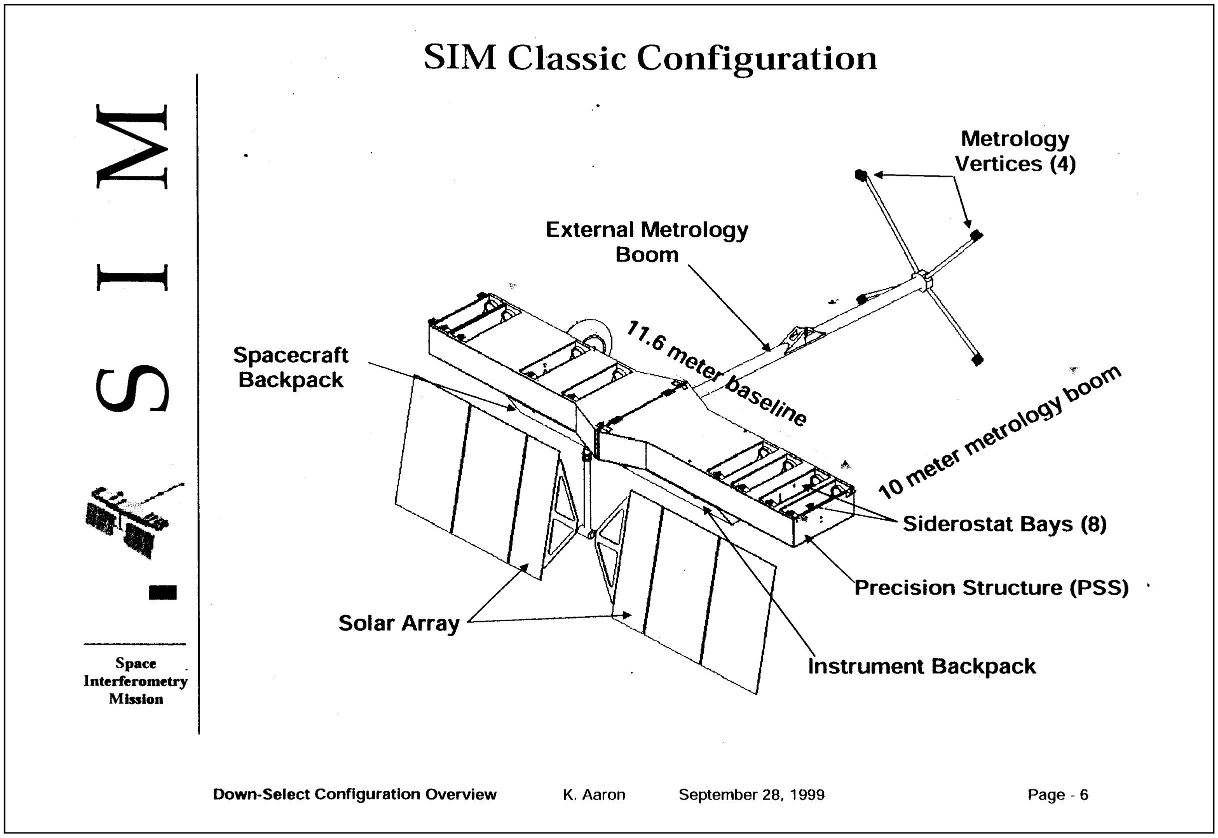
Wavelength (μm)	1300 K Planet (51 Peg) Planet/Star Intensity Ratio (x 10^4)	Δϕ relative to next shorter channel	650 K Planet (ρ CrB) Planet/Star Intensity Ratio (x 10^4)	Δϕ relative to next shorter channel
1.6	0.39		0.000	
2.2	1.50	1.11	0.010	0.01
3.5	4.90	3.40	0.200	0.19
5	8.50	3.60	0.830	0.63
10	15.00	6.50	3.400	2.57

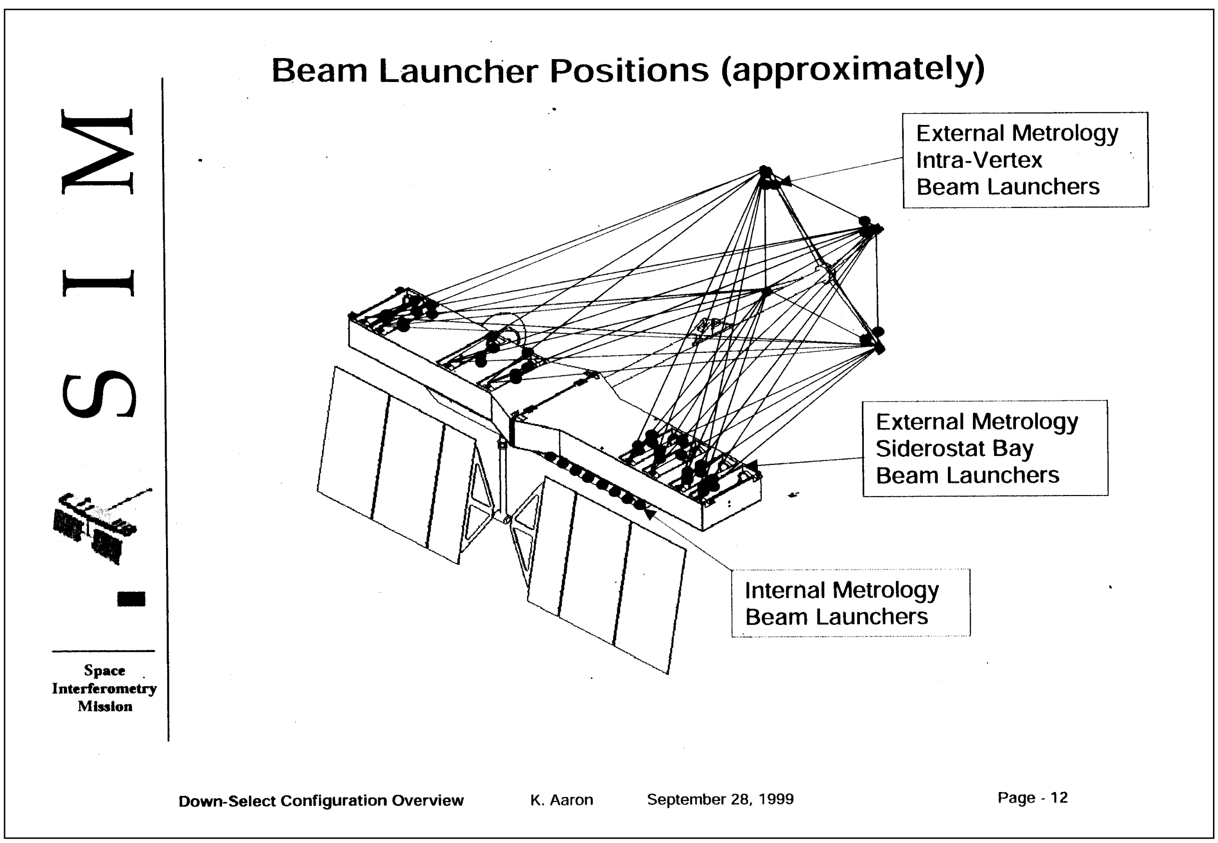
Conclusions

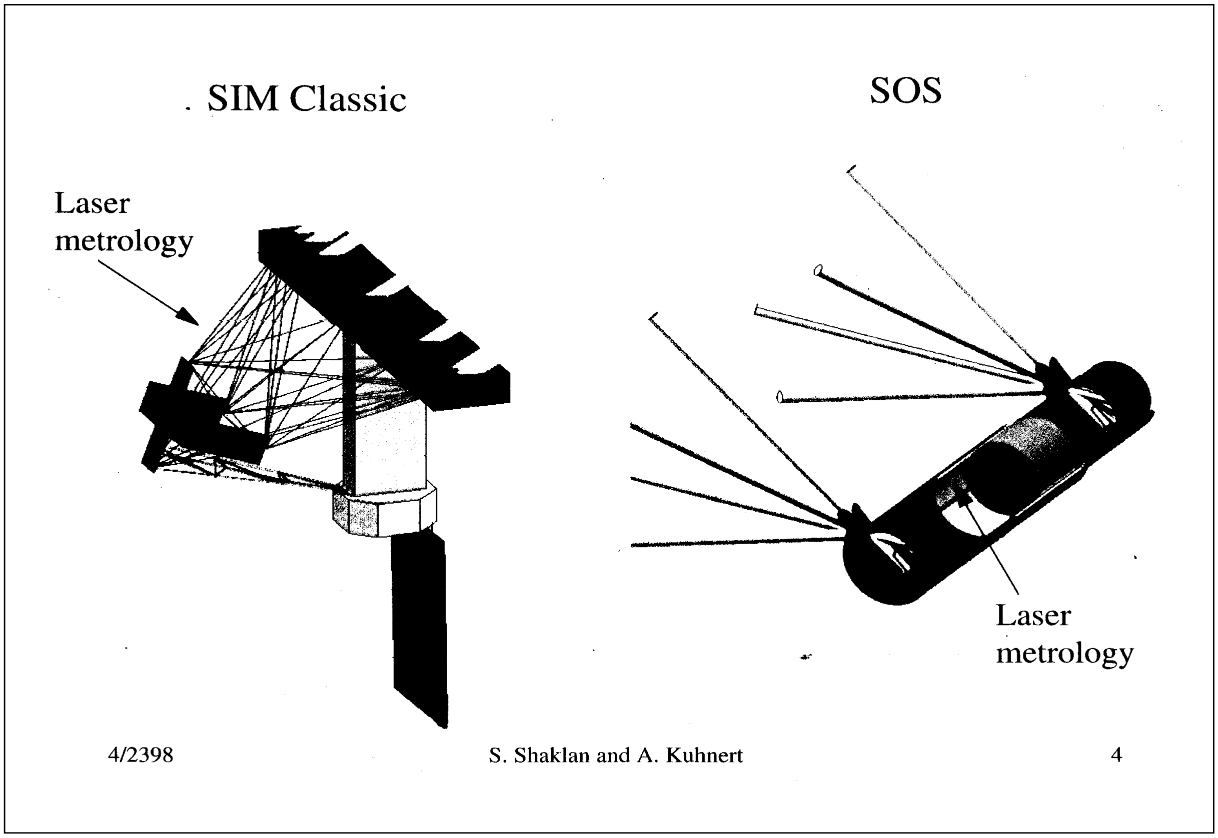
- Interesting planet detection projects possible at 50 μas precision (brown dwarfs, gas giants)
- Additional science with 10 μas precision (planets around pre-main-sequence stars, multiplicity surveys, large terrestrial planets)
- Search for Earth twins requires going to space (important driver for NASA's Space Interferometry Mission)
- Careful preparation and selection of target and reference stars needed

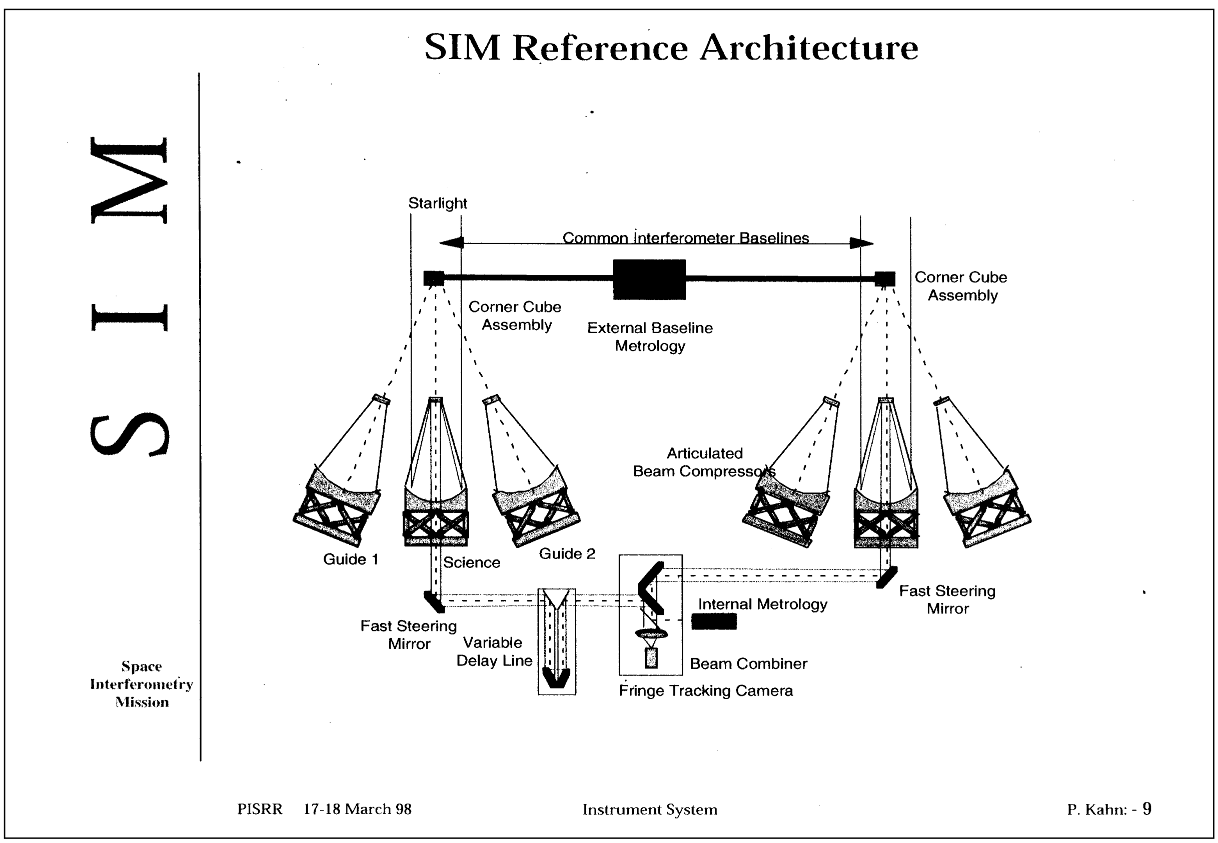


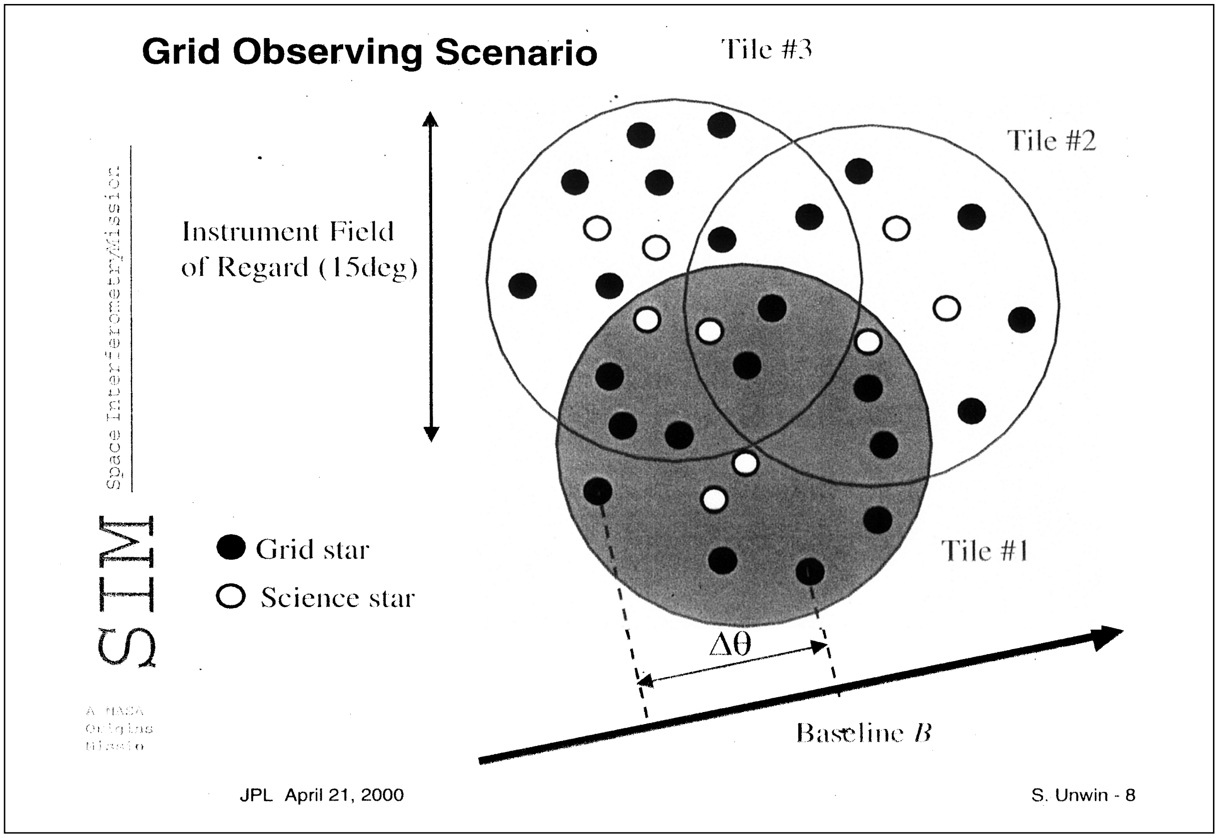

Mircoarcsecond precision opens a new window to
a multitude of phenomena observable with SIM
Hipparcos Error Circle (0.64 milliarcsec)
Reflex Motion of Sun
from 100 pc
relativistic
displacement
of distant star
due to Jupiter
(100 mircroarcsec)
Parallactic Displacement
of Galactic Center
(150 as)
SIM Error Circle
(4 microarcsec)
HST- WFPIC2
Full Width Half Maximum
(53 milliarcsec)
FWHM
1/2
1/2
point response function
of WFPIC2 (symbolic)


SIM Classic Configuration
SIM
Space Interferometry Mission
Metrology Vertices (4)
External Metrology Boom
11.6 meter baseline
Spacecraft Backpack
10 meter metrology boom
Siderostat Bays (8)
Precision Structure (PSS)
Solar Array
Instrument Backpack
Down-Select Configuration Overview
K. Aaron
September 28, 1999
Page - 6


Beam Launcher Positions (approximately)
SIM
Space Interferometry Mission
External Metrology Intra-Vertex Beam Launchers
External Metrology Siderostat Bay Beam Launchers
Internal Metrology Beam Launchers
Down-Select Configuration Overview
K. Aaron
September 28, 1999
Page - 12


SIM Classic
SOS
Laser metrology
Laser metrology
4/2398
S. Shaklan and A. Kuhnert
4


SIM Reference Architecture
SIM
Space Interferometry Mission
Starlight
Common Interferometer Baselines
Corner Cube Assembly
External Baseline Metrology
Corner Cube Assembly
Articulated Beam Compressors
Guide 1
Science
Guide 2
Fast Steering Mirror
Variable Delay Line
Internal Metrology
Beam Combiner
Fringe Tracking Camera
Fast Steering Mirror
PISRR 17-18 March 98
Instrument System
P. Kahn: - 9



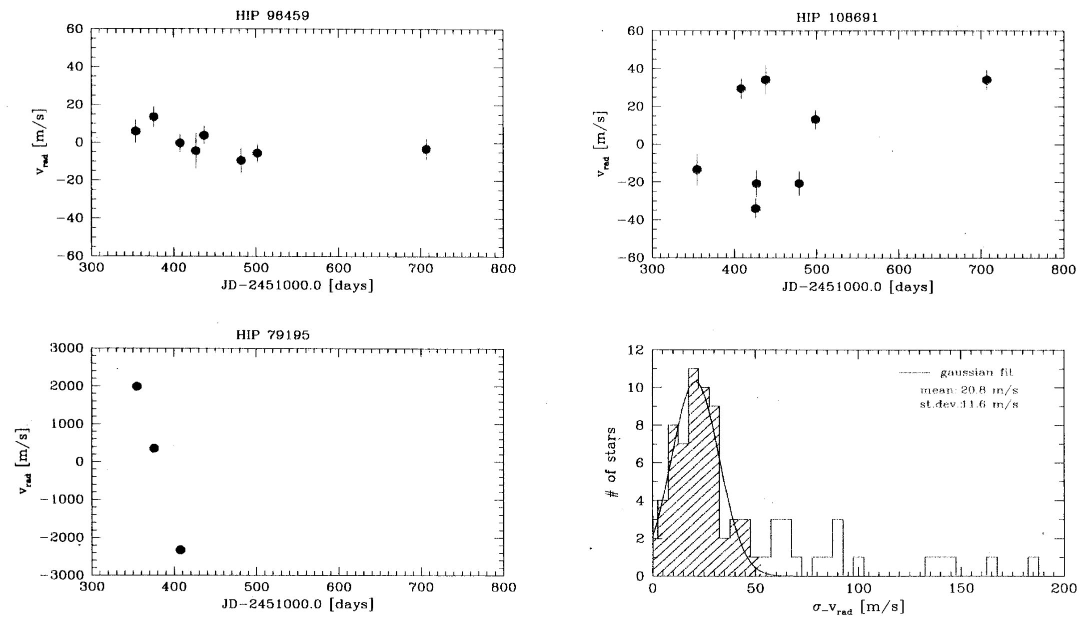
How to Find Reference Stars for SIM

Need $\sim$ 3000 stars distributed evenly over the sky that are stable on the microarcsecond level

1. Select stars that are sufficiently far away so that planetary companions don't matter (K giants at $\sim 2\,\mathrm{kpc}$)
2. Take advantage of "brown dwarf desert"
3. Weed out binaries with stellar companions through high-resolution spectroscopy

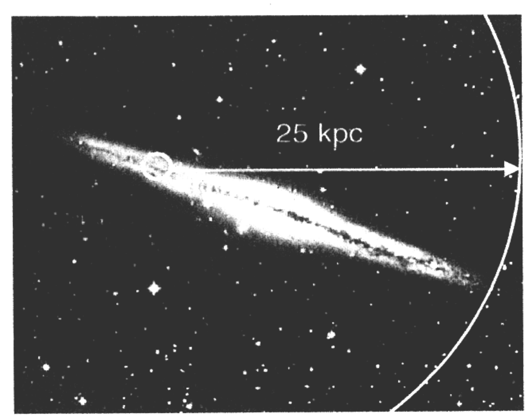
$\Rightarrow$ Have to demonstrate that K giants have sufficiently stable photospheres

Proxy Sample Results



Measuring Distances in the Galaxy

- SIM will reach high accuracy on faint targets
  - 4 μas positions
  - 3 μas / yr proper motions
  - Limiting mag V = 20
- G-dwarf at 3 kpc:
  - V = 17.5, accuracy 1 %
- KIII giant at 25 kpc:
  - V = 15, accuracy 10 %
- Combination enables demanding programs, like:
  - rotational parallaxes
  - tidal tails of disrupted dwarf galaxies



SIM Space Interferometry Mission

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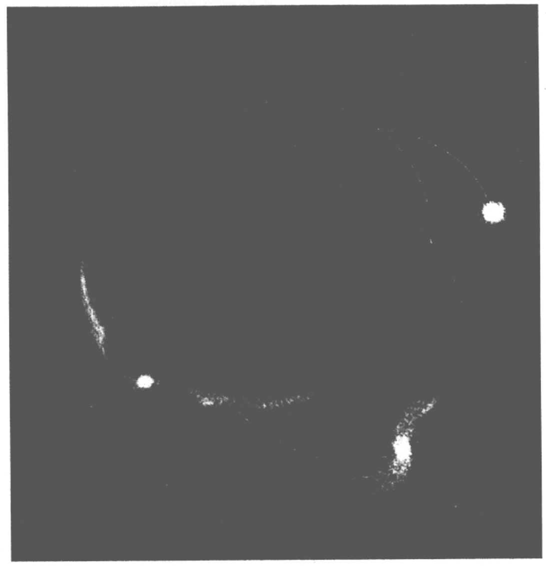
Galactic Dynamics

SIM Space InterferometryMission

A NASA Origins Missin

- Study the 'classical' problems of size, mass distribution, and dynamics of the Galaxy, using stellar velocities
- Example:
  - Debris tail orbits (Sagittarius dwarf galaxy)
    - characteristic phase space signature
  - Distances to 5% at 10 kpc, for stars with V < 20
  - Proper motions to 0.1 km/s at 10 kpc
  - Combine with ground-based radial velocities



'Tidal tail' simulation:
Dwarf galaxy in orbit around the Milky Way

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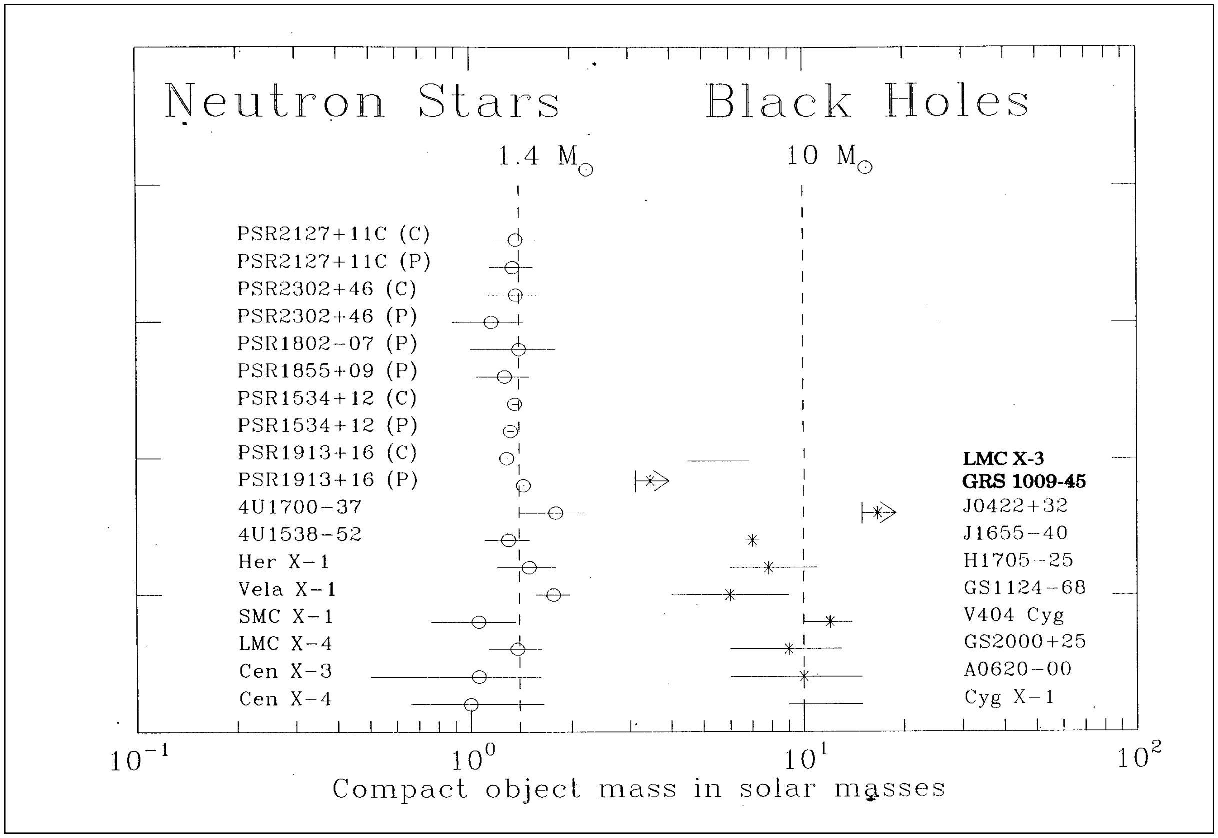
SIM Observations of X-Ray Binaries

- Mass function of Black Hole Candidates (BHCs)
- Existence of black holes with $M \lesssim 5\, M_\odot$ formed via accretion-induced neutron star collapse?
- Existence of black holes with $M \gtrsim 20\, M_\odot$ whose progenitors retained most of their mass until collapse?
- Mass of Neutron Stars: constraints on equations of state
- Luminosities from parallaxes: test of models (existence of event horizon in BHCs, ADAF models)
- Age of population from proper motions


Neutron Stars
Black Holes
1.4 M⊙
10 M⊙
PSR2127+11C (C)
PSR2127+11C (P)
PSR2302+46 (C)
PSR2302+46 (P)
PSR1802−07 (P)
PSR1855+09 (P)
PSR1534+12 (C)
PSR1534+12 (P)
PSR1913+16 (C)
PSR1913+16 (P)
4U1700−37
4U1538−52
Her X−1
Vela X−1
SMC X−1
LMC X−4
Cen X−3
Cen X−4
LMC X-3
GRS 1009-45
J0422+32
J1655−40
H1705−25
GS1124−68
V404 Cyg
GS2000+25
A0620−00
Cyg X−1
10^{-1}
10^{0}
10^{1}
10^{2}
Compact object mass in solar masses