PRIMA
Astrometry with the VLTI

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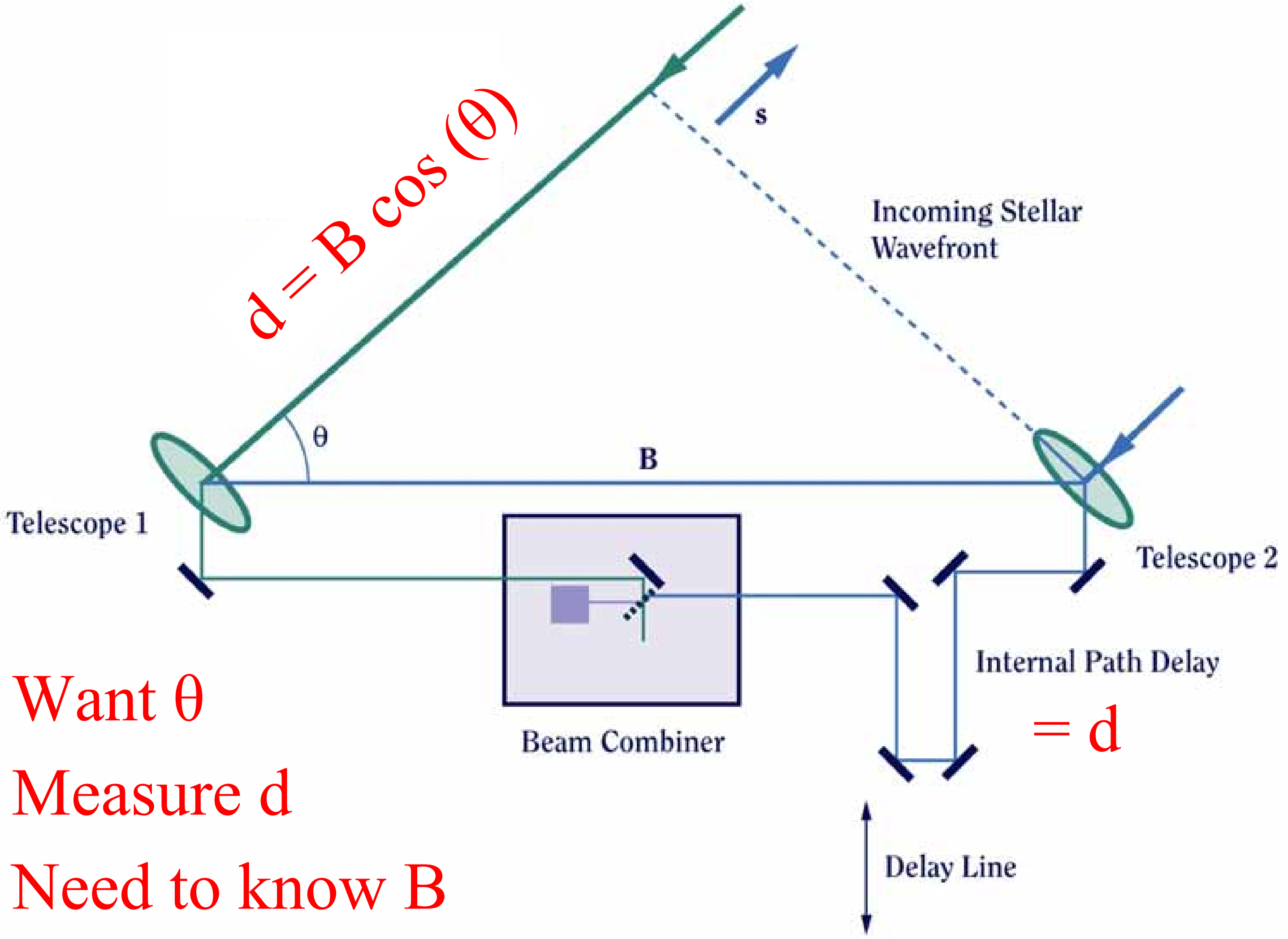
The VLT Interferometer

The First Two VLTI Auxiliary Telescopes (ATs)

Astrometric Measurement with an Interferometer



$d = B \cos(\theta)$

$= d$

Want θ

Measure d

Need to know B

PRIMA Operational Principles

- Extremely high precision (many things need to be done to 1/1000th of a wavelength)

⇒

- Use only ATs for high-precision astrometry
- Differential measurements wherever possible
- Monitoring of system and environment
- Systematic data reduction and calibration

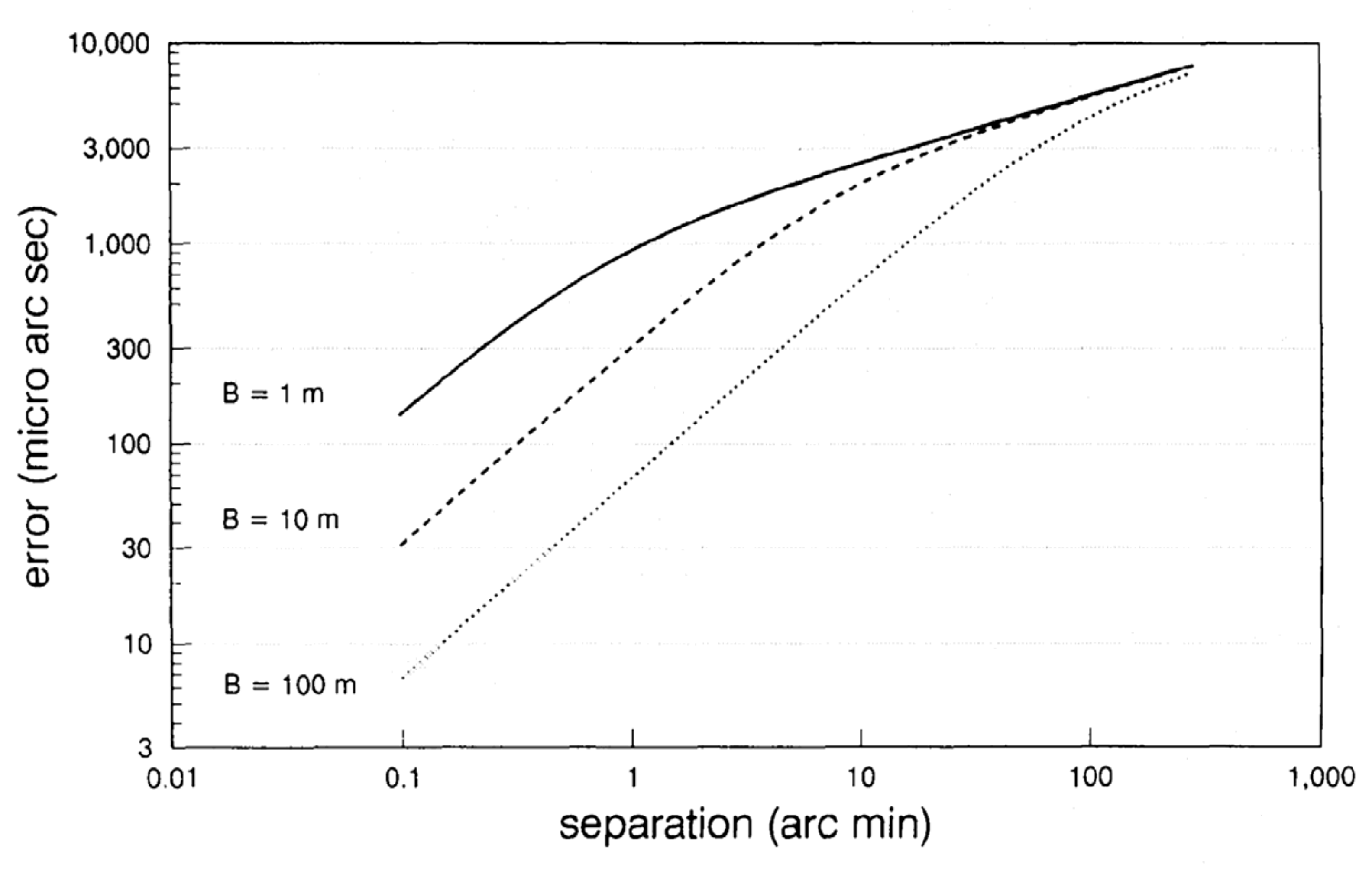
Some Complications and their Solutions

- Atmosphere induces random variations of stellar position
- Internal motion of mirrors (vibrations, thermal drifts) cause delay errors

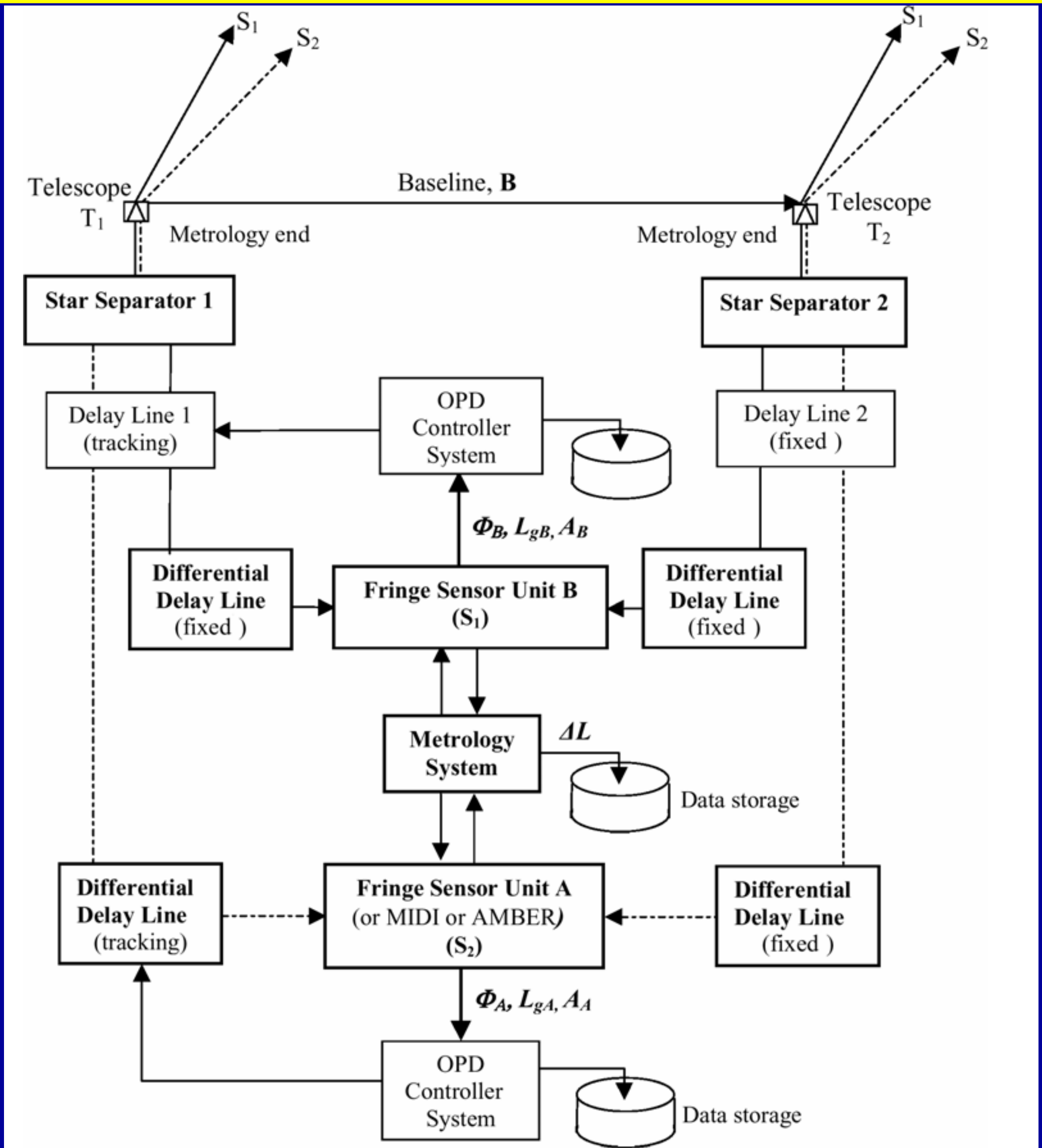
$$\Rightarrow$$

- Observe two stars simultaneously
- Monitor internal pathlength with laser metrology system

Atmospheric Limitation of Narrow-Angle Astrometry



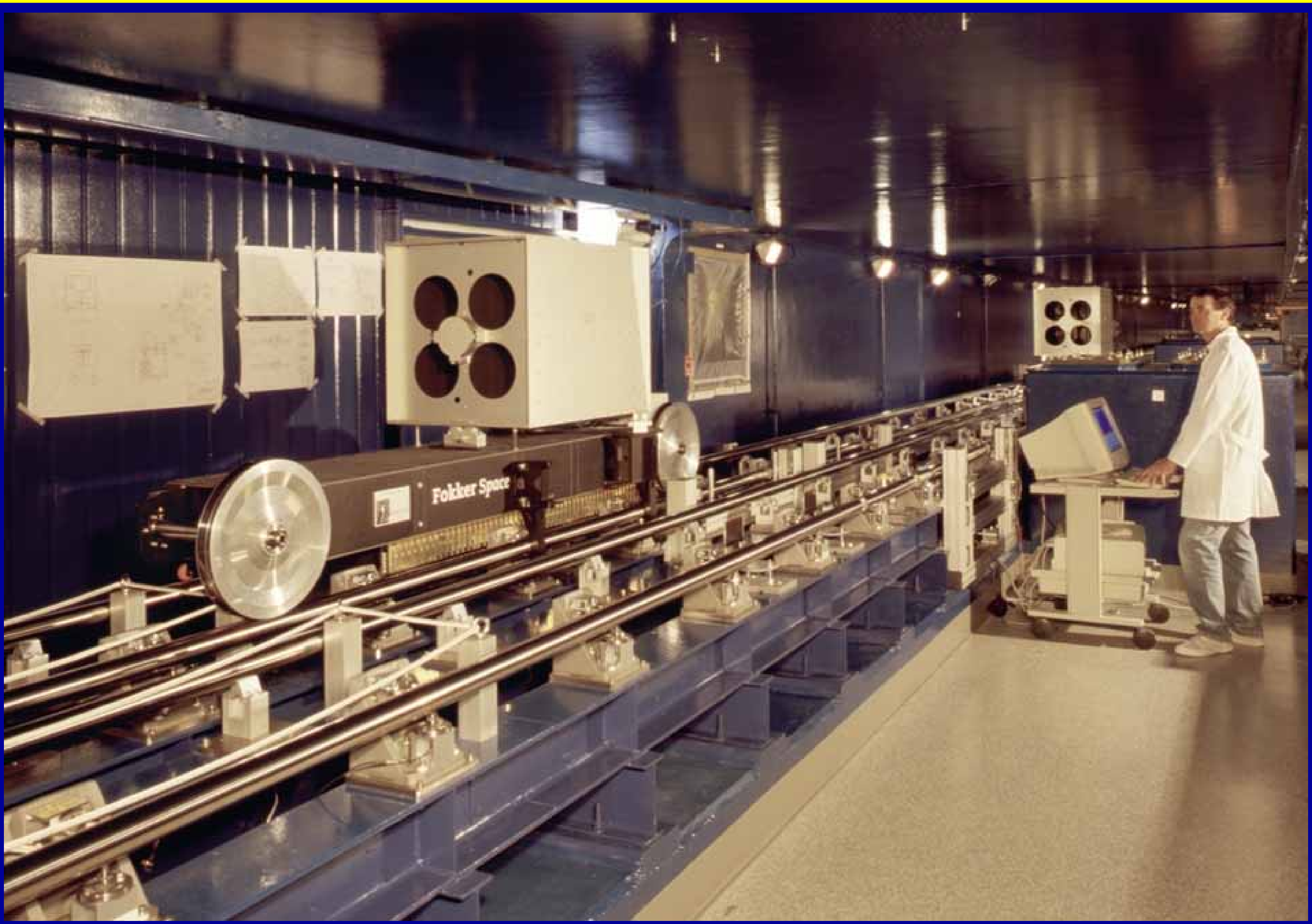
Dual-Star Interferometry



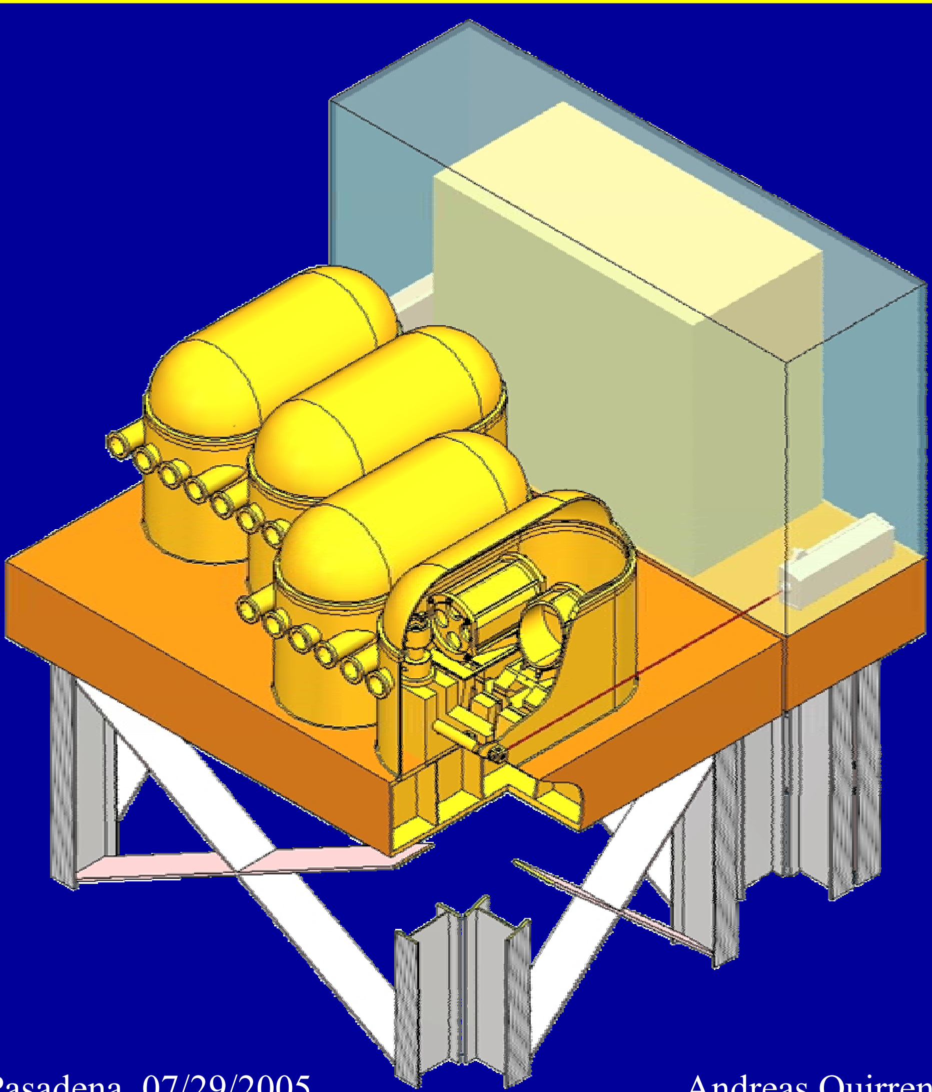
PRIMA = Phase-Referenced Imaging and Microarcsecond Astrometry

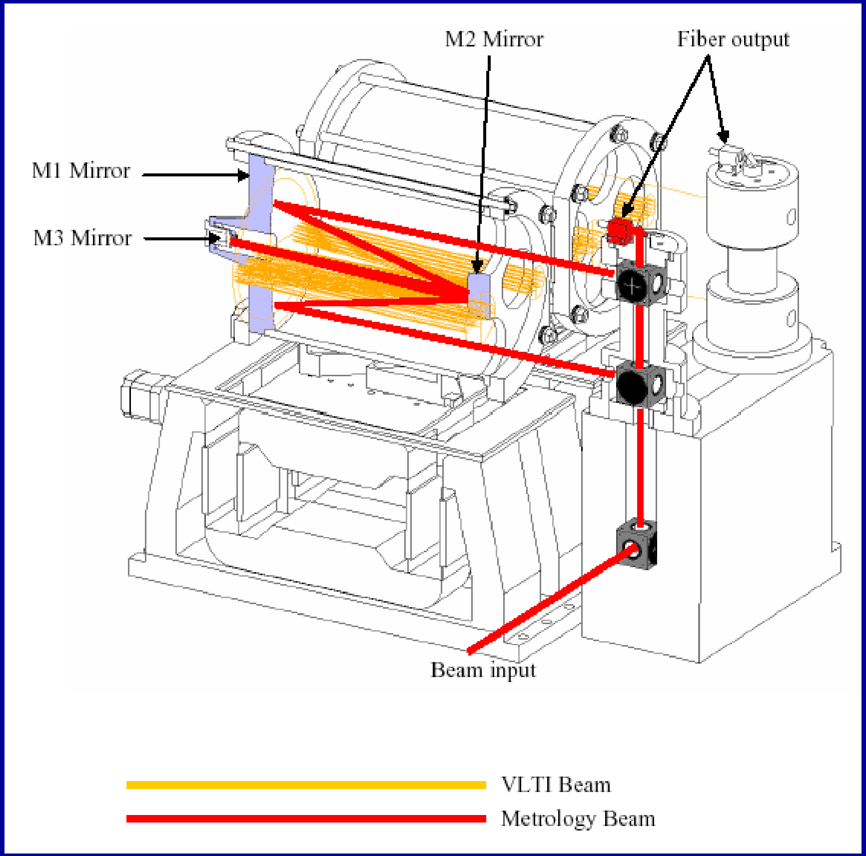
- VLTI infrastructure for dual-star interferometry
  - Dual-star modules at ATs and UTs
  - Delay lines which support beams from two stars
  - Differential delay lines
  - Beam combining instruments for primary and secondary star
  - Metrology system to tie delay measurements together
  - Software and operational concepts
- Phased implementation has started

VLTI Delay Lines

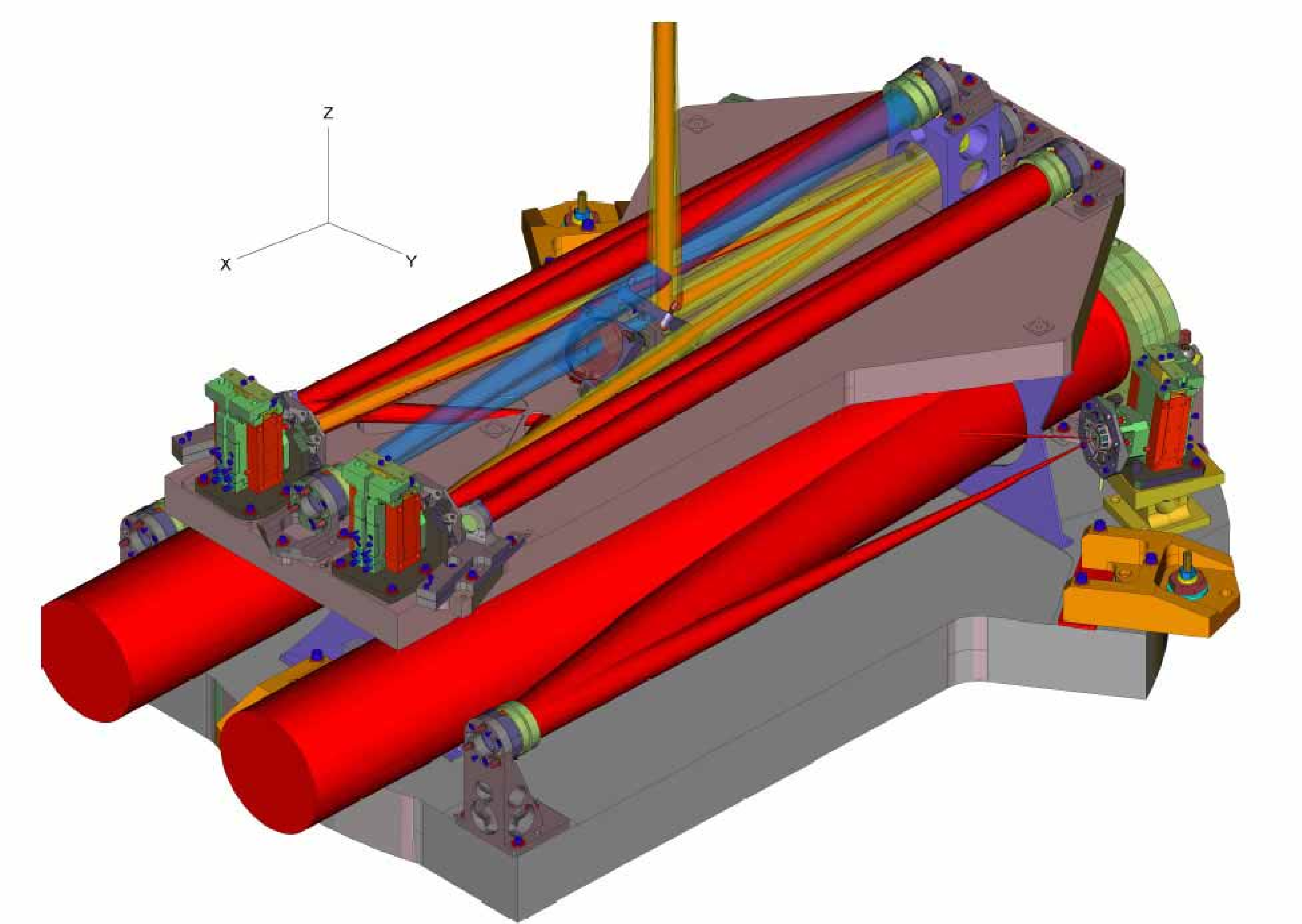


Differential Delay Line Design (PRIMA Planet Search Consortium)

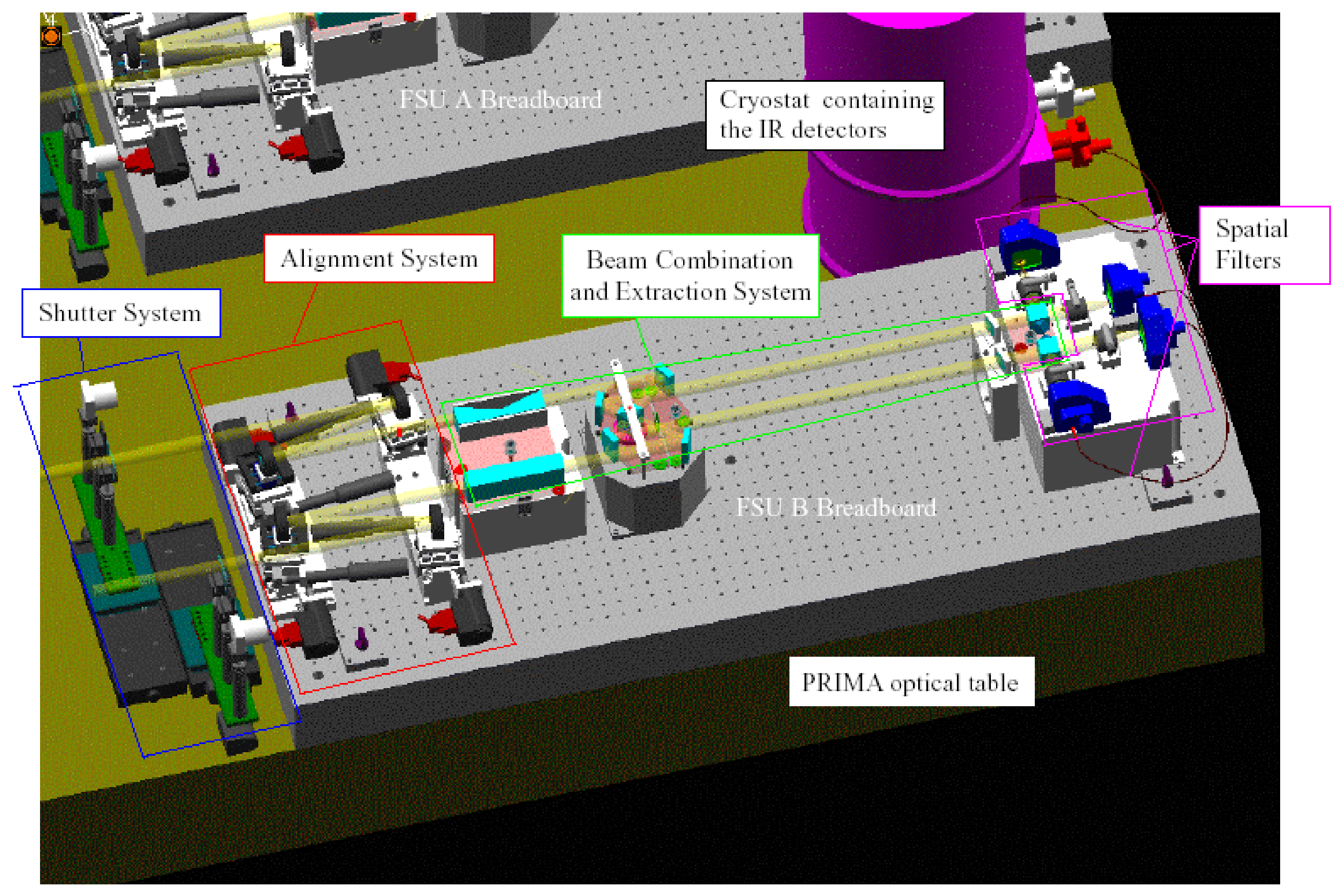




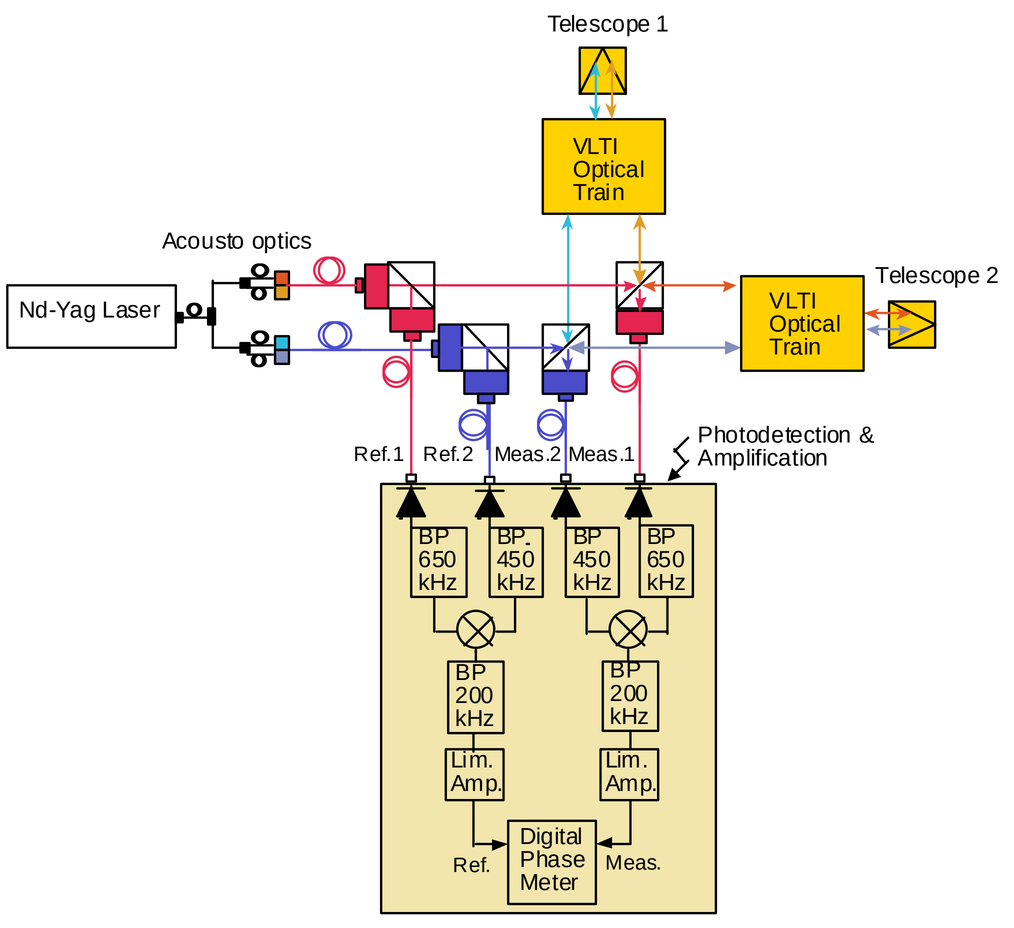
PRIMA Star Separator (TNO-TPD, Delft, Netherlands)

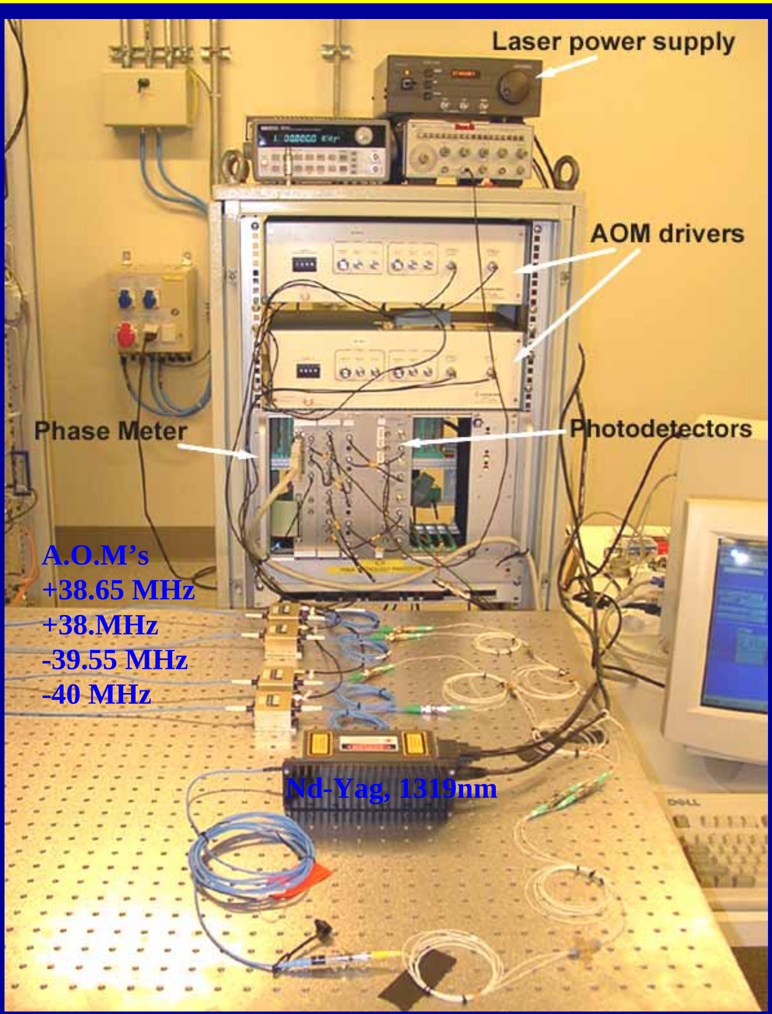


PRIMA Fringe Sensing Units (Alenia Spazio, Italy)



PRIMA Metrology System (ESO and IMT, Switzerland)

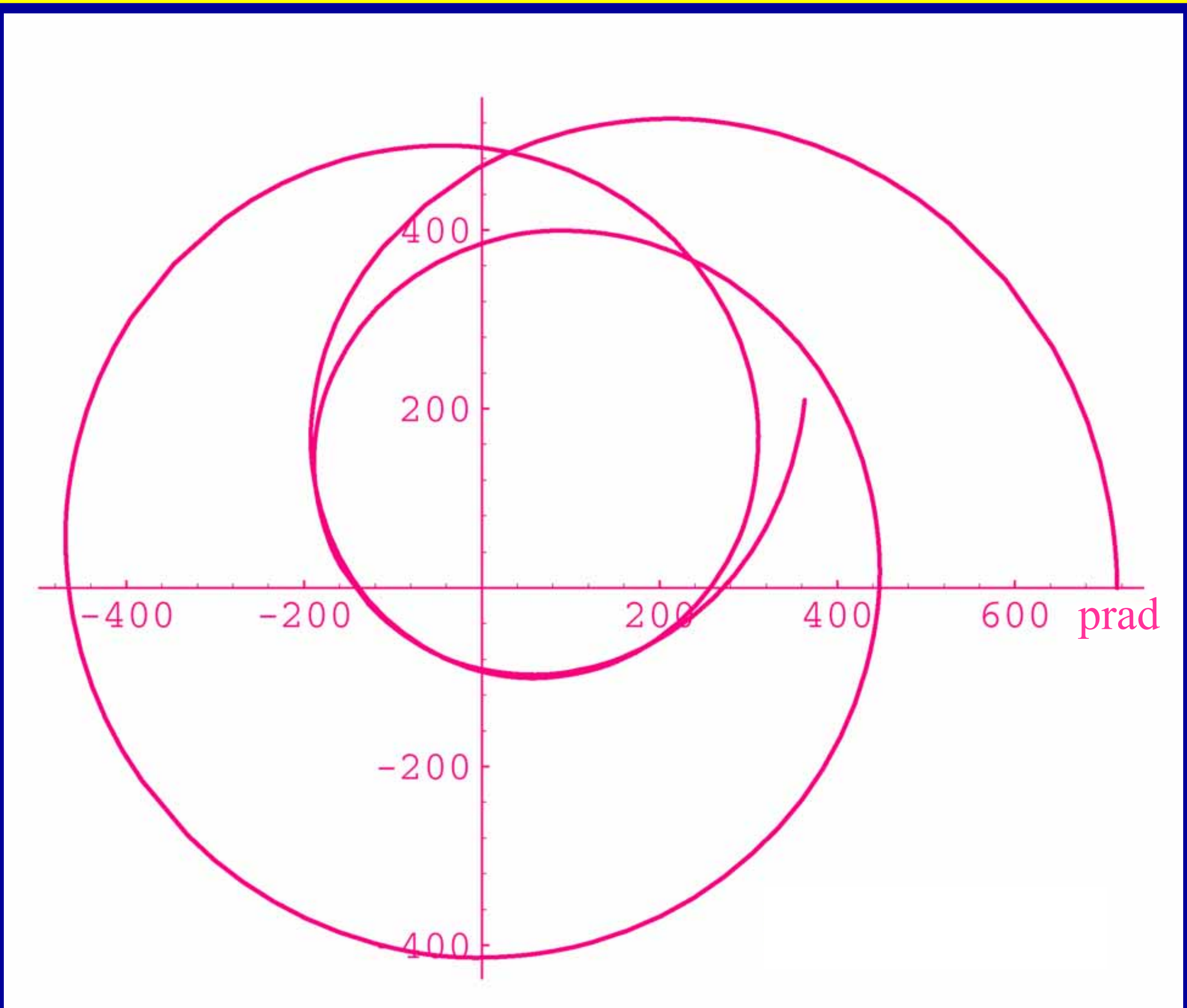




The PRIMA Planet Search Consortium

- U Geneva
  - IMT Neuchâtel
  - EPF Lausanne
- MPIA Heidelberg
- U Leiden
  - ASTRON
- Close interaction and collaboration with ESO

Motion of the Sun, Viewed Pole-on from 100 pc

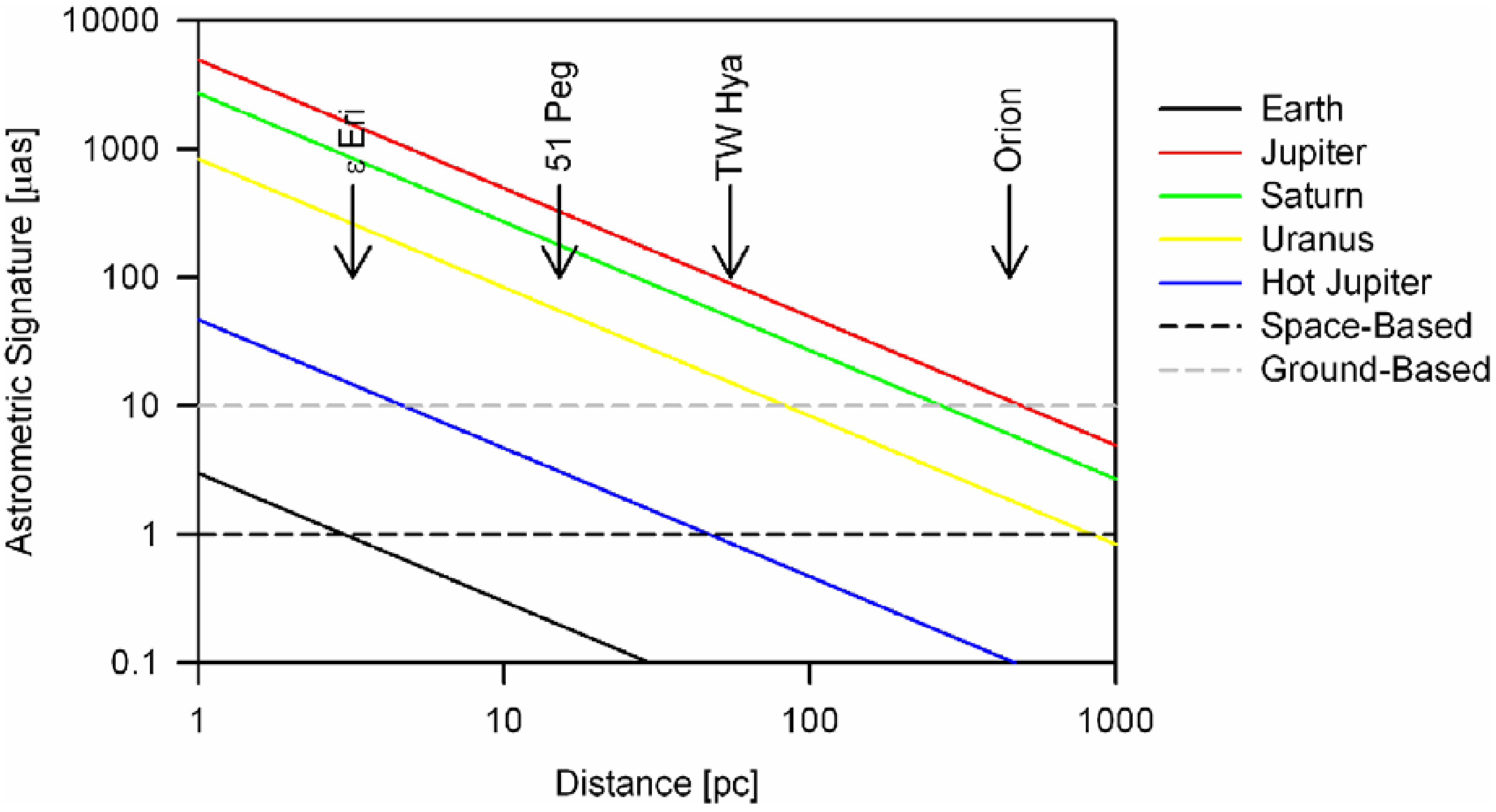


Amplitude:

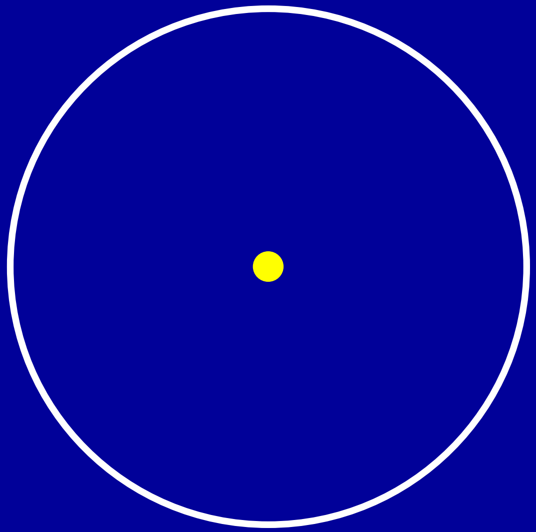
500 pico-radians

100 micro-arcsec

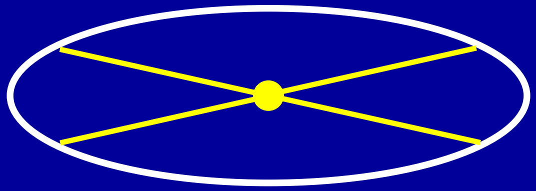
Requirements for Astrometric Planet Detection



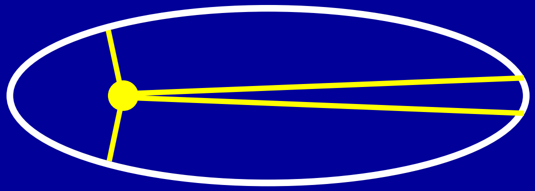
Deriving Inclination from Astrometric Observations



Circular Orbit
Face-on



Inclined
Circular Orbit

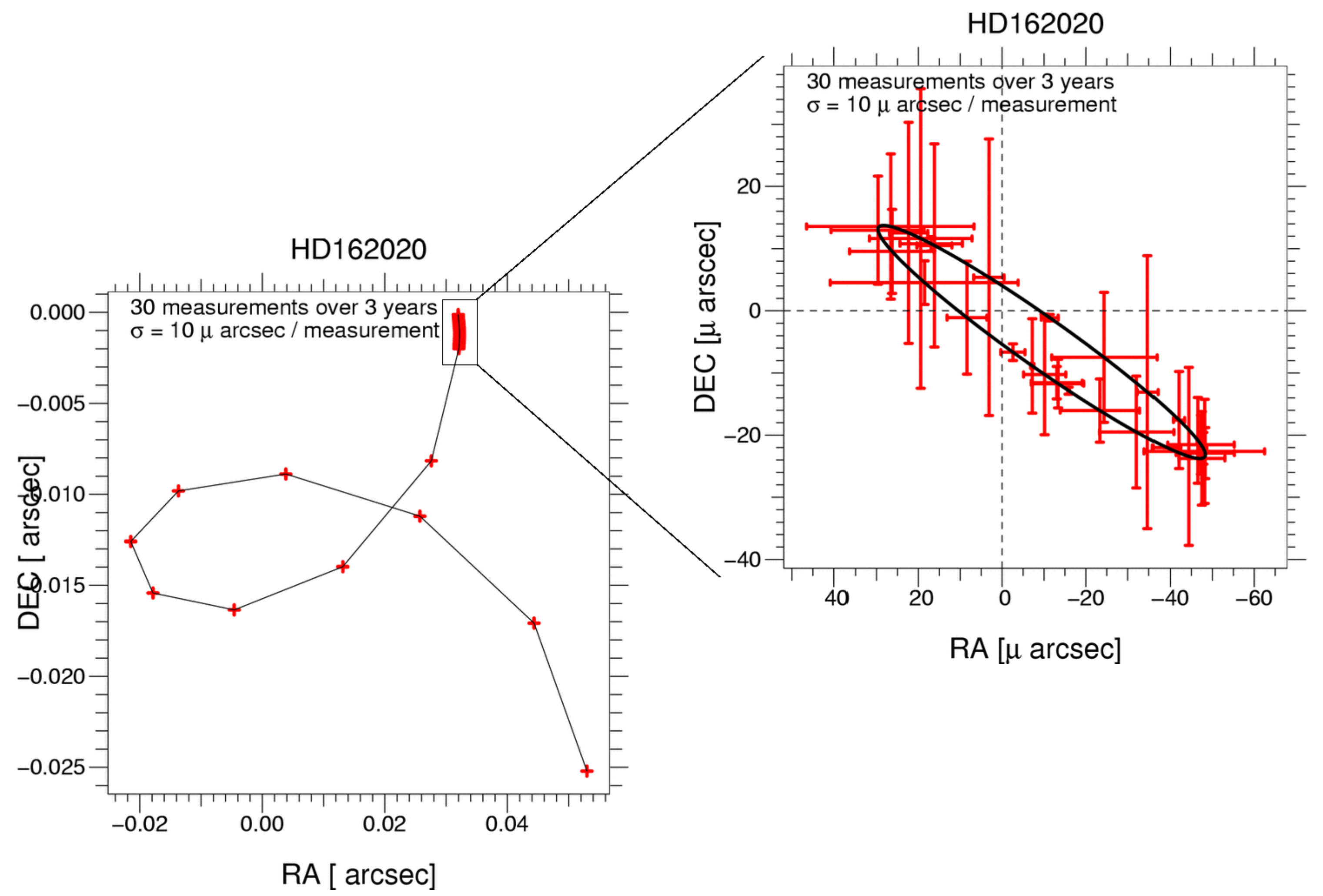


Elliptical Orbit
Face-on

Goals of Astrometric Planet Surveys

- Accurate mass determination for planets detected in radial-velocity surveys (no sin *i* ambiguity)
- Frequency of planets around stars of all masses
  - Relation between star formation and planet formation
- Gas giants around pre-main-sequence stars
  - Time scale of formation, test formation theories
- Coplanarity of multiple systems
  - Test interaction and migration theories
- Search for Solar System analogs
  - Detection of icy or rocky planets

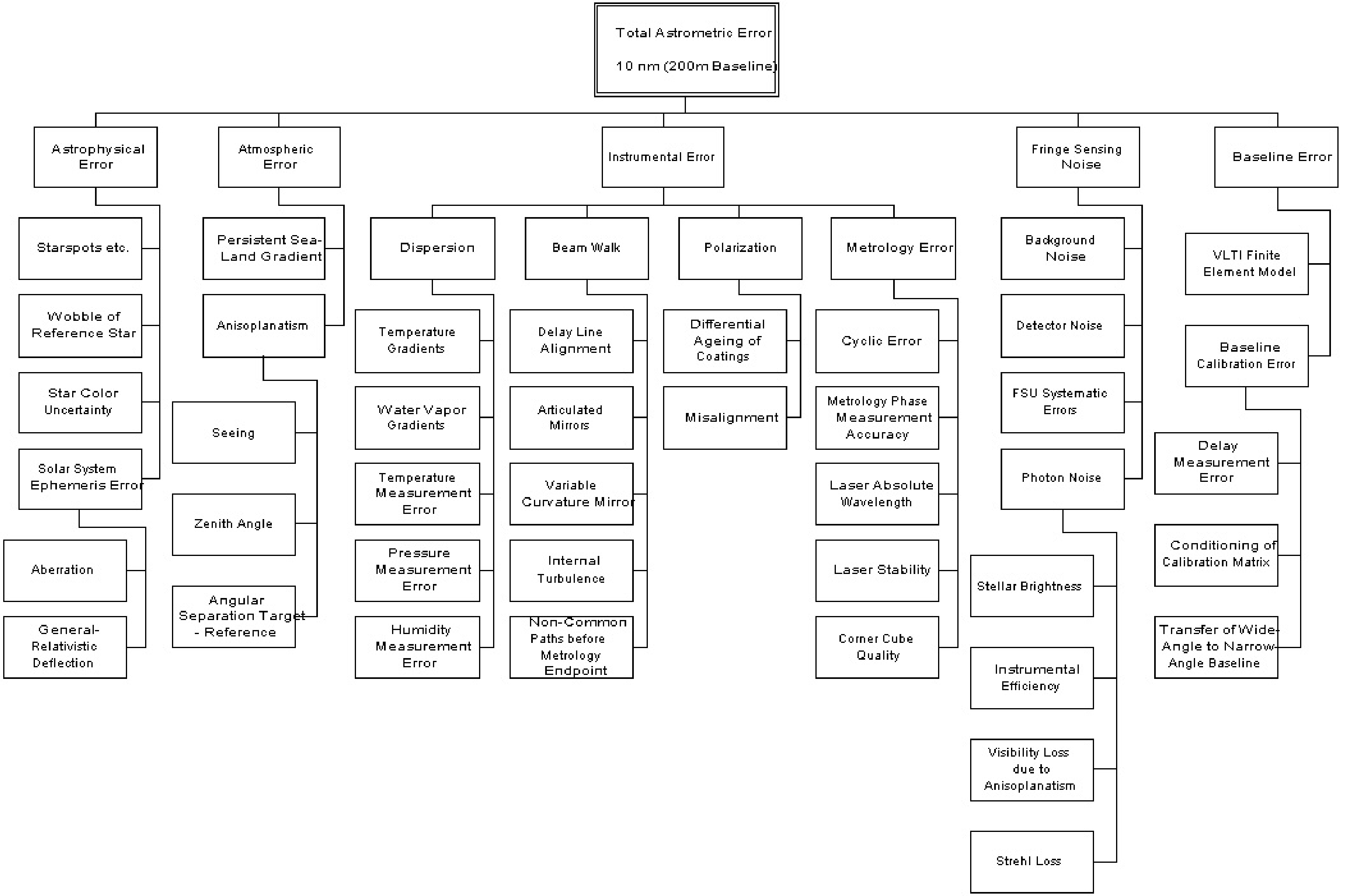
Simulation of Planet Observations with the VLTI



PRIMA Error Budget

- Step 1: Construct tree of all anticipated error sources for PRIMA
  - Systematic approach needed, but still danger of overlooking important effects
  - Methodological difficulty: many differences of large numbers
- Step 2a: Allocate admissible errors (top-down)
- Step 2b: Estimate predicted errors of components / sub-systems etc.
- Step 3: Iterate until 2a and 2b match

PRIMA Astrometry Error Tree



- Total Astrometric Error 10 nm (200m Baseline)
  - Astrophysical Error
    - Starspots etc.
    - Wobble of Reference Star
    - Star Color Uncertainty
    - Solar System Ephemeris Error
      - Aberration
      - General-Relativistic Deflection
  - Atmospheric Error
    - Persistent Sea-Land Gradient
    - Anisoplanatism
      - Seeing
      - Zenith Angle
      - Angular Separation Target - Reference
  - Instrumental Error
    - Dispersion
      - Temperature Gradients
      - Water Vapor Gradients
      - Temperature Measurement Error
      - Pressure Measurement Error
      - Humidity Measurement Error
    - Beam Walk
      - Delay Line Alignment
      - Articulated Mirrors
      - Variable Curvature Mirror
      - Internal Turbulence
      - Non-Common Paths before Metrology Endpoint
    - Polarization
      - Differential Ageing of Coatings
      - Misalignment
    - Metrology Error
      - Cyclic Error
      - Metrology Phase Measurement Accuracy
      - Laser Absolute Wavelength
      - Laser Stability
      - Corner Cube Quality
  - Fringe Sensing Noise
    - Background Noise
    - Detector Noise
    - FSU Systematic Errors
    - Photon Noise
      - Stellar Brightness
      - Instrumental Efficiency
      - Visibility Loss due to Anisoplanatism
      - Strehl Loss
  - Baseline Error
    - VLTI Finite Element Model
    - Baseline Calibration Error
      - Delay Measurement Error
      - Conditioning of Calibration Matrix
      - Transfer of Wide-Angle to Narrow-Angle Baseline

Principal Current Error Budget and Calibration Activities

- Fringe tracking and FSU output
- Dispersion effects and spectral channels in FSU
- Metrology zero-point calibration
- Polarization calibration
- Calibration of narrow-angle baseline

Fringe Measurement Requirements

- Fringe measurement precision is essential
  - Substantially better than 1° needed
- Reliable fringe identification is essential
  - Fringe jumps are unacceptable
  - Dispersed fringe detection is the best scheme
- Fringe tracking robustness is important
  - Atmosphere can be very unstable (Kolmogorov predictions cannot be used)
  - Need to recover from spells of bad seeing quickly

Types of Error

- Random errors with zero mean
- Systematic errors which can be accurately corrected
- Systematic errors which are difficult to correct

Random Errors with Zero Mean

- Eliminated by: Averaging many independent measurements – residuals easily determined by scatter in independent measurements
- Example: Effect of atmospheric turbulence after systematic contribution subtracted

Easily Corrected Systematic Errors

- Eliminated by: Accurate measurements of well-defined, easily measured parameters and application of basic physics
- Example: Relativistic effects due to the motion of Paranal with respect to the solar system center, and due to the gravitational potential well of the Sun and planets

Difficult Systematic Errors

- Eliminated by: Minimizing the error through the hardware design or observing strategy, and then trying to estimate the remaining error as best as possible
- Examples: Effect of cold outside air blowing through the VLTI ducts and tunnels, permanent or seasonal “wedge” of atmosphere from sea to mountains

Resolution of Problems

- If a single error term is too large, one can take one of several measures to solve the problem:
    1. Change the observation strategy
    2. Change the calibration strategy
    3. Improve the hardware performance
    4. Change the hardware design
- Error budget and Calibration / Operation Strategy are intimately related
    - Error budget reflects residuals after calibration

PRIMA Calibration Strategy

- PRIMA data are essentially quadruple-differential
  1. Target – Reference
  2. Stellar beam – Metrology beam
  3. Beam swap 1 – Beam swap 2
  4. Sky position at time 1 – Sky position at time 2
- In addition, there is a complicated relation between sky position and observed delay
- There is no way to meet specifications without getting all differences right ⇒ calibration and observing strategy are essential

Difference Target – Reference

- Random error: atmospheric anisoplanatism
  - Fundamental limitation of ground-based astrometry
  - Can in principle be integrated out
- Systematic error: PRIMA metrology zero point
  - Calibrated by injecting the light from the two stars alternatingly into the two feeds of the star separator ("beam swap")

Difference Starlight – Metrology

- Three fundamental sources of error
  - Dispersion between the two wavelengths
  - Beam walk on optical surfaces (different footprint of stellar and metrology beams)
  - Misalignment (metrology not on optical axis of telescope)
- Many complicated terms in error budget
  - Temperature differences, …
  - Alignment, straightness of delay line rails, …

Difference Beam Swap 1 – Beam Swap 2

- Good alignment of image de-rotator / star separator required
- Sensitive only to non-linear optical path drifts in light ducts (reduces some of the problems on previous slide)
- Introduces more stringent requirements on speed of re-acquisition
- Potential interruption of metrology beam during polarization swap

Difference Time 1 – Time 2

- Some errors (e.g., “wedge”) can be minimized by always observing at same hour angle
  - Implications for scheduling (“absolute time driven” versus “integration time driven”)
- Observing at many hour angles during one night produces over-constrained system
  - Enables consistency checks
  - Alternative calibration strategy
  - Implications for observing efficiency

Metrology Zero-Point Calibration Strategy

- Use image de-rotator to swap target and reference star beams
- Each observation consists of a few (perhaps 2) “swap cycles”
- Eliminates metrology zero point
- Applies time filter to differences between metrology and star light
    - Solves main issue with dispersion between starlight and metrology in the delay lines and feed system

Polarization Calibration

- PRIMA FSUs use S polarization for measuring fringe sine, and P for fringe cosine
- Potential concerns:
  - Phase shift between S and P polarizations
  - Difference in efficiency for S and P
  - Polarized stars
- Calibration strategy: exchange roles between S and P in (or close to) FSUs

Preferred Implementation

- Exchange role of S and P inside FSU by rotating λ/4 plate by 90°
  - Position 1: sine from S, cosine from P
  - Position 2: cosine from S, sine from P
- Can construct complete set of observables (A, B, C, D) from S and P separately
  - Non-simultaneous, but should be ok for referenced phase
- No loss in efficiency, complete symmetry

Operational Implications of Beam Swap Strategy

- Each observation broken into short segments
  - Typical sequence: 1s, 2s, 2p, 1p, 1p, 2p, 2s, 1s
- Time needed to swap beams must be minimized
  - For example 2 minutes integration, 30 sec for swap
- Role of FSU1 and FSU2 get exchanged with each swap
  - Fringe tracking signal alternates between FSUs
  - Detector read time has to be changed

Baseline Calibration

- Requirement on knowledge of baseline vector is of order 50 μm
- One of the most difficult terms in error budget
  - What defines baseline (very complex issue)?
  - How sophisticated a telescope model do we need?
  - Transfer of wide-angle to narrow-angle baseline
- Baseline calibration strategy (observations of stars with wide sky distribution) depends on attainable cadence of observations

Wide-Angle Baseline

- The wide-angle baseline is defined by delay measurements of many stars distributed over the sky
  - Can be related to telescope pivot point
  - Can be calibrated from science data (if they have sufficient sky coverage) or additional observations
- Main error sources:
  - Non-intersecting telescope axes
  - Telescope flexure
  - Temporal drift of optical elements in beam train

Narrow-Angle Baseline

- The narrow-angle baseline is defined by the mechanism that combines the starlight with the metrology (STS)
- In the PRIMA STS design, the narrow-angle baseline is defined by the image of the “optical pivot point” of M11 in the entrance pupil
  - The “optical pivot point” is defined by the footprint of the metrology on M11
- The narrow-angle baseline must be computed from opto-mechanical model of the ATs

Baseline Calibration Strategy

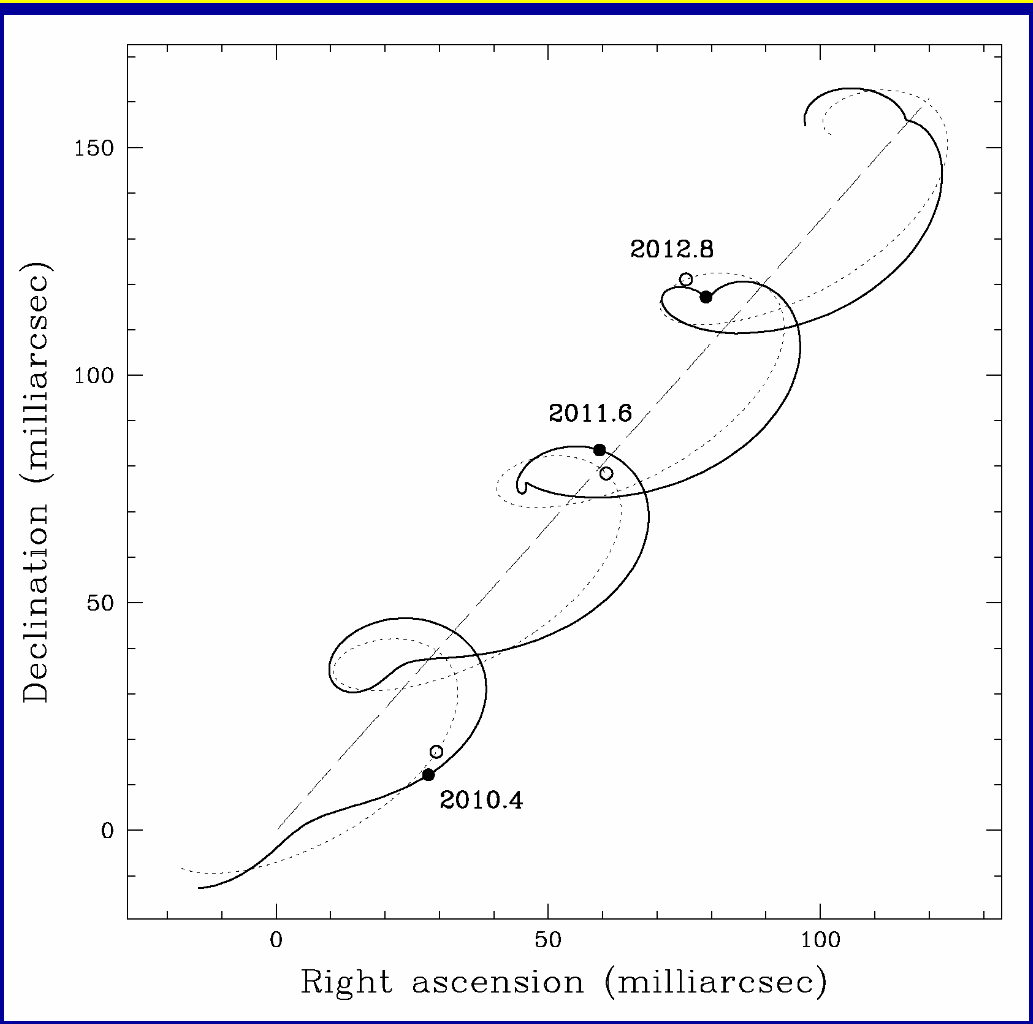
- Collect delay data from one or several nights
- Use telescope model with delay data to compute separation vector of telescope pivot points (wide-angle baseline)
- Use optical prescription and FEM of telescopes to compute narrow-angle-baseline
- Main difficulty: mechanical stability of ATs, tight tolerance of knowledge for M1 – M10

Data Analysis Facility

- Data base with all observations for several years
- Tools to select and visualize sub-sets of data
- Identification and removal of trends

Proper Motion, Parallax, and Planet Signature

- $d = 50$ pc
- $\mu = 50$ mas yr^{-1}
- $M_p = 15\ M_{jup}$
- $e = 0.2$
- $a = 0.6$ AU
- Planet signature shown 30× exaggerated



Why Do We Need a DAF?

- Astrometric precision requirement: 50 prad
  - Equivalent OPD precision requirement 5 nm / 100m
- Data have eleven (!) significant digits
- No way to check integrity without doing quadruple-differencing first
- Quadruple-difference dominated by parallax / proper motion
  - 10,000 times larger than precision requirement
  - Natural time scale 1.5 years
  - Only three free parameters ⇒ can (must) be fitted

Need for a DAF (cont'd)

- If something goes wrong, we'll know 1.5 years later!
- DAF is an indispensable tool for debugging the interferometer
  - Error budget is complicated – we may overlook important terms
  - 1.5 year time scale ⇒ record <u>everything</u>
- Time differencing ⇒ need to do <u>consistent</u> data analysis for years worth of data

More Benefits of DAF / IDAF

- Systematic calibration of instrument (not of individual data sets)
  - Better quality of calibration
  - More efficient observing
  - Better diagnosis of instrumental problems
  - Instrument useable by whole community
- Version control for calibrated data
  - Needed for determining motions over many years
  - Ability to improve calibration when problems are identified
- Minimization of overall calibration effort

Summary

- First phase of PRIMA optimized for astrometry with the 1.8m Auxiliary Telescopes
  - Goal to reach 10 μas class precision
  - Planet detection is the main scientific driver
- PRIMA implementation is well underway
  - All components sub-contracted by ESO to various vendors
  - Differential delay lines, operational analysis, and data analysis software by Planet Search Consortium

Positions Available!

- Openings for postdocs and temporary staff
- Some prior experience in interferometry desired
- Exciting project, pleasant international team
- See me during the break for more information!

END

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