Metrology for astronomical instruments in optical interferometry

Ground and space based applications

Contents:

Very Large Telescope at Cerro Paranal

VLTI: Quick Facts

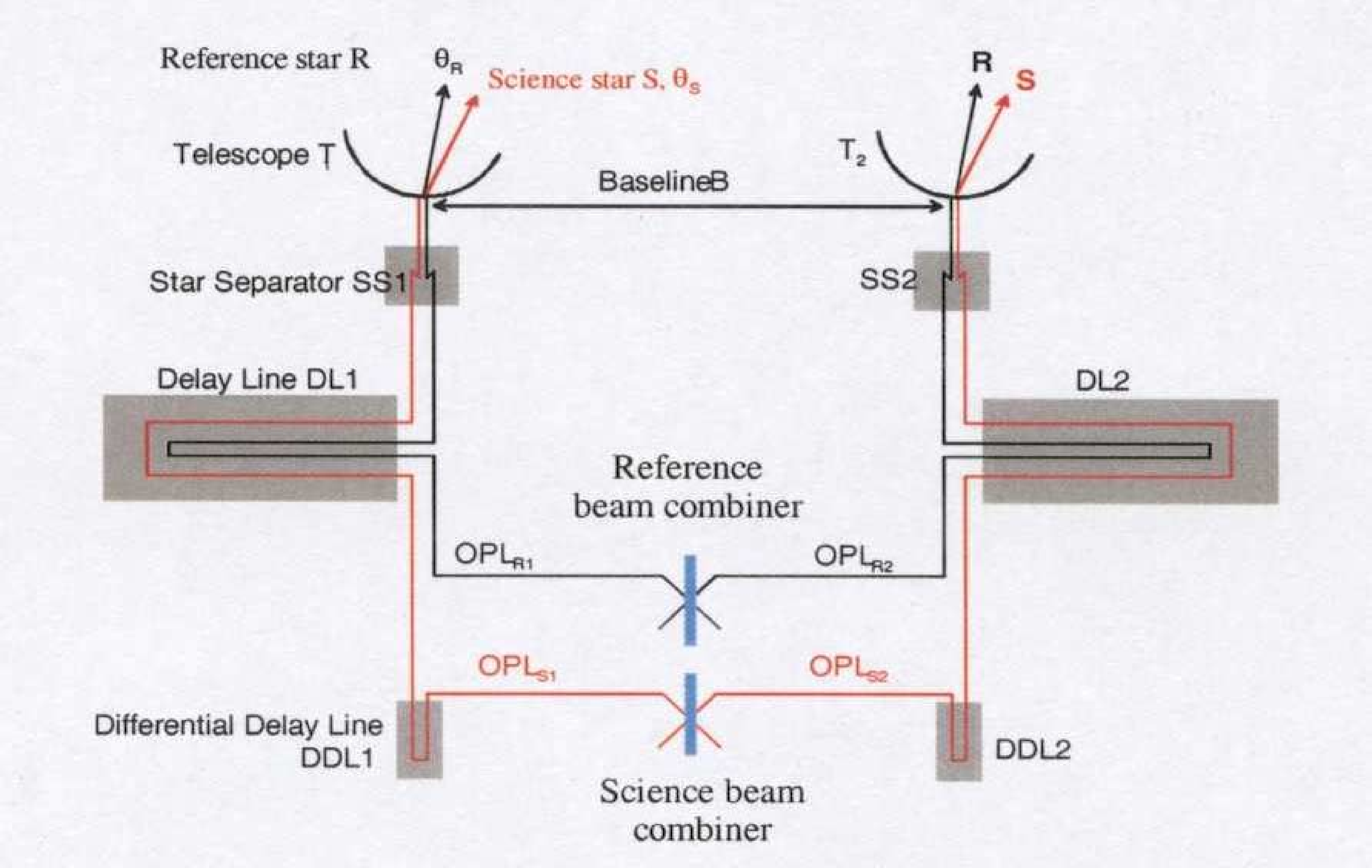
- **Four 8m Unit Telescopes:**
  - Max. Baseline 130 m => angular resolution: 1.5 - 30 milli arcsec
- **Three 1.8m Auxiliary Telescopes**
  - Baselines between 8m and 200m => max. angular resolution: 1-20 milli arcsec
- **Excellent uv coverage due to interferometer lay-out**
- **Instruments:**
  - MIDI: Mid IR Instrument (10 - 20 µm), Limiting Magnitude N~5
Angular resolution 20 milli arcsec, Two beam design
  - AMBER: Near IR Instrument (1-2.5 µm), Limiting Magnitude K~14
Angular resolution 4 milli arcsec, Three beam design (closure phase)
  - PRIMA: Phase Referenced Imaging for Microarcsecond Astrometry

    Dual Feed Mode for: Observations of faint objects (K~20)
    Imaging of faint objects (UTs and ATs)
    Astrometry on ATs (10 micro arcsec)

VLTI metrology

- **Delay Lines metrology:**
    - Heterodyne laser interferometer over 130 m with 2.4nm path length sensing resolution
    - Optimal optical lay-out: laser beam follows same path as stellar light for most accurate optical stellar path length variations sensing
- **Internal optical path metrology for PRIMA:**
    - Super-heterodyne laser metrology (ref: Y. Salvade and R. Dändliker, 2001)
    - Total optical path (two telescope optical paths) ~ 400 - 500m, 5 nm accuracy for monitoring the difference optical path length of max. 60 mm.

VLTI Dual Feed System



Laser metrology for PRIMA

Phase-Referenced Imaging for Micro-arcsecond Astrometry
simultaneous observations of two stellar objects separated by max. 1 arcmin.

$OPD_s \approx B \cdot \Delta S + \Delta L$ **for** $OPD_r = 0$

B: distance between the two telescopes
ΔS: angular separation of the two objects
ΔL: internal optical path difference between reference and science object

Knowledge of B and measuring OPD_s and ΔL independently,

- **an image of the science object can be reconstructed (Phase referencing)**
- **measurement of the star separation (narrow angle astrometry)**

Laser metrology for PRIMA II

Metrology system needed to monitor ΔL with accuracy of 5 nm to measure the angular distance of two stars at the 10 microarcsecond level

Proposed system by Salvade and Dandliker:

- **Two heterodyne laser interferometers, one for science object and one for reference object**
- **Two different frequency shifts to avoid crosstalk, f1 = 650 kHz, f2 = 450 kHz**
- **Frequency offset between the two interferometers : Δv = 80 MHz**
- **Two interference signals:** $\varphi 1 = 4\pi\nu L_1 / c$ $\varphi 2 = 4\pi(\nu + \Delta\nu)L_2 / c$

where L1 and L2 are the internal optical path differences for the science and reference object

The value ΔL = L1 - L2 is the interesting value for PRIMA and is restricted to 60 mm due to maximum angular distance and telescope lay-out

Laser metrology for PRIMA III

Individual measurements of $\varphi 1$ and $\varphi 2$ have disadvantages:

- simultaneous measurements are needed due to the speed of the ‘ delay lines (5 mm/s)
- $\varphi 1$ and $\varphi 2$ vary fast, so integration times short
- phase noise by laser frequency fluctuations high due to large OPD (130 m)

Solution: Superheterodyne detection, i.e. measuring $\Delta\varphi = \varphi 1 - \varphi 2$, by mixing the two interference signals electronically and bandpass filtering around f1-f2.

Laser metrology for PRIMA IV

Advantages of Superheterodyne detection

- Direct measurement of differential optical path difference ΔL
- The phase difference $\varphi 1$ - $\varphi 2$ varies slower than individual phases, i.e. longer integration time for phase measurement
- If the same laser is used for both individual interferometers, phase noise much lower than of the individual heterodyne signals

Metrology for future VLTI instrument: homothetic mapping

Second generation instrument for VLTI:

Wide-field of View imaging through homothetic mapping:
Input apertures inside beamcombiner equal to telescope arrangement

Monitoring and controlling in the beamcombiner:
- **pupil positions (lateral and longitudinal)**
- **pupil scaling**
- **pupil rotations**
- **image matching**

Keck Interferometer

Keck Interferometer metrology

- Local metrology of the fast delay lines. This is implemented with a conventional heterodyne metrology system, and will be used primarily for delay-line servo control.
- End-to-end, or constant-term, metrology of the complete optical path from beam combiner to dual-star module. This metrology references the primary and secondary beam paths to identical fiducials in order to implement co-phasing and narrow-angle astrometry. The metrology will also monitor vibrations in the beam-transport optics.
- Accelerometer sensing of optics. Accelerometers on key optics not monitored by laser metrology will sense vibrations which could affect fringe visibility. Vibrations measured with the accelerometers will be fed forward to the delay lines for high-bandwidth compensation.

Keck Interferometer: Quick Facts

85m Baseline

Initial Wavelength Coverage H and K bands
Low resolution spectrometer (lambda/d_lambda ~25)
All wavelengths available simultaneously

Fringe tracker Faint mag limit: ~9 Kmag (initially), ~14 Kmag (late 2002)
Bright limit: ~3 Kmag

Adaptive Optics limit R mag: 5 mag (bright), 13 mag (faint)

Slew and fringe acquire time <10 minutes to switch between stars
(Includes Adaptive Optics acquisition time)

Expected Visibility err < 5%

Special operating modes Differential phase: March 2002
Nulling: June 2002

Number of interferometers 2 2.2um combiners
2 10um nulling combiners
1 10um cross combiner (combines the two nullers)

DARWIN Key characteristics

- Science objectives: Planet Detection and high-resolution astrophysics

Design

- 6 optical 1.5 m telescope free flyers
- 1 central hub for beam combination
- master satellite for data handling, Earth communication and out-of-plane interferometer motion

DARWIN metrology

Requirements:

• Baseline accuracy:	< ~ 1 cm
• Optical path differences	< ~ 20 nm rms
• Telescope pointing errors	< ~ 24 mas rms
• Flux differences	< 1.0 E-3

Several metrology systems are defined to fulfil the requirements.

Darwin metrology systems

- **Coarse metrology:**
  - What? In and out-of-plane translation detection
  - How? RF ranging and laser goniometry or ?? => accuracy < 1cm
- **Medium metrology:**
  - What?
    - Transverse alignment of FF beams w.r.t. the Hub receiver telescopes
    - Differential drift between Hub and FF
  - How? Laser interferometer and Wide Field Camera
- **Fine metrology**
  - What?
    - OPD sensing
    - telescope pointing
  - How?
    - Laser interferometer or fringe sensor / tracker
    - Wide Field Camera
    - laser pointer for detecting tilts of FF w.r.t. Hub receiver

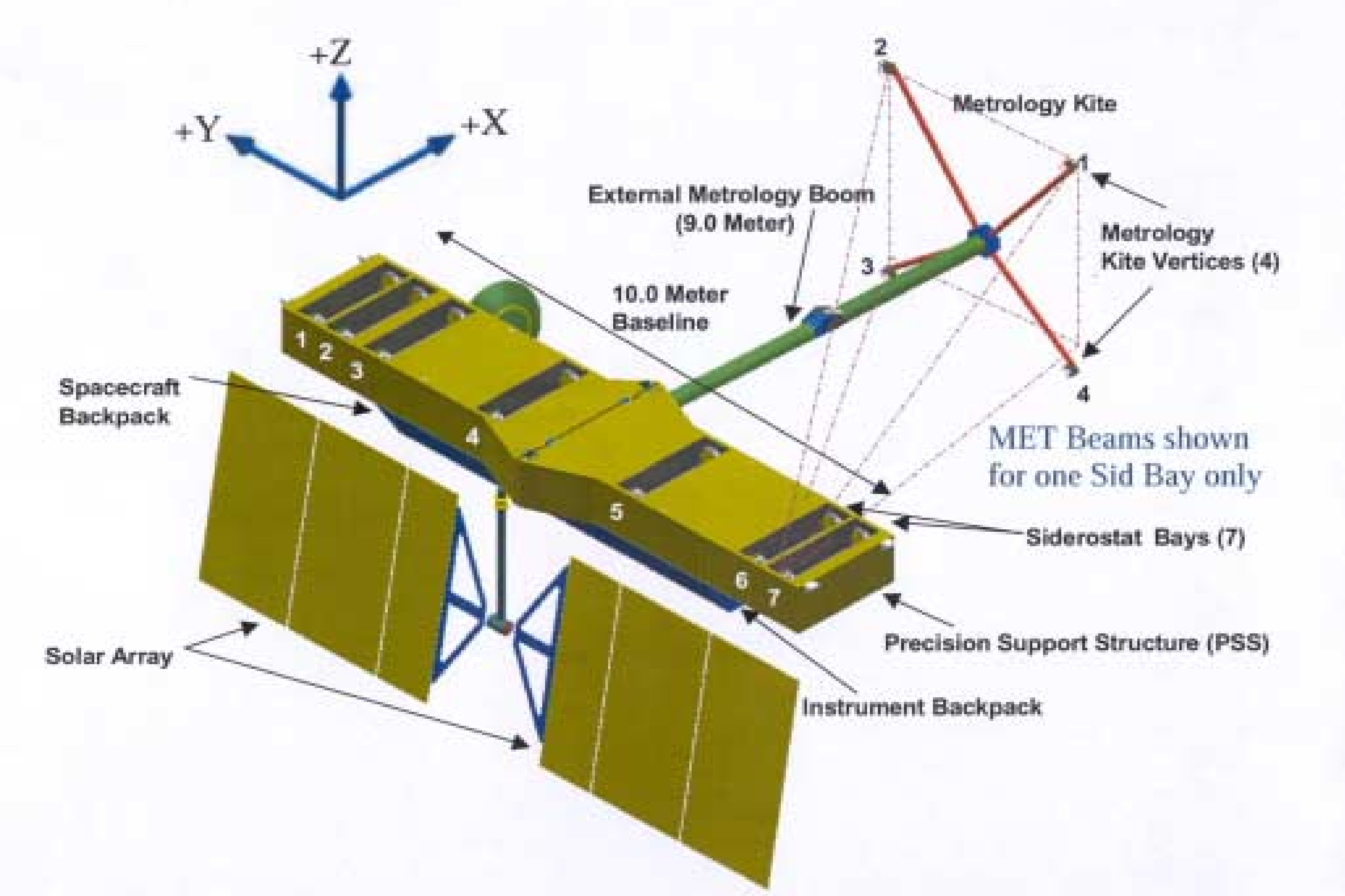
All these systems can be replaced by simpler and better ones!

Terrestrial Planet Finder; the US Darwin mission

Darwin (ESA)	TPF (NASA)
- 6 FF 1.5 m diameter	- 4 FF 3.5 m diameter
- Baseline 25-500 m	- Baseline 75-1000 m

No major differences and the same science objectives makes a cooperation between ESA and NASA likely.

Space Interferometer Mission



Space Interferometer Mission Metrology characteristics

SIM requirements to achieve astrometry with 1 μarcsecond accuracy:

- relative OPL measurement accuracy of 20 picometer
- Baseline measurements in three dimensions with the metrology kite
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Technology validating pre-cursor missions

ESA: SMART-2
NASA: StarLight

Similar concept of two free-flying satellites to validate a number of critical technologies for DARWIN, LISA and TPF

- **laser metrology**
- **stellar fringe detection**
- **formation flying**
- **data control / handling**

Future research

More research is needed make all projects described technically and economically viable:

- **Laser frequency stabilisation**
- **Optical designs**
- **Miniaturisation of components**
- **Space-qualified components**
- **New ideas for metrology systems**

Conclusions

- **Stellar interferometry will be *the* method of observing stars in the nearby future.**

- **Monitoring and controlling optical components in these instruments will need a range of existing and to be developed metrology systems, which gives an opportunity for Dutch industry to become more involved.**