Superheterodyne Laser Metrology for the Very Large Telescope Interferometer (VLTI)

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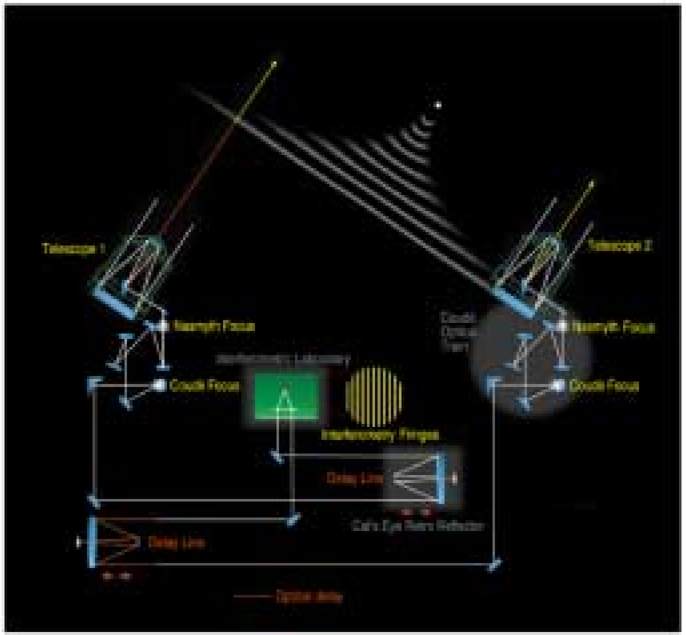
Very Large Telescope Interferometer (VLTI)

- Four 8-m Unit Telescopes (UT)
- Three moveable 1.8-m Auxiliary Telescopes (AT)

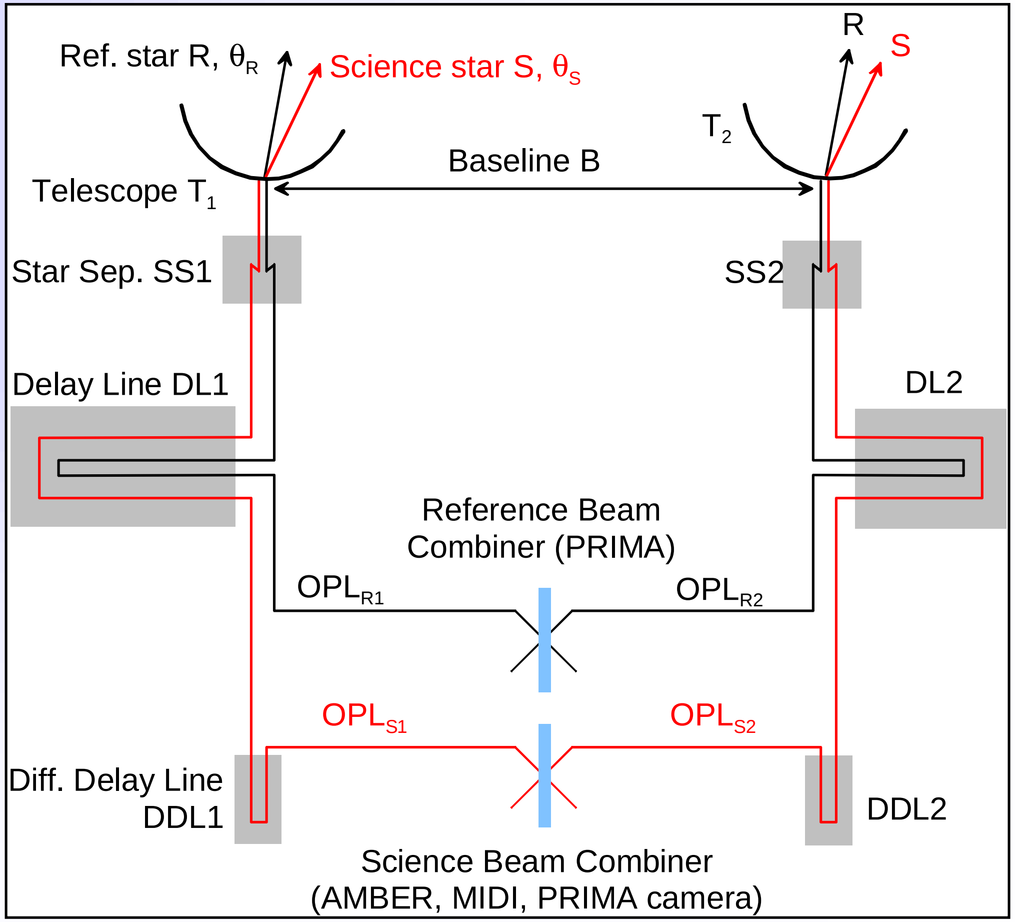
The VLT Array on the Paranal Mountain



The VLT Interferometer (schematic)

Phase-referenced imaging and µas astrometry (PRIMA)

- **Goals**
  - Observation and imaging of faint objects
  - Micro-arcsecond astrometry
- **Principle**
  - Bright star as reference star (fringe tracking)
  - Laser metrology for controlling internal optical path lengths
  - Angular separation of the two objects:
    - $OPD_R - OPD_S = \Delta \mathbf{S}\ \mathbf{B} + \Delta L$



PRIMA metrology - requirements

Range and accuracy	
Max propagation path (return way)	550 m
Individual OPD L_1, L_2 (return way)	240 m
Differential OPD, ΔL (1 arcmin)	60 mm
Accuracy of ΔL (μas accuracy)	< 5 nm
Resolution of ΔL	< 1 nm

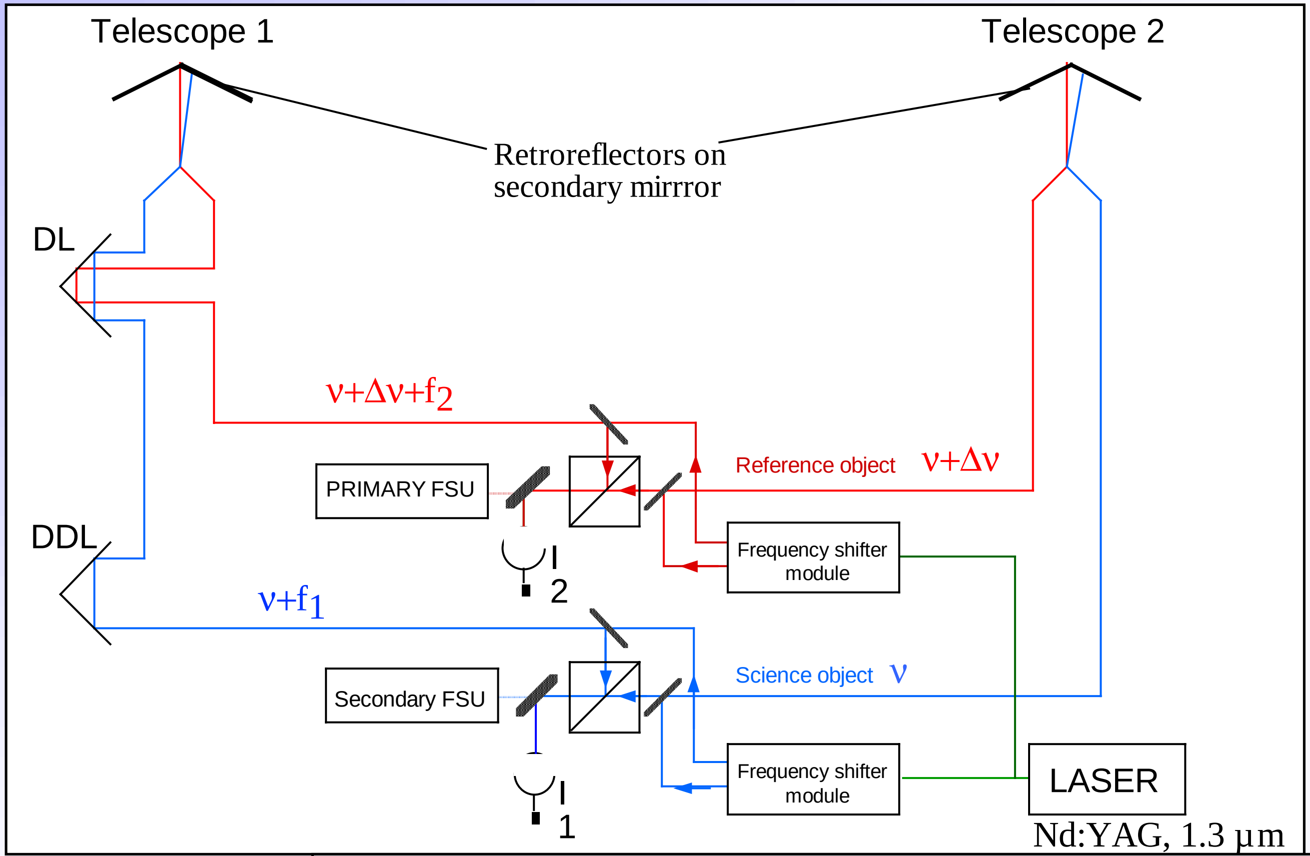
Expected dynamic phase variations (λ = 1 μm)	
on individual OPD	**Typical value**
Tracking of DL & STS ($\partial L / \partial t$ = 11 mm/s)	22 kHz
Variable curvature mirror	about 4 kHz
on differential OPD	
Tracking of DDL & STS ($\partial \Delta L / \partial t$	20 Hz
Slewing of DDL & STS ($\partial \Delta L / \partial t$	30 kHz

PRIMA metrology - additional requirements

- Laser source
  - Coherence length: > 500 m
  - Frequency stability: < 10^{-8} (same laser is used for both interferometers)
  - Wavelength between 1.1 µm (bandgap of Si) and 1.45 µm (H band), to avoid straylight on existing stellar detectors
  - ➟ Frequency stabilized Nd:YAG laser @ 1.319 µm (to be developed)

- Phase detection technique
  - High-resolution technique (2π/660 phase resolution)
  - Suppression of crosstalks between reference and science channels (Calibration mode: Star separator inject the same star in both channels)
  - ➟ Two heterodyne interferometers:
    - Different heterodyne frequencies f_1 and f_2
    - Frequency offset $\Delta\nu$ between the two interferometers

Heterodyne interferometers



- Interference signals: $I_1(t) = \cos(2\pi f_1 t + \phi_1)$ $\quad I_2(t) = \cos(2\pi f_2 t + \phi_2)$

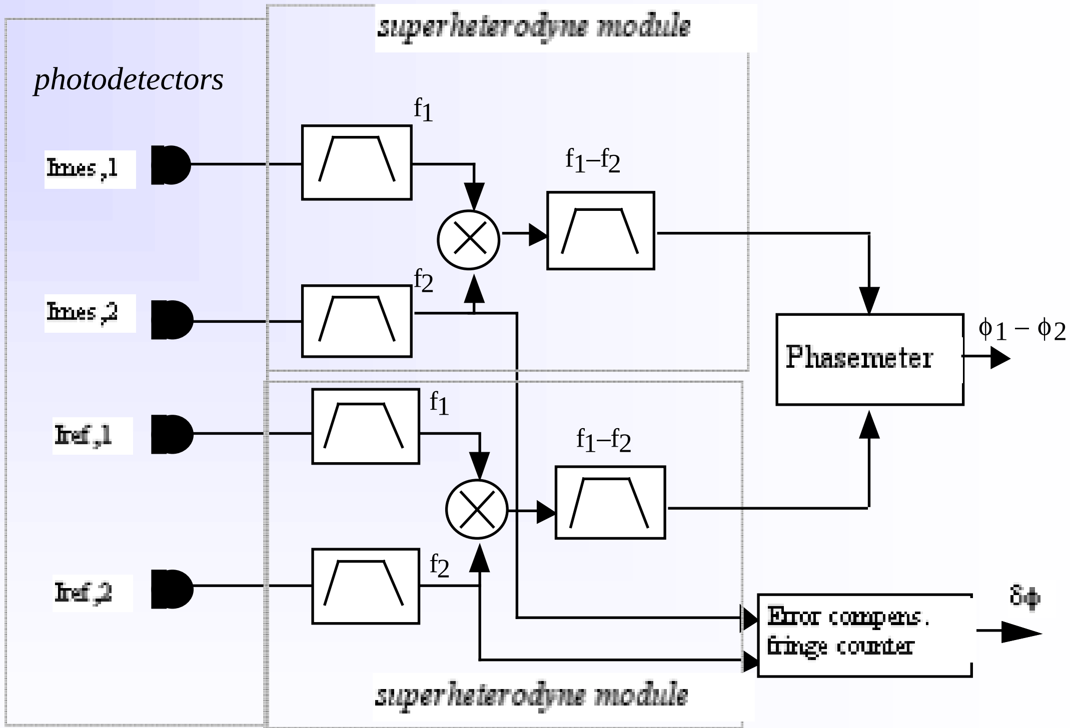
$$\phi_1 = \frac{4\pi}{c}\nu\ L_1 \qquad \phi_2 = \frac{4\pi}{c}(\nu + \Delta\nu)L_2$$

Superheterodyne detection

- Electronic mixing + low-pass filtering

$$I_{mes}(t) = I_{12}\cos\left[2\pi(f_1 - f_2)t + \phi_1 - \phi_2\right]$$

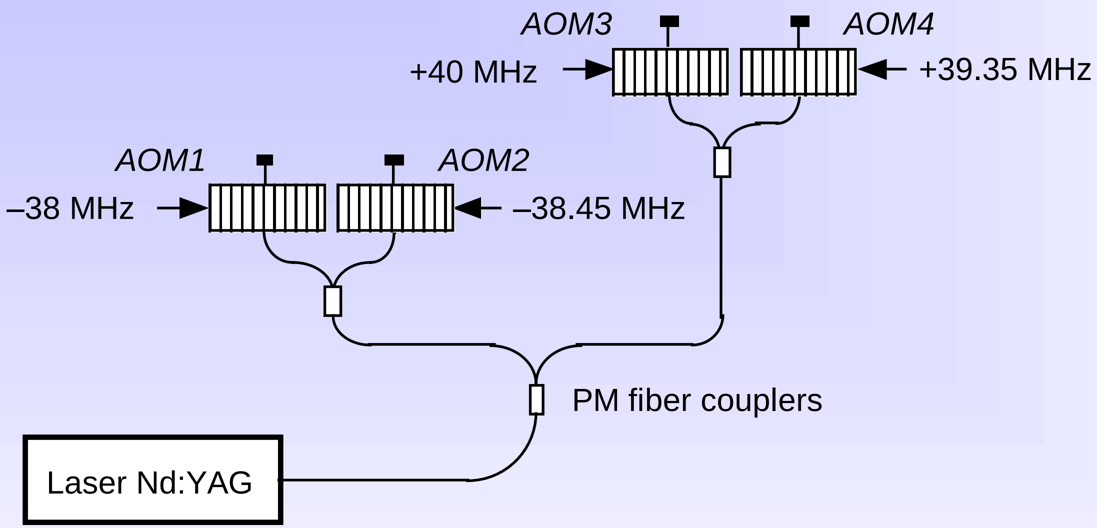
$$\phi_1 - \phi_2 = \frac{4\pi\ \nu}{c}\Delta L - \frac{4\pi\ \Delta\nu}{c}L_2 \approx \frac{4\pi\ \nu}{c}\Delta L$$



- Advantages
  - Direct access to ΔL
  - Slower phase variations
    $\rightarrow$ enable longer integration times
  - Phase noise less important

Frequency shifters

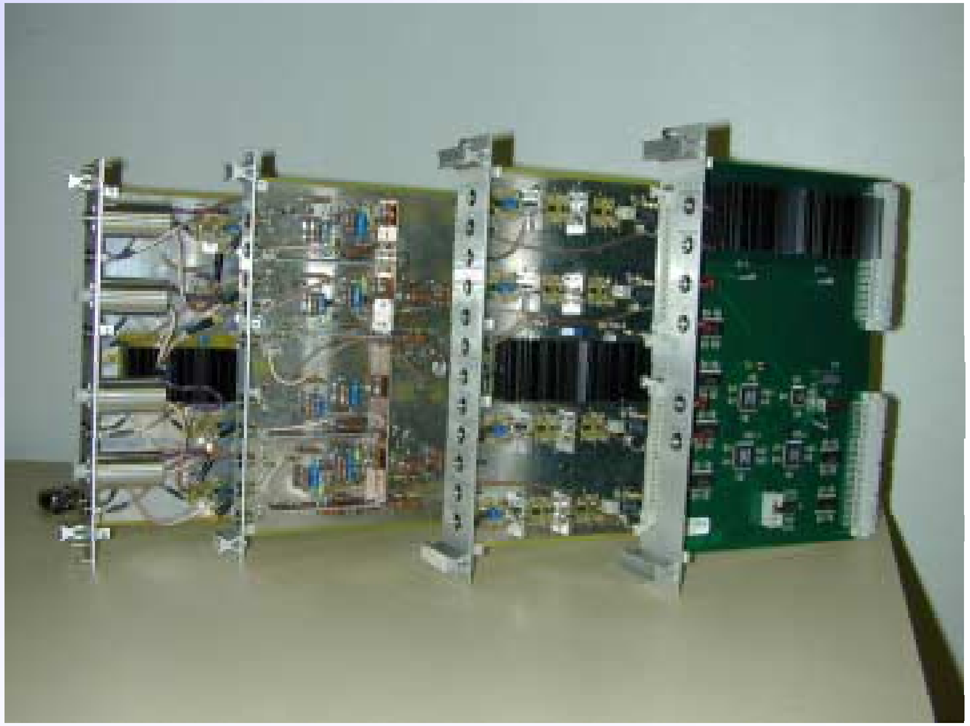
- Fiber pigtailed acousto-optic modulators (IntraAction Corp.)



- Heterodyne frequencies: f_1 = 650 kHz and f_2 = 450 kHz
- Frequency offset: $\Delta\nu$ = 78 MHz

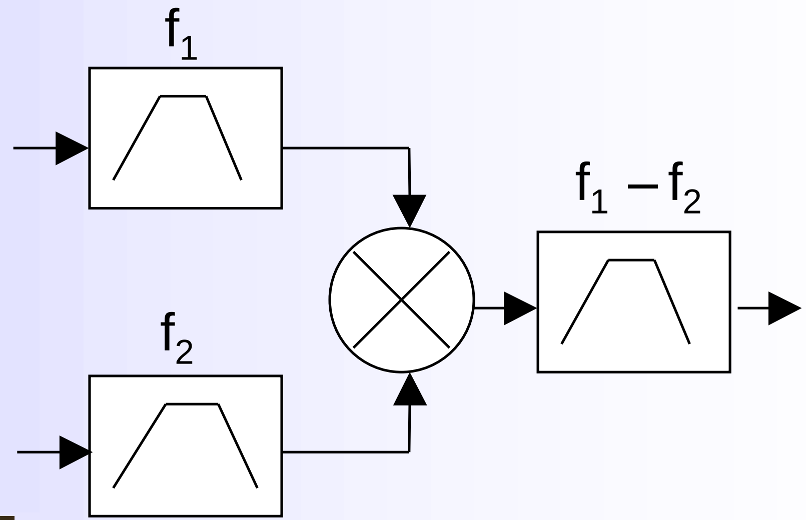
Electronic prototype

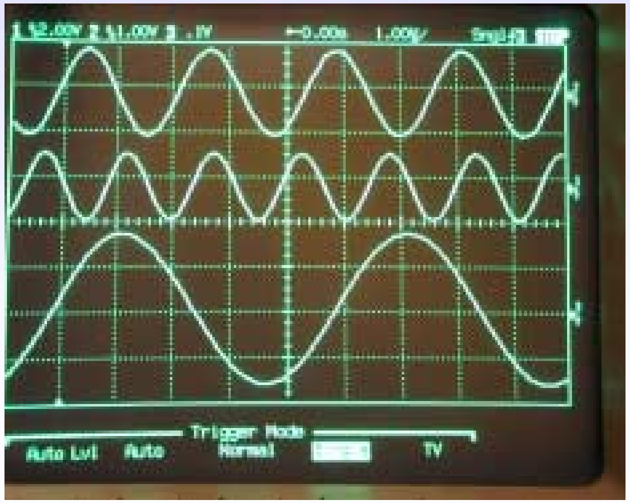
- VME boards
  - Low-noise photodetectors + preamplifiers
    - Sensitivity of 0.9 V/µW
    - NEP of 0.2 $pW/Hz^{0.5}$
    - ➡ Required optical power: 10 nW
  - Superheterodyne modules
  - Limiting amplifiers
  - Digital phase-meter
    - Zero-crossing phasemeter
    - On board averaging capability



Superheterodyne modules

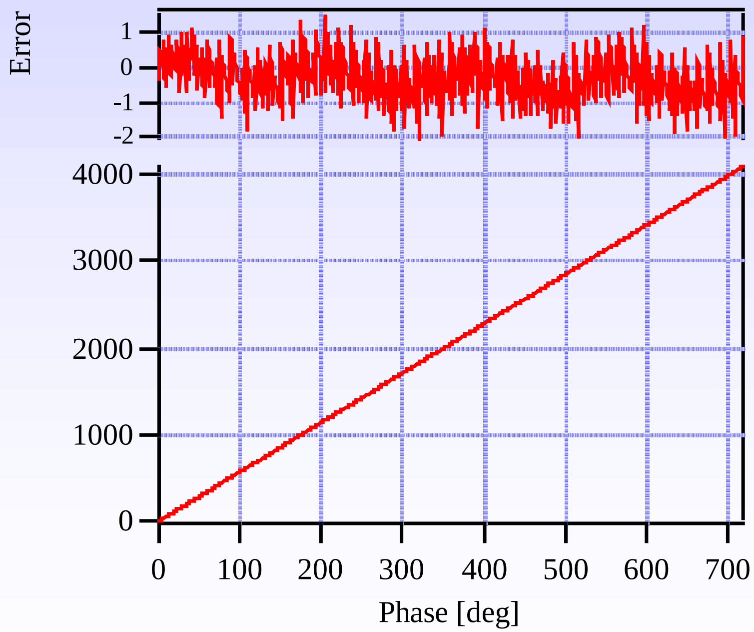
- Superheterodyne modules
  - Input bandpass filters
    - 450 kHz and 650 kHz
    - Bandwidth > 50 kHz
    - Minimized phase shifts (!)
  - Ouput bandpass filters
    - 200 kHz
    - 50 kHz bandwidth

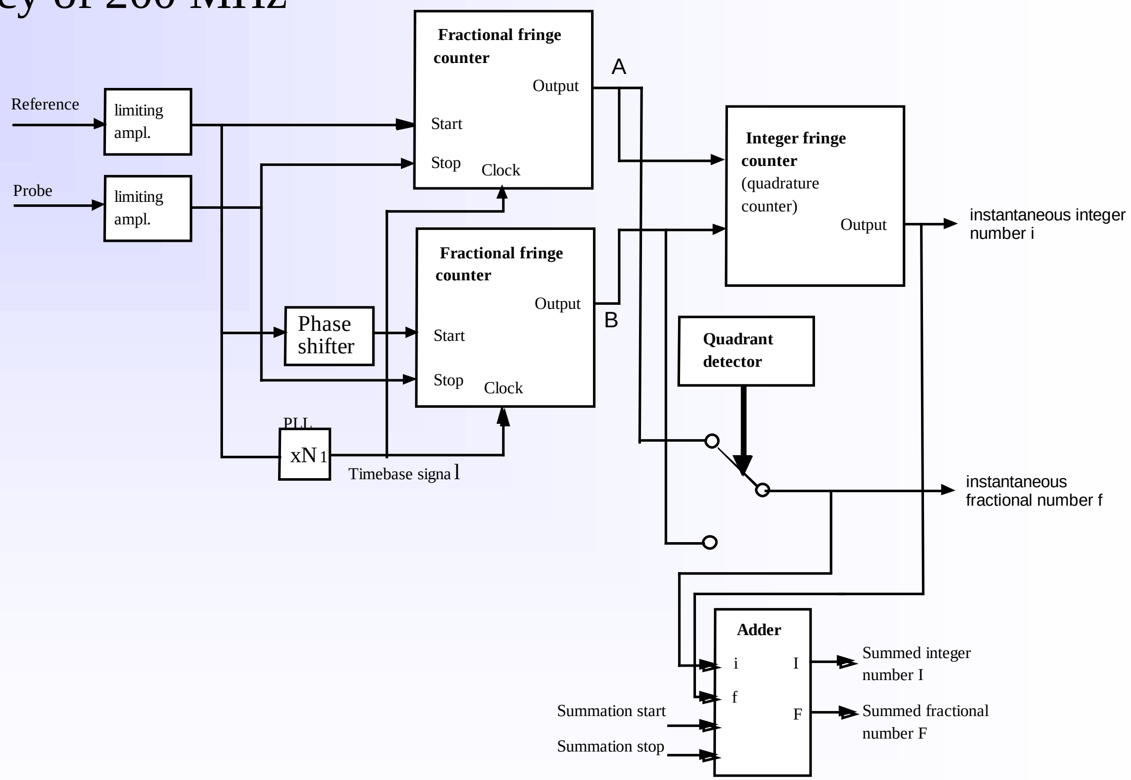




Digital phasemeter

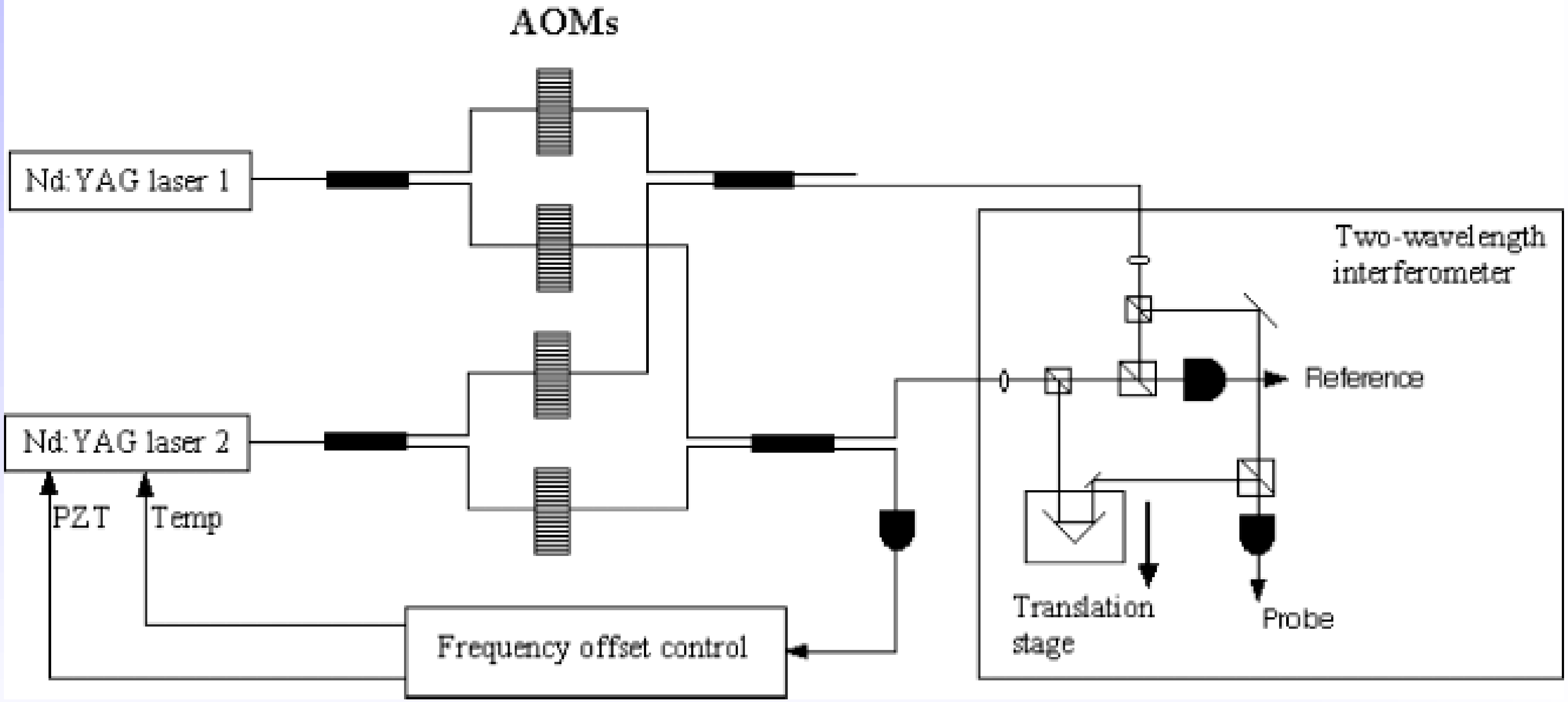
- Digital zero-crossing
  - FPGAs (Altera) to measure the « instantaneous » phase and the number of 2π cycles
  - On-board averaging (Average over 2^n periods)
  - PLL to generate a clock frequency of 200 MHz
  - ➨ $2\pi/1000$ phase resolution





Test of accuracy

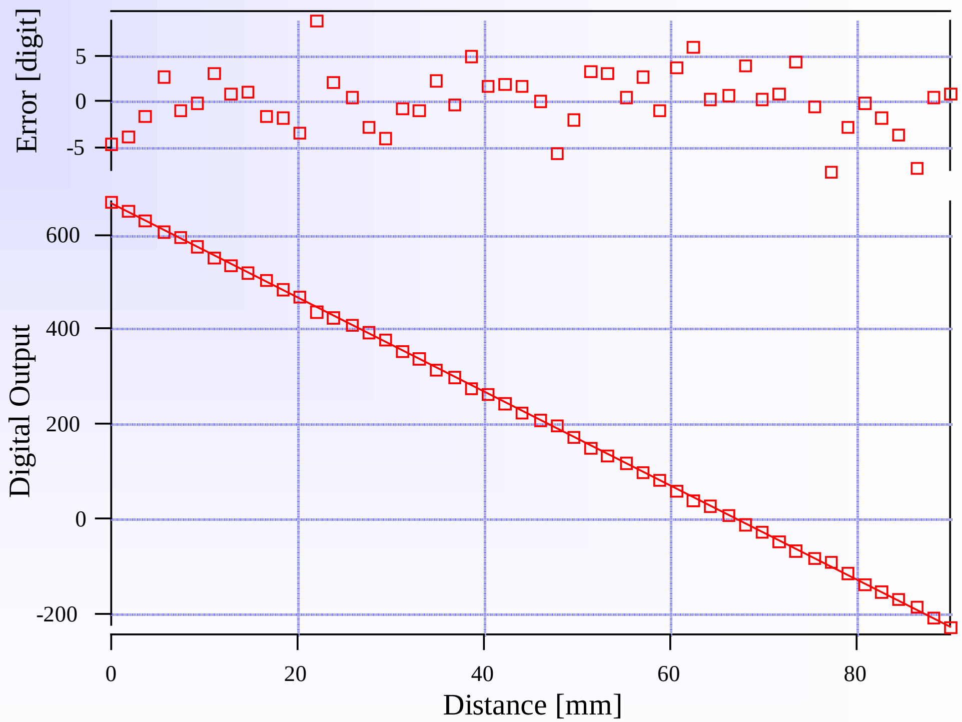
- Two-wavelength interferometry



- Interference signals: $I(t) = a_1\cos(2\pi f_1 t+\phi_1) + a_2\cos(2\pi f_2 t+\phi_2)$
- Reduced sensitivity: $\phi_1 - \phi_2 = 4\pi(\nu_2 - \nu_1)L/c$

Results

- Two-wavelength interferometry
  - $\nu_2 - \nu_1 = 1.5$ GHz → $\Lambda = 200$ mm (stability of 10^{-5})
  - Required mechanical stability > 100 µm
  - Measured accuracy:
    - Standard deviation of 2p/300
    - Corresponding to 2.3 nm accuracy
  - Bandwidth: 50 kHz
  - Optical power: 100 nW
  - Improvement by averaging over several periods



PRIMA metrology - Test Campain at Paranal- Q1 2002

- Main Objectives
  - Quantify the influence of environmental parameters (OPD and Tilt Disturbance)
  - Quantify the influence of the VLTI optical train (transmission, polarization)
  - Determine straylight levels
  - Retro-fit results to the Design of the PRIMA metrology system.
- Infrastructure
  - VLTI Instrument "VINCI" for injection in the stellar path
  - full VLTI optical train up to Retro-reflectors mounted on 2 UT 's (optical path ≈ 350m)

Picture of VINCI Instrument (Courtesy of P. Kervella)

Conclusion

- Concept based on superheterodyne detection for PRIMA
- Electronic prototype:
  - Manufacture and preliminary tests
  - Accuracy better than 5 nm for optical power of 100 nW and 50 kHz bandwidth
    - Good hopes to improve this performance
  - Suitable for two-wavelength interferometry (absolute distance measurement)
- Next step: full scale tests at the VLTI
  - Retro-fit results to the Design of the PRIMA metrology system.