VLTI Tutorial

The VLTI conceptual design
VLTI Tutorial: VLTI Concept & technical aspects, B. Koehler, 20 November 2001, Garching

VLTI Concept...The birth

From a 16m telescope (1980)

...nice dream, but no interferometry ...

...to a linear array of four 8m telescopes... (1988)

...the baby was born!

...to a mature VLT Interferometer layout (1990)

...the troubles could start!
The Final VLTI Array Layout

- **4 UT’s** as ‘trapezoidal’ as possible (wind shadow, ground quality)
  - Baselines 47 – 130m
    ⇒ 1.5 milli arcsec
- **30 Stations** for AT’s
  - Baselines 8 – 200m
    ⇒ 1 milli arcsec
- **Delay Line Tunnel** (160 x 8m) positioned to minimize path differences. Can house 8 DL’s
- **Central combining Lab** (20 x 7m) with specific **VLTI building** / control room
- All elements are located on an 8m grid
- Light travelling **underground** for high thermal stability (vacuum alternative **not selected** for cost reasons)

The VLTI Optical Layout
The telescope family

- **The ‘Appetizers’** (2 Siderostats)
  - Installed early 2001
  - Relocatable in day(s)
  - Primary: 0.4 m
  - Autoguiding only
  - Airy disk (in K): 1.1"

- **The ‘Workhorses’** (3 Auxiliary Tel.)
  - Relocatable in 3h
  - Primary: 1.8 m
  - Fast Tip-Tilt
  - Limited Chopping
  - Airy (in K): 0.25"

- **The ‘Kings’** (4 Unit Tel.)
  - Fixed position!
  - Primary: 8 m
  - Adaptive Optics
  - Airy disk (in K): 0.06"

Telescope Optical Design

- **Intermediate Focus** below M4:
  - Various artificial light sources for calibration & alignment

- **Intermediate pupil** image on M8:
  - Deformable mirror for MACAO

- **Coude Focus**:
  - Fast Tip-tilt sensor (STRAP) and later Wave Front Sensor (MACAO)
  - TCCD for Field acquisition
  - Field of View at Coude: 2 arcmin. (FoV 2 arcsec in laboratory)

Relay Optics
Relay Optics

● ‘Grasping’ the UT-photons
  ♦ M9: large dichroic.
    » Reflects IR to VLTI
    » transmits Visible to STRAP and later MACAO Curvature sensor.
    » Optimized for polarization.
  ♦ M10: convex spherical.
    » Re-image telescope pupil (M2) in Tunnel center.
    » Articulated mount to adjust lateral pupil position in Lab.
  ♦ M11: off-axis parabola.
    » Collimates beam and sends it into light duct towards M12 in DL Tunnel
The Delay Lines
The Delay Lines

- **The ‘Paranal-Express’**
  - Stroke: 60 m (120m in OPL)
  - Resolution: <5nm
  - Max. velocity: 0.5 m/s
  - Stability (jitter): <14nm rms
  - Power dissipation: <15W

- **Variable Curvature Mirror (VCM)**
  - re-image pupil inside the Laboratory
  - mounted on piezo translator for fast OPD correction

Transfer Optics
Transfer Optics

- The beam bending ‘gadgets’
  - Very high optical quality flats ($\lambda/60$ surf.)
  - Coating optimized for transmission and polarization (45° incidence)
  - Very stiff mounts and tables for immunity to $\mu$-seismic noise
  - M12 eventually on robotic arm for automatic array reconfiguration
  - M16 on translation stages for beam switching inside lab.
  - Support future dual-feed (PRIMA)
Beam Make-up

STRAP (Tip-Tilt) or MACAO (Adaptive Optics)

FINITO (Fringe Tracker)
STRAP (Tip-Tilt)

- **Quad-cell** detector with **APD** at telescope Coude focus

- Pure tip-tilt correction is optimal when $D/r_0 < 4$, i.e. UT/10µm (MIDI) or AT/2 µm (VINCI, AMBER, MIDI)

- Gain on Strehl up to 5.

- Will be used on UT till MACAO is available

- Will be resident on AT

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**Tilt loop residual rms angular jitter**

- AT lab results, diffir. limit at 2.2 microns = 0.255 arcsec
- UT lab results, diffir. limit at 10 microns=0.26 arcsec

MACAO (Adaptive Optics)

- A **must** for UT in **K-band** (AMBER). Gain in coherent flux ≈100
- **60 elements Curvature System** at telescope Coude
  - WaveFrontSensor using APD coupled with optical fibers
  - Bimorph Deformable Mirror on Tip-Tilt mount
  - vibrating membrane,
  - radial geometry micro-lenses,

- **X-Y Table** allows reference source different from target
0.65" @ 500 nm,
\( \tau_0 \sim 4 \text{ms}, \)
V=20.5 sky background
FINITO (Fringe Tracker)
The VLTI Laboratory

- High thermal stability; limited access, low power dissipation
- Telescope Exit Pupil re-imaged into instruments
- Optical design for up to 8 beams (4 UTs with dual feed)

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Inside the Laboratory

- **The Beam Switchyard**
- **The Beam Compressors**
  - 3-mirror design (compress 80 $\rightarrow$ 18 mm)
  - High optical quality off-axis parabolas (surface error 7 rms)
- **LEONARDO Reference sources**
  - Laser and white-light sources
  - Light can be sent to any instrument or backwards to telescope
  - Provide reference axis for each beam and reference OPD between beams
  - Enable instrument to obtain fringes in ‘autotest’
- **VINCI Test Instrument**
  - Used for VLTI commissioning & later as reference for performance tracking.
- **Fringe Tracker FINITO**
  - Co-phases (3 beams) to allow long exposures
  - mH<12 (UT)
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The VLTI

selected critical technical aspects
OPD variation with time (Piston errors)

- Error sources:
  - Atmosphere
  - Internal seeing
  - Vibration (wind, natural & man-made seismics, acoustics, pumps, etc.)
- Compensated (Partially) by fringe tracking.

- Top Level requirement:
  Instrumental errors (internal seeing & vibrations) < atmosphere

<table>
<thead>
<tr>
<th></th>
<th>0.6 µm</th>
<th>2.2 µm</th>
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<tbody>
<tr>
<td>Wavelength</td>
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<tr>
<td>Exposure time</td>
<td>10 msec</td>
<td>48 msec</td>
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<tr>
<td>OPL requirement (each arm) in [nm]</td>
<td>21</td>
<td>75</td>
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<tr>
<td>Telescope (UT or AT, each)</td>
<td>14</td>
<td>50</td>
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<tr>
<td>Delay Line (each)</td>
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<td>50</td>
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<tr>
<td>Beam Combiner</td>
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<td>21</td>
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<tr>
<td>Transfer Optics</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Internal Seeing</td>
<td>3</td>
<td>10</td>
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</table>
Unequal beam intensity

- Visibility loss due to intensity mismatch: \[ \frac{\Delta V}{V} = 1 - 2 \cdot \frac{\sqrt{I_1} \cdot \sqrt{I_2}}{I_1 + I_2} \]

- Error sources:
  - Atmospheric scintillation (negligible)
  - Coatings (small)
  - For fiber-fed instrument (large):
    - Tip-tilt errors
    - Instantaneous Strehl fluctuation

- VINCI measure I1 & I2 (photometry channels) to correct for this effect.
Polarization Effects

- **Linear Retardation**
  - Error sources: Coatings
    - Different coatings in the two arms
    - Differential incidence angles (between arms)
    - Differential coating characteristics (e.g. thickness of the protecting layer)
  - Can be very critical in Near IR/Visible and for multi-dielectric coatings (M9).
Polarization Effects

- Rotation of polarization frame
  - Error sources:
    - Differential frame-of-reference/pupil rotation due to optical design and/or misalignment
  - Can be avoided by proper optical design and alignment.
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Some results from on-going VLTI commissioning
Measured micro-seismic vibration

- OPD as measured with accelerometers at the back of Transfer Optics mirrors (M12, M16, Switchyard, Beam Compressor)

- Error budget:

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>VIS</th>
<th>NIR</th>
<th>TIR</th>
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<tr>
<td>Transfer Optics</td>
<td>3</td>
<td>10</td>
<td>45</td>
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</tbody>
</table>

\[
s_{OPD} \text{ [nm rms]}: \begin{array}{ccc} 
\text{VIS} & 4 & \\
\text{NIR} & 7.6 & \\
\text{TIR} & 38 & 
\end{array}
\]
OPD stability inside UT

- Measured with high sensitive accelerometers on UT#1&3
- Few improvements on sub-system identified and on-going
- Overall stability excellent

Measured OPD spectrum

- OPD as measured on a star by VINCI with Siderostats
Measured Internal seeing (tip-tilt)

- Nasmyth laser beacon (UT3) imaged on VINCI CCD (after 25 mirrors and 200m distance)
Measured Image Quality

First UT Light in VINCI

Airy disk

Radial Plot

FWHM 0.45"

(Note: the light reaches VINCI after 25 reflections and 200m travel)

- **Image Quality** from UT Nasmyth laser beacon to VINCI CCD:

  FWHM < 0.040” (limited by pixel size)

Conclusion

- Specific and stringent **error contributions** need to be taken into account for an Interferometer:
  - **OPD stability** (vibrations from equipment, wind buffeting, micro-seismic noise, residual atmospheric piston,...)
  - **Polarisation** (optical layout, coatings)
  - **Image Quality** (mirror figuring, alignment, internal seeing,...)

- The two major technical risks have been:
  - **OPD stability** within the UT
  - The **internal seeing**

- Both proved to be **according** (or very close) to the required performance

- Ready for the **next step**: PRIMA + ...