


Optical interferometry: problems and practice

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Outline

- Aims.
- What is an interferometer?
- Fundamental differences between optical and radio.
- Implementation at optical wavelengths.
- Conclusions.
- A warning:
 - When say “optical”, what I mean is $0.4\mu\text{m} - 2.4\mu\text{m}$.
 - Over this wavelength range there is little change in the technology required.

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Aims of this talk

- To present interferometry in a somewhat different light to that you have been exposed to.
- To identify the essential differences between radio and optical interferometry and clear up some common misconceptions.
- To give you a flavor of the implementation of interferometry at optical wavelengths.
- Not to teach you optical interferometry!

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Radio vs Optical (i)


VLA - 27 antennae

$B_{\text{max}} \sim 5.2 \text{ M}\lambda$ at 44 GHz




NPOI - 6 antennae


$B_{\text{max}} \sim 967 \text{ M}\lambda$ at 667 THz



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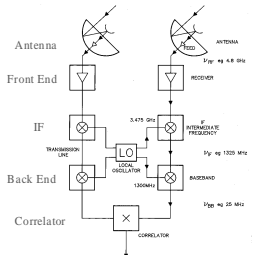


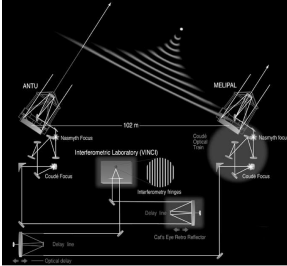
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Radio vs Optical (ii)

Exactly how do these implementations differ?






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What is an interferometer?

- A device whose output oscillates co-sinusoidally, varying with pointing angle like λ/B_{proj} :
 - The properties of these fringes encode the brightness distribution of features at this angular scale on the sky.
 - This encoding takes place via the fringe contrast (amplitude) and offset (phase).
 - The actual relationship between the fringe properties and the sky brightness distribution is (in most cases) a 2-d Fourier transform.
- Note that in this description the spatial coherence function does not appear explicitly.

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What is an interferometer made of?

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- Necessary components:
 - Antennae: to collect the radiation.
 - Waveguides: to transport the radiation to the correlator.
 - Delay lines: to compensate for the geometric delay.
 - Correlators: to mix the signals together.
 - Detectors: to measure the interference signals.
- Optional components:
 - Amplifiers: to increase the signal strengths.
 - Mixers and local oscillators: to down-convert the signals.



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Principal differences

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- Technical issues:
 - Optical wavelengths are very much smaller than radio wavelengths, typically by a factor between 10^4 - 10^7 .
- Logistical issues:
 - The impact of the atmosphere is far more significant at optical wavelengths than in the radio.
- Fundamental issues:
 - The properties of the radiation received by a typical optical interferometer is very different to that received by its radio equivalent.



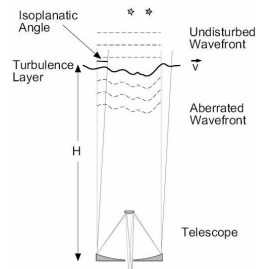
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The effect of the atmosphere

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- Can characterize the turbulence as a thin phase screen at altitude, being blown past the telescope at some speed v .
- Hence, initially plane wavefronts become corrugated and lead to poor image quality.



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The effect of the atmosphere - spatial fluctuations

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- Fried's parameter, r_0 :
 - The circular aperture size over which the mean² wavefront error is ~ 1 rad²:
 - $r_0 = [0.432 (2\pi/\lambda)^2 \sec(\xi) \int C_n^2(h) dh]^{-3/5}$, so $r_0 \sim \lambda^{6/5}$.
 - $D_0(r) = \langle [\phi(x+r) - \phi(x)]^2 \rangle = 6.88 (r/r_0)^{5/3}$, i.e. we can characterise the wavefront phase fluctuations with a "structure function".
 - Telescopes with diameters $<$ or $>$ than r_0 in size give very different images:
 - $D < r_0 \Rightarrow$ diffraction-limited images with FWHM $\sim \lambda/D$.
 - $D > r_0 \Rightarrow$ speckled distorted images with FWHM $\sim \lambda/r_0$.
 - At good sites, $r_0 \sim 15$ cm at 500nm:
 - Compare this to the VLA, where $r_0 \sim 15$ km at 22GHz.
 - The useful aperture diameter for interferometers is $\sim 2r_0$.



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The effect of the atmosphere - temporal fluctuations

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- Coherence time, t_0 :
 - The time over which the mean² wavefront error changes by ~ 1 rad². Usually this means we can:
 - Define a characteristic timescale $t_0 = 0.314 r_0/v$, with v the wind velocity. So $t_0 \sim \lambda^{6/5}$.
 - Define a structure function: $D_\phi(t) = \langle [\phi(t+\tau) - \phi(\tau)]^2 \rangle = (t/t_0)^{5/3}$
 - At good sites, $t_0 \sim 10$ ms at 500nm:
 - Can compare this timescale with the characteristic timescale for phase self-calibration at the VLA, i.e. minutes.
 - But note that the phase fluctuations at the VLA are typically of much smaller amplitude.
 - The useful coherent integration time for interferometers cannot be greater than $\sim t_0$.



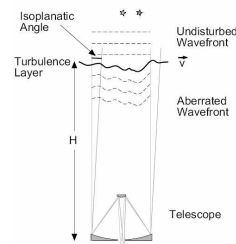
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The effect of the atmosphere - angular isoplanicity

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- Isoplanatic angle, θ_0 :
 - The angle beyond which the effects of the atmosphere become uncorrelated along different lines of sight.
 - Depends on r_0 and the height of the turbulence:
 - $\theta_0 \sim r_0/H$.
 - Hence $\theta_0 \propto \lambda^{6/5}$.
 - At good sites, $\theta_0 \sim 5''$ at 500nm:
 - Compare with VLA, where this angle is measured in degrees.
 - This limits the sky-coverage for potential calibrator stars.



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Fundamental issues

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- The occupation number for each mode of the radiation field in the optical is $\ll 1$:

- This number, $\langle n \rangle$, is given by the Planck function:

$$\langle n \rangle = \frac{1}{\exp(h\nu/kT) - 1}$$

- Radio: 30GHz (1cm), $T=2.7K$ $\langle n \rangle \sim 1.4$
15GHz (2cm), $T=5000K$ $\langle n \rangle \sim 7000$
- Optical: 600THz (0.5μm), $T=5000K$ $\langle n \rangle \sim 0.003$
150THz (2.0μm), $T=1500K$ $\langle n \rangle \sim 0.008$

- Bottom line: $\langle n \rangle \geq 1$ when $T \geq \frac{h\nu}{k}$

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Why does this matter?

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- Fluctuations in the mode occupation number are different:

- These 2 terms are identifiable as wave and shot noise.
- If $n \gg 1$, $\text{rms} \propto n$, otherwise $\text{rms} \propto \sqrt{n}$.

$$\begin{aligned} \langle (\Delta n)^2 \rangle &= \langle (n - \langle n \rangle)^2 \rangle \\ &= \langle n^2 \rangle - \langle n \rangle^2 \\ &= \langle n \rangle^2 + \langle n \rangle \end{aligned}$$

- Coherent amplification is not helpful:

- Under very general conditions, a phase coherent amplifier must inject at least one photon/mode of noise. $\Delta E = h\nu \cdot \Delta n$ $\Delta \phi = \Delta t \nu \cdot 2\pi$
- Thus $\Delta n \Delta \phi \geq 1$, and hence if $\Delta \phi < 1$, $\Delta n > 1$
- So, amplification is not helpful if $n \ll 1$.



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How does this impact implementation?

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- It is the combination of these atmospheric & quantum limits that makes optical interferometry different:
 - Splitting the signal to provide more correlations \Rightarrow S/N penalty.
 - Phase unstable conditions always prevail \Rightarrow "self-cal" is necessary at all times.
 - The instantaneous S/N per integration time is almost always $\ll 1$.
 - Real-time compensation for the atmospheric fluctuations is needed at all times so that $\Delta \text{OPD}_{\text{atm}} < \lambda^2 / \Delta \lambda$.



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Some quantitative context

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- Consider an observation of a bright quasar:
 - $m_v \sim 12$.
 - $r_0 = 10\text{cm}$, $t_0 = 5\text{ms}$.
 - Telescope diameter $\sim 2.5r_0$, exposure time $1.5 t_0$.
 - $\Delta \lambda / \lambda \sim 10\%$, total throughput $\sim 10\%$.
 - 4 photons are detected per telescope in our array!
- Basic observables are fringe amplitudes, phases and bispectra (the product of complex visibilities round a closed loop of interferometer baselines).
- These have to be suitably averaged over many integrations.



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Some scribbles on sensitivity (i)

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- At optical wavelengths the sensitivity that matters is the sensitivity to sense the atmospheric fluctuations and correct them in real time (c.f. AO sensitivity).
- This will depend on:
 - The type of correlator.
 - The type of detectors (CCD, photon counter...).
 - The apparent source visibility, i.e. the true source visibility scaled down to include de-correlation due to temporal and spatial perturbations of the wavefront and instrumental effects.
 - The number of photons detected in the relevant "exposure" time.



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Some scribbles on sensitivity (ii)

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- At the faintest light levels, the S/N for this type of "interferometric wavefront" sensing will be given by:

$$\begin{aligned} \frac{S}{N} &\propto \frac{[VN]^2}{\sqrt{(N + N_{\text{Dark}})^2 + 2(N + N_{\text{Dark}})N^2V^2 + 2N^2V^2\sigma_{\text{Fixed}}^4\sigma_{\text{Read}}^4}} \\ &\approx \frac{[VN]^2}{\sqrt{N^2 + 2N^3V^2 + 2N^2V^2\sigma_{\text{Fixed}}^4\sigma_{\text{Read}}^4}} \\ &\approx V^2N \end{aligned}$$

- Note the relative importance of V , the apparent source visibility, as compared to N , the number of detected photons.
- Note also that this sensitivity limit must be comparable to that for conventional AO, as both aim to do the same thing, i.e. sense the atmosphere.



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Some scribbles on sensitivity (iii)

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$$\frac{S}{N} \approx \frac{[VN]^2}{\sqrt{[N^2 + 2N^3V^2 + 2N^2 \sigma_{Pixel}^4 \sigma_{Read}^2]}}$$

$$\approx V^2 N.$$

- What happens if the target is resolved ($V \ll 1$)?
 - Tracking fails - you can't even attempt to measure anything!
 - The only ways to track the atmospheric fluctuations on a long baseline ($V \ll 1$) are to:
 - Decompose the baseline into lots of shorter ones and track on each simultaneously. This is called "baseline bootstrapping".
 - Monitor the atmosphere at a wavelength at which the source isn't so resolved. This is called "wavelength bootstrapping".
 - Monitor the atmosphere in real time using an off-axis reference source that is both brighter and more compact than the science target. Finding such references is difficult.



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Some scribbles on sensitivity (iv)

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- So, well designed optical interferometers allow for:
 - Maintaining enough V^2N to stabilize the array.
 - Photon limited detectors.
 - High throughput and low instrumental decorrelation.
 - Redundant array layout with each long baseline being made up of many short legs.
 - Use of off-axis reference stars - so-called "dual-feed":
 - Needs parallel transport and correlator.
 - Limited by isoplanatic angle.
- Subsequently, collecting enough data to build up a good enough S/N on the complex visibilities.



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Some nonsense you should forget

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- The fact that you can't measure the amplitude and phase of the electric field at optical wavelengths is an important difference.
- Optical interferometers can't measure the amplitude and phase of the coherence function directly.
- Adaptive optics can significantly increase the limiting magnitude of optical interferometry.
- It is necessarily scientifically valuable to build an optical interferometer with kilometeric baselines.



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Now for the practice!

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The VLTi in Chile, showing the four 8m unit telescopes and the first 1.8m outrigger. Note also the rail system and foundation pads for the ATs.

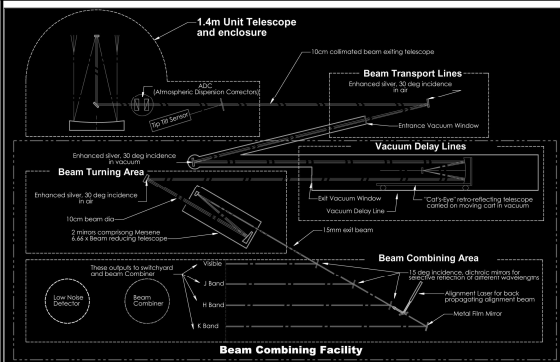


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A typical optical interferometer - the MROI

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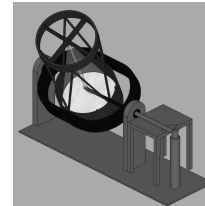


Telescopes

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- 1.8m Keck outrigger. The output follows a coude path and travels off M7 to the beam combining lab. The collimated output beam is 100mm in diameter.



- 1.4m alt-alt design for the MROI. The 100mm collimated beam is directed out off only 3 mirrors. This mount design was used for the ESO CAT.

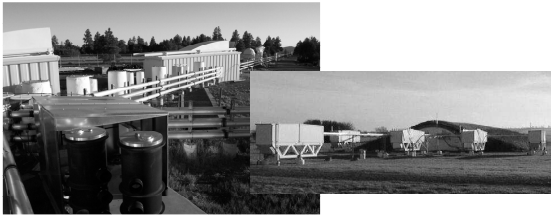


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Transport

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- Beam relay pipes at NPOI and COAST. Usually these are evacuated to $< 1/50$ th atmosphere to limit longitudinal dispersion and turbulence.
- Generally a beam diameter $D > (\lambda z)^{1/2}$ is used, where z is the pipe length, to minimize diffraction losses.

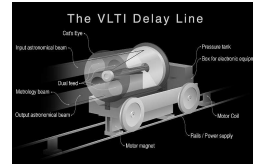


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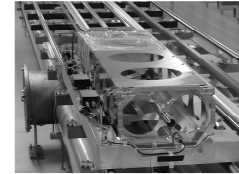


Delay lines

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- Schematic cartoon of the VLT delay line carriages which act as an optical trombone, i.e. we have physical switching-in of delay. Note the precision rails, and the use of an in-place laser beam for metrology.



- The CHARA JPL-designed delay lines. Like the VLT design, these run on precision rails in air. Additional stages of motion are provided by a voice-coil and a piezo-actuated stage.

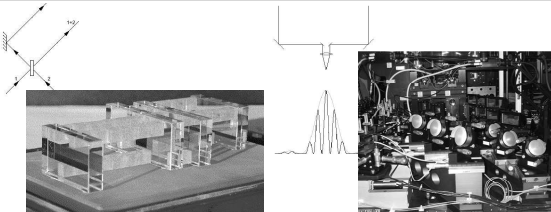


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Correlators

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- Cartoon and photo of a typical pupil-plane correlator where collimated light beams are combined. The fringes are visualised by modulating the OPD between the beams.
- Cartoon and photo of a 3-beam image plane correlator at the VLT. The complexity of the system results from its multi-wavelength spectroscopic capability.

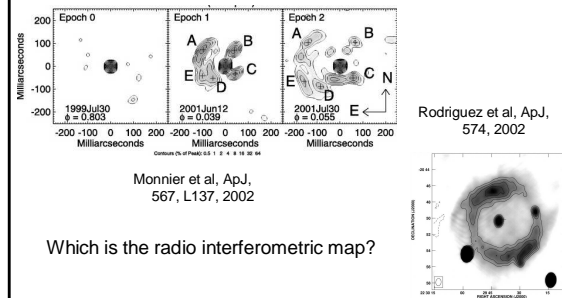


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Results

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Summary

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- An optical interferometer works the same as a phase-unstable radio interferometer at ~ 300 THz.
- The key differences are to do with the lack of signal amplification and the impact of the atmosphere:
 - Other differences are not that important.
- One can expect useful scientific advances in the next few years from the VLT, Keck and CHARA arrays.



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