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 m - 2.4\,\mu m.
  – Over this wavelength range there is little change in the technology required.

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!

Radio vs Optical (i)

VLA - 27 antennae
B_{\text{max}} \sim 5.2\,\text{M}_{\text{\lambda}} at 44\,\text{GHz}

NPOI - 6 antennae
B_{\text{max}} \sim 967\,\text{M}_{\text{\lambda}} at 667\,\text{THz}

Radio vs Optical (ii)

Exactly how do these implementations differ?

What is an interferometer?

• A device whose output oscillates co-sinusiodally, varying with pointing angle like \frac{\lambda}{B_{\text{max}}}
  – 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.
What is an interferometer made of?

- **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.

Principal differences

- **Technical issues:**
  - Optical wavelengths are very much smaller than radio wavelengths, typically by a factor between $10^4$ - $10^6$.

- **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.

The effect of the atmosphere

- 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.

The effect of the atmosphere - spatial fluctuations

- Fried's parameter, $r_p$:
  - The circular aperture size over which the mean squared wavefront error is $\sim 1 \text{ rad}^2$.
  - $r_p = 0.432 \left( 2x/\lambda \right) \frac{\sec \phi}{d} \frac{\phi}{H}$, so $r_p \sim 13h$.
  - $\phi_r(x) = |\phi(x)|^2 = 6.88 (r_0 \lambda)^{\frac{3}{5}}$, i.e. we can characterize the wavefront phase fluctuations with a "structure function".
  - Telescopes with diameters < or > than $r_p$ in size give very different images:
    - $D < r_p$ : diffraction-limited images with FWHM $\sim D$.
    - $D > r_p$ : speckled distorted images with FWHM $\sim \lambda / r_p$.
  - At good sites, $r_p = 15 \text{cm}$ at $500 \text{nm}$:
    - Compare this to the VLA, where $r_p = 15 \text{km}$ at $22 \text{GHz}$.
    - The useful aperture diameter for interferometers is $\sim 2r_p$.

The effect of the atmosphere - temporal fluctuations

- **Coherence time, $t_c$:**
  - The time over which the mean squared wavefront error changes by $\sim 1 \text{ rad}^2$. Usually this means we can:
    - Define a characteristic timescale $t_c = 0.314 r_p / v$, with $v$ the wind velocity. So $t_c \sim \lambda^4 / (2\pi v)$.
    - Define a structure function: $D(t) = |\phi(x + t) + \phi(t)|^2 = (\theta_c t)^{\frac{3}{5}}$.
  - At good sites, $t_c \sim 10 \text{ms}$ at $500 \text{nm}$:
    - 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 $t_c$.

The effect of the atmosphere - angular isoplanaticity

- **Isoplanatic angle, $\theta_i$:**
  - The angle beyond which the effects of the atmosphere become uncorrelated along different lines of sight.
  - Depends on $r_p$ and the height of the turbulence:
    - $\theta_i = r_p / H$.
    - Hence $\theta_i \sim \lambda / r_p$.
  - At good sites, $\theta_i = 5^\circ$ at $500 \text{nm}$:
    - Compare with VLA, where this angle is measured in arcminutes.
    - This limits the sky-coverage for potential calibrator stars.
Fundamental issues

- 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), \( T = 2.7K \)  
    \( \langle n \rangle \approx 1.4 \)
  - 15GHz (2cm), \( T = 6000K \)  
    \( \langle n \rangle \approx 7000 \)
  - Optical: 600THz (0.5µm), \( T = 5000K \)  
    \( \langle n \rangle \approx 0.003 \)
  - 150THz (2.0µm), \( T = 1500K \)  
    \( \langle n \rangle \approx 0.008 \)
- Bottom line: \( \langle n \rangle \geq 1 \) when \( T \geq \frac{h\nu}{4} \)

Why does this matter?

- Fluctuations in the mode occupation number are different:
  - These 2 terms are identifiable as wave and shot noise.
  - If \( n \gg 1 \), \( \text{rms} = n \); otherwise \( \text{rms} = \sqrt{np(n)} \).
- Coherent amplification is not helpful:
  - Under very general conditions, a phase coherent amplifier must inject at least one photon/mode of noise.
  - Therefore, amplification is not helpful if \( n < 1 \).

How does this impact implementation?

- It is the combination of these atmospheric & quantum limits that makes optical interferometry different:
  - Splitting the signal to provide more correlations \( \propto \) 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 \( \Delta O P D_{\text{atm}} < \lambda/\Delta \lambda \).

Some quantitative context

- Consider an observation of a bright quasar:
  - \( m_i = 12 \).
  - \( \text{t}_0 = 10\text{cm}, \text{t}_p = 5\text{ms} \).
  - Telescope diameter \( = 2.5\text{m} \), \( \text{exposure time} = 1.5 \text{t}_p \).
  - \( \Delta \lambda / \lambda \approx 10\% \), total throughput \( \approx 10\% \).
  - \( 4 \) 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.

Some scribbles on sensitivity (i)

- 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 (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.

Some scribbles on sensitivity (ii)

- At the faintest light levels, the S/N for this type of "interferometric wavefront" sensing will be given by:
  \[
  \frac{S}{N} = \left( \frac{N + N_{\text{cl}}}{\sqrt{2N + N'_{\text{cl}}}} \right)^{-1} \left( \frac{2N + N'_{\text{cl}} + 2N_{\text{cl}}}{N'_{\text{cl}} + 2N_{\text{cl}} - \sigma^2_{\text{cl}}} \right)^{-1/2} \]
  \[
  = \left( \frac{\sqrt{N'_{\text{cl}} + 2N'_{\text{cl}} + 2N_{\text{cl}} - \sigma^2_{\text{cl}}}}{N_{\text{cl}}} \right)^{1/2} \]
  \[
  = \left( \frac{V}{N} \right) \left( \frac{N'_{\text{cl}}}{N_{\text{cl}}} \right)^{1/2} \]
- 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.
Some scribbles on sensitivity (iii)

\[ \frac{S}{\Delta f} \approx \sqrt{V^2 + 2N V^2 + 2N_{\text{noise}} G_{\text{inst}}} \]

- What happens if the target is resolved ($\nu<1$)?
  - Tracking fails - you can't even attempt to measure anything!
  - The only ways to track the atmospheric fluctuations on a long baseline ($\nu<1$) 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.

Some scribbles on sensitivity (iv)

- So, well designed optical interferometers allow for:
  - Maintaining enough $V/N$ 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.

Some nonsense you should forget

- 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 kilometric baselines.

Now for the practice!

Telescopes

- 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.
- 1.8m K{"o}rner outtrigger. The output follows a coude path and travels off M7 to the beam combining lab. The collimated output beam is 100mm in diameter.
Transport

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

Delay lines

- Schematic cartoon of the VTI 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 VLTI design, these run on precision rails in air. Additional stages of motion are provided by a voice-coil and a piezo-actuated stage.

Correlators

- 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 VLTI. The complexity of the system results from its multi-wavelength spectroscopic capability.

Results


Which is the radio interferometric map?

Summary

- 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 VLTI, Keck and CHARA arrays.