The COAST interferometer

Chris Haniff

Abstract

The talk will consist of two parts :

- Part I : Actual implementation of the COAST interferometer telescopes, beam pipes, delay lines, beam combination, and detection.
- Part II : Science with the COAST interferometer.

The COAST interferometer

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A case study: COAST

- Scientific and technical rationale.
- Straw-man design.
- Actual implementation.
- Typical scientific results.
- Lessons for the future.

Introduction to COAST

- The Cambridge Optical Aperture Synthesis Telescope.
  - First generation interferometer, now 10 years old.
  - Built to test the principles of optical aperture synthesis:
    - Simplest possible array for imaging.
    - Cheap, since built as a prototype.
    - Built as an in-house university project.
  - No initial astronomical goals.
  - Located at the Mullard Radio Astronomy Observatory, just outside Cambridge at an elevation of 17m.

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COAST today

- Current status:

  - Up to 100m baselines, with 5 x 40cm telescopes.
  - First image in 1995, now with routine operation for astrophysics (every clear night).
  - A research instrument, under continual development.
  - Supported by 4 graduate students plus 3 academic staff, 2 post-docs, 2 engineers and 1 emeritus professor.

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Functional design

- In principle, we can identify the following functional components:
  - Collectors: receives radiation from source.
    - Size, number, location, mobility and stability.
  - Beam transport mechanism: delivers radiation to a "central" laboratory.
    - Throughput losses along long propagation paths, stability, spectral bandwidth.
  - Path equalisation system: allows interference to take place for finite bandpasses.
    - Precision, repeatability, spectral bandwidth.
  - Combiner: "correlates" signals between pairs of collectors.
    - Method, number of simultaneous correlations, stability, wavelength capability.
  - Detection: final measurement of the coherence function.
    - Signal to noise achievable.

Site selection

- Significantly more important than for a conventional telescope:
  - Effectively governs the limiting sensitivity of the array, scales as $\sim r_0^{3.5}$.
  - Requires knowledge of both the spatial and temporal behaviour of atmosphere, c.f. the similar situation in adaptive optics research where the vertical stratification of the turbulence becomes relevant.
  - Seismic activity and wind-shake are potential sources of instability.
  - Generally prefer a large flat site, unlike conventional sites, so as to allow expansion to kilometric baselines in the future.
- One can see this demonstrated with current interferometer sites:
  - CHARA Mount Wilson, California. NPOI Flagstaff, Arizona.
  - KECK Mauna Kea, Hawaii. VLTI Paranal, Chile.

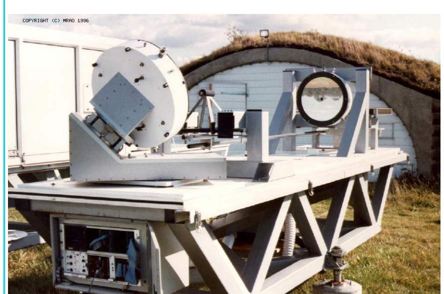
The collecting telescopes

- Requirements include:
  - Stability in optical path:
    - Tracking should cause no differential path fluctuations.
    - Requires good thermal stability and repeatable behaviour.
  - Good vibration damping.
  - Small central beam obscuration:
    - Limits diffraction losses and can improve coupling efficiency in later optics.
  - Must provide good wavefront quality otherwise:
    - Beams will not arrive in beam combination laboratory (tilts).
    - Instantaneous visibility amplitude will be degraded (higher orders).
  - Low cost and high level of automation since many will be required.
  - Mobility:
    - To allow array reconfiguration for different science programmes.

Telescope implementation

- COAST uses small siderostat-fed afocal telescopes:
  - Stiff and rigid with only a single moveable component.
  - Small number of reflections - 3 including beam compressor.
  - Full of kinematic mountings.

    BUT
  - Have limited unvignetted sky coverage.
  - Require two large mirrors.
- Alternatively can use articulated focal telescopes. In these cases:
  - Can be easier to implement AO.
  - Focal plane useful for source selection.

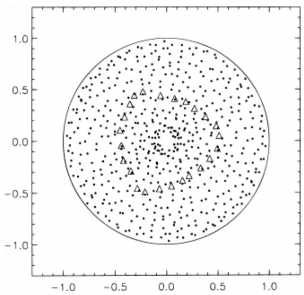


One of the 40cm diameter unit telescopes at the COAST array in Cambridge. The white rear face of the articulated siderostat mirror can be seen in the foreground. The collimated beam sent to the lab has a diameter of 25mm.

Array Layout

Radio

- Fourier plane coverage in the context of the point source response.



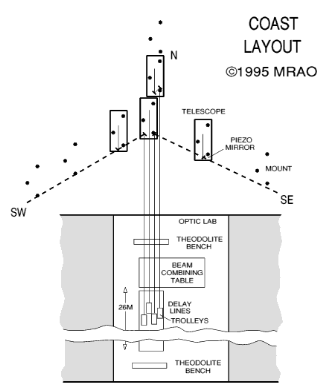
- Snapshot Fourier plane sampling for a source at the zenith using a reuleaux triangle array.

Optical

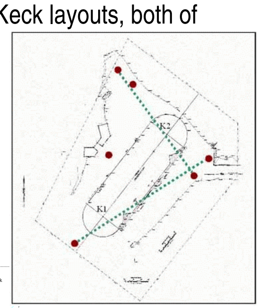
- Fourier plane coverage.
- Planar configuration:
  - Minimise atmospheric dispersion.
- Beam-pipe layout:
  - Broadband transport.
- Symmetric paths:
  - Polarisation matching.
- Boot-strapping:
  - Fringe tracking on long baselines.
- Scalability:
  - Imaging flexibility.

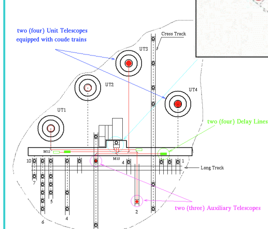
COAST array configuration

- COAST uses a "Y" configuration, as do the NPOI and CHARA arrays.



- The VLTI and Keck layouts, both of which have to accommodate the presence of the unit telescopes.





Transport to the correlator (i)

- At radio wavelengths the signals are transferred to the correlator using coherent waveguides.

  In principle this can be replicated at optical wavelengths with single-mode optical fibres but a number of new problems arise:

  - Longitudinal dispersion , i.e. the mismatch between the air and glass paths in each arm of the interferometer. This can be difficult to control for long fibre paths.
  - The polarisation state of the fields must be matched for interference to occur.
  - Current single-mode fibres do not have the optical bandwidths desired by astronomers: a typical application might require observations at 0.65 and 2.2µm simultaneously.

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Transport to the correlator (ii)

- At COAST we use free-space propagation in an air filled pipe:
  - Few problems with longitudinal dispersion since baselines are relatively short.
  - Use a reduced beam size to limit wavefront perturbations.
  - Need to ensure beam diameter $D > (\lambda z)^{1/2}$, where z is the distance traveled, to minimize diffraction losses.
    - At COAST we use a 2.5cm beam.
    - Note, however, that NPOI (for example) has a 12cm beam.
- This approach has significant repercussions on the array layout, and is one of the principal drivers behind Y-shaped configurations.

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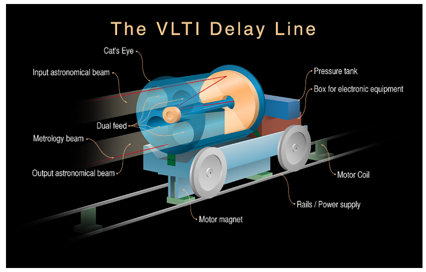
Principles of path equalisation

- Roughly speaking identical to early radio interferometers:
  - Introduce additional optical path by physical switching.
  - Typically use an optical trombone, travelling along precision rail.
  - Many designs exist, e.g:
    - Pair of flat mirrors.
    - Paraboloid + flat.
  - Generally utilise multi-stage control:
    - Coarse motorised motion along track.
    - Voice-coil actuation of larger optical components.
    - PZT control of smaller optics for high speed OPD modulation.



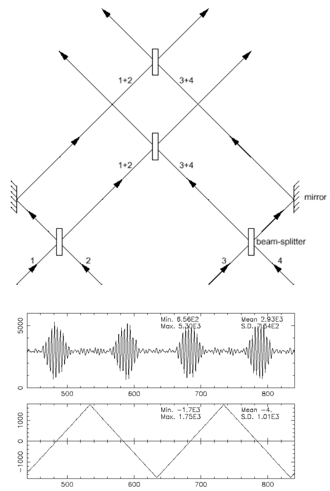
Path equalisation at COAST

- Uses relatively standard technology:

– Movable roof-mirror on a motorised trolley.
– Carriages move in air along steel rails.
– Second order control via voice-coil.
– Metrology with commercial sensors at $\lambda/128$ level.
– Allows for 100m of path compensation.
– Introduces $\lambda/40$ position jitter.

Beam combination at COAST

- Afocal beams combined in a pupil plane using beamsplitter plates.
- Mixed signals then focused onto single element detectors.
- Fringes encoded by non-redundant modulation of delays to give a temporally modulated output.
- All beams mixed together at once to maximize signal-to-noise.
- Spectral selection via filters in front of detectors.



More on pupil plane combination

- Considerations when contemplating design:
  - Ease of initial and subsequent alignment.
  - Spectral capability: will it operate successfully over a broad bandpass?
  - Stability of optical system, in particular whether errors affect beams from individual telescopes or specific baselines.
- Problems for the future:
  - How to accommodate much larger numbers of input beams?
  - Difficulty of introducing non-redundant frequency modulation, and the effects of crosstalk.
  - The use of large and unstable bulk optics.

Detection

- Requirements at COAST:
  - Single pixel devices for single channel measurements with pupil plane combiners.
  - 1 dimensional arrays for spectrally dispersed measurements in the pupil plane, i,e. to measure channelled spectra for Group Delay measurements.
- No spatial filtering available.

Optical 0.5-1µm

- Avalanche photodiodes - photon-counting single pixels devices with >55% QE for 500-850nm and negligible thermal background.
- CCDs not currently competitive due to high readout noise ($\geq 5e^-$) at the fast readout rates required. Used for group-delay measurements.

Near infrared 1-2.2 µm

- Use standard IR array (NICMOS) as a single pixel detector. Typical noise of $\sim 25\ e^-$ at 6kHz pixel rate.

Observing at COAST

- Not automated – observers sit in beam-combining lab!
- Optics inside lab are very stable – start-of-night procedure involves adjusting one mirror at the telescope.
- Fringes are acquired by ear or via real-time data reduction.
- Main limit to observing efficiency is acquiring 5 stellar images each time a switch from source to calibrator is made.
- Fringe crosstalk means that for the highest fidelity visibilities, separate observations are made for visibilities and closure phases

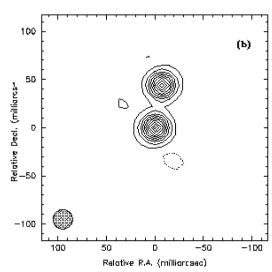
Data reduction

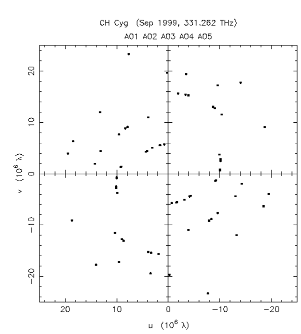
- In general this involves the following:
  - Raw photon counts/IR pixel values immediately saved to disk.
  - Real-time analysis available to check instrumental performance.
  - GUI-driven data-analysis software available for use to observers.
  - All but raw data stored as text files: editing is a crucial part of reduction.

  - Visibility amplitudes extracted from accumulated temporal power-spectra.
  - Closure phases extracted from integrated bispectrum phases.

Image reconstruction

- Mostly standard software:
  - Caltech VLBI.
  - Difmap.
- Some in-house software:
  - VLBMEM.
  - BSMEM.
- Quantitative information from:
  - Modified version of Caltech MODELFIT.
  - Bayesian model-fitting.





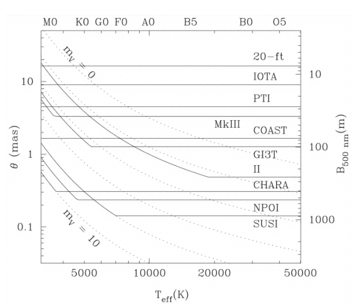
Other issues

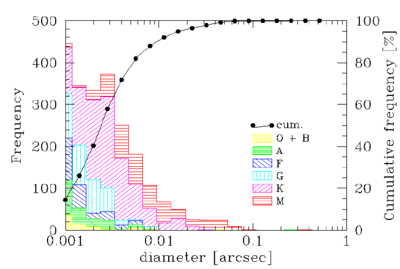
- The following are all issues relevant to the effective operation of a synthesis array.
  - Calibration: how time consuming is this, and how reliable?
  - Alignment: how time consuming will this be and how reliable?
  - Automation: this will be a requirement for the next generation of arrays. Can it be achieved straightforwardly?
  - Reliability: the large numbers of array elements and subsystems in future arrays will demand a level of reliability beyond that currently available. Can this be achieved?

Astrophysics: what's possible?

- Governed by the capability of the array and the physics of stars:

Stellar type	Typical radius	Angular diameter at 250pc (mas)
Dwarfs	0.2 – 15 R_{solar}	0.007 – 0.56
Giants	3 – 100 R_{solar}	0.11 – 3.7
Supergiants	20 – 700 R_{solar}	0.7 – 26



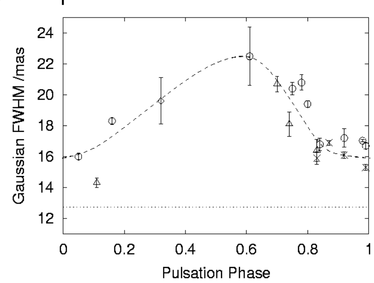


Stellar astrophysics

- Actually rather broad in principle:
  - Fundamental parameters: radii, effective temperatures, masses (through binary star orbits).
  - Detailed atmospheric studies: stratification of cool stellar atmospheres, limb-darkening, stellar surface imaging.
  - Dynamical studies of pulsating stars: Miras, Cepheids.
  - Studies of outer atmospheres and circumstellar environments:
    - Be star envelopes.
    - Cool: dust shell emission in evolved systems.

COAST programmes (i)

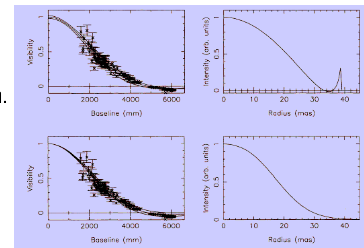
- Diameter monitoring of Mira variables in broad and narrow (1.04µm) bands.
  - Aim to test dynamical models and investigate implications for shocks and mass loss.



  - Problems include:
    - Isolating appropriate bandpasses.
    - Need for lengthy campaigns.
    - Large variation of brightness during cycle.
  - Results for χ Cyg:
    - Measurements at 905nm in “contaminated” bandpass.
    - Indicative of changes in outer envelope but probably not physical motion.

COAST programmes (ii)

- Limb-darkening of late-type giants and supergiants.
  - Offers direct check of stellar atmospheres.
  - Can distinguish between different limb-darkening approximations.
  - Useful for interpreting eclipses etc.
  - Problem issues:
    - Needs multiple baselines & phase information.
    - Have to measure small visibilities.
    - Interpretation is non-trivial.
  - Results for Betelgeuse:
    - Measurements at 830nm.
    - Highlight inadequacy of linear approximation.



Burns at al, MNRAS, 290 (1997)

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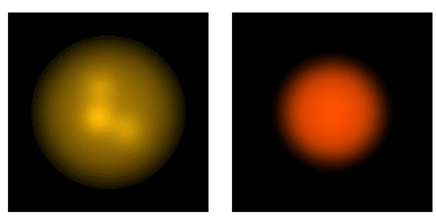
COAST programmes (iii)

- Surface imaging of M supergiants.
  - Allows investigation of:
    - Convection and magnetic activity.
    - Structure of upper atmosphere.
    - Mass-loss.
  - Problems include:
    - Only possible for nearest targets.
    - Needs excellent uv-plane coverage (>4 tels).
  - Results for Betelgeuse:
    - Measurements at 700, 905, 1290nm.
    - Indicative of spatial opacity variations in the outer atmosphere.



Young et al, MNRAS, 315 (2000)

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Conclusions

- In principle the functions required of an imaging array are straightforward to define.
- Individually, they are also relatively straightforward to address.
- The principal difficulty is to accommodate all of these, some of which inevitably conflict, simultaneously.
- Goal to keep in mind must be some particular astrophysical problem that demands a given capability.
- Defining that goal is as important as building the array.
- A next generation imaging array should look something like this:

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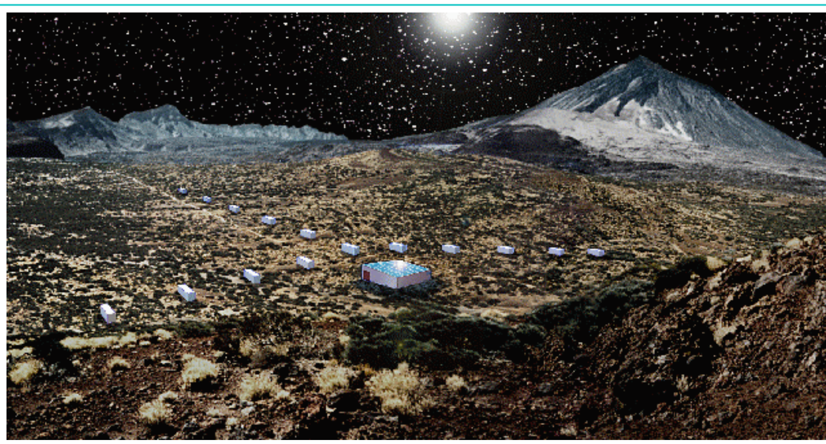
LOA - the Large Optical Array



15x1.2m telescopes, 500m baselines, 0.6-2.4μm detection, extragalactic capability.

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