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Know Your Instrument

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Know Your Instrument

Know what you can and cannot measure with an optical/infrared interferometer

Know how to verify that what you have measured is (close to) the truth (and just how close)

Know what might make what you measure further from the truth than you might expect

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What are we measuring?

- An interferometer is characterized by being able to directly measure only two types of things:
  1. Fringe amplitude (contrast, visibility)
  2. Fringe phase or (nearly equivalently) fringe packet location
- Generally, one of each per (a very few) baselines
- To make any scientific use of these we usually need to model the source
- Because of the small number of basic measurements and the need to model, small errors in the measurements can mean large differences in the scientific interpretation

What are we measuring?

- Fringe amplitude is measured by observing the variation of light intensity on the detector behind the beam combiner
  - So we'll need to characterize our detector well
- Fringe position is measured by reference to the distribution of light intensity variations on your detector and to the measured position of the delay lines
  - So we'll need to characterize our detector well
  - And we'll need to measure the delay line positions well

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What are we measuring?

- An interferometer (at least on the ground) is characterized by having very low signal to noise per coherent integration interval
- Measurements are the result of incoherently averaging a large number of single integrations
- This takes time
- Things change over time

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What are we measuring?

- No interferometer measures absolute phase and visibility
- Thus, we have the mantra of interferometric measurement:
- Calibration, calibration, calibration
- A science measurement must be accompanied by a calibration source measurement
- Provided all the conditions for measurements are the same, the calibration can be as exact as you like (given time) and the science measurements can be as accurate as you like (= Nobel prize)
- But… things change over time!

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What are we measuring?

- Know the difference between accuracy and precision
- Many interferometers can make very precise visibility measurements (~0.1% internal consistency)
- But the science depends on the calibration!
- All interferometers are limited by their calibration accuracy (~1-2%)
  - Its physically difficult to make any measurement accurate to better than ~1%
- All interferometers have (largely unknown) systematic uncertainties
  - We don’t have a body of comparisons of measurements on known sources from a large range of instruments

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Visibility Measurement

What can go wrong?

Visibility Measurements – the wrong stuff

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- All things tend to reduce the measured visibility
  - (except for those that increase it…)
- As always calibration is the key:
- Try to keep the calibrator source and science source measurement conditions the same
  - Interleave calibrator and science targets
  - Take calibrations as close as possible in space and time to science targets
  - Make your calibrator source physically as similar as is possible to your science source
- You will need to make internal instrument calibrations as well
  - Because the closer your measurements are to correct in the first place, the easier they are to calibrate

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Visibility Measurements – the wrong stuff

- What can affect the visibility?
  - And that can change over time and space?
- The strehl of the individual beams
  - The wave front flatness and parallelism
- The equality of the individual beams at the beam combiner
  - Do the beams have the same intensity?
  - Do the beams overlap completely?
- The way the beams fall on the detector
  - How much light from the beam makes it to the pixel you are reading out?

Visibility Measurements – the wrong stuff

- The phase difference between the beams
  - How good is your group delay tracking?
- The phase change during a coherent integration period
  - How well does the fringe tracking work?
  - How well do your delay lines perform?

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Strehl fluctuations

- The atmosphere changes with time, and position of the source on the sky
  - So you can never make your calibrator source calibration exactly the same as your science source!
  - But you should try to minimize the differences
- The performance of your adaptive optics system changes with time and with the characteristics of the source its working on (even if it is only first order – AKA tip-tilt)
  - The source brightness (AO bandwidth)
  - The source color (AO in a different waveband?)

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Strehl fluctuations

- Surface quality fluctuations
  - Mostly static, but some variation (e.g. telescope beam steering)
  - Beam walk (see later)!
- Minimize the effects of Strehl by back end filtering
  - E.g. use single mode fibers
  - But beware of replacing strehl problems with intensity variation problems…

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Beam combination/intensity problems

- The dreaded beam walk!
- Many reflections and long optical paths
- Small angular variations at the input end result in large variations in beam shear at the detector end
- Beams can change their overlap at the beam combiner
- Beams can be vignetted at stops or mirror edges
- Bad strehl from the AO can result in diffraction losses
- All of this probably changes with telescope position (so its different from science to calibrator target)

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Detector Problems

- Even if the beams combine properly on the beam combiner, they still have to hit the same pixel on the detector
- Coupling variations into your single mode fibers?
  - High frequency uncorrected tilt variations?
- No fibers?
  - Then take care with the detector internal alignment!

Phase variation problems

- How well does the fringe tracker work?
- Source brightness variations
  - Affects the signal to noise
- Source visibility variations
  - Affects the signal to noise
  - The calibrator and science sources are almost certainly of (very!) different visibility
- Source color variations
  - Distribution of flux on the detector with wavelength can affect a group delay calculation

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Got Vibrations?

- At the nanometer level everything vibrates!
- Vibration sources vary with time
- Telescope shake varies with position
- Seeing… the atmosphere is, once more, not your friend (even when its inside your instrument!)
- Measure it all with end to end metrology?
  - Beam walk again:
  - Make sure what you measure is what you want – does the starlight beam match the metrology beam?
  - (probably not)
  - Difficult to measure the telescope position
  - (Accelerometers can help)

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Phase and Optical Path Difference Measurement

What can go wrong?

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Phase and OPD measurement problems

- Generally easier to deal with than visibility measurement problems
  - Like the difference between wavelength and intensity in traditional astronomy
- Most vexing systematic problem is once again beam walk:
  - End to end metrology beam must match the starlight beam as exactly as possible
  - Even small displacements on mirrors (even flat ones) can result in large path variations at the nm level
  - What are the unmonitored parts of the path (= telescopes) doing?
- Once more must consider fringe tracker performance
  - Same problems as for visibility measurements

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What can you do about it?

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Making it come out right

- Take internal calibration measurements
  - Measure the beam equality on the fringe detector
  - Do so as close as possible in time to the fringe measurements
  - Measure variations in the backgrounds:
  - 1) the sky background
  - 2) the off fringe visibility background
- Carefully use these calibrations in your data reduction

Making it come out right

- Measure everything you can and record it
  - Candidate things to measure are:
  - End to end metrology variations – can reveal changes in vibration sources
  - AO performance – can reveal changes in atmospheric conditions
  - Fringe tracker performance – can reveal systematic differences in source properties
- Keep everything as constant as possible
  - Keep the internal alignment well adjusted to minimize beam walk
  - Consider carefully the properties of your calibration sources (see next talk)

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Making it come out right

- In the end there is no substitute for persistence:
- Measure the performance of your instrument under as widely different conditions as possible
- Measurements to make:
  - Measurements of system visibility and variations
  - Measurements of system phase fluctuations
- Conditions to consider
  - Source properties (color, brightness, visibility,…)
  - Instrument configuration (sky position, time of night,…)
  - Environment (seeing, temperature,…)

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Conclusions

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Main Points

- Know your instrument!
  - The better you understand the internal operation of your instrument the better you will be at catching potential systematic errors
- Beam walk can be pernicious
  - Make sure you are measuring what you want to measure
- Watch out for variations:
  - In conditions
  - In sources
  - In your instrument
- If you are careful you can probably measure visibilities to ~1%

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To Sum up:

- If anything can go wrong it will go wrong!
  - Interferometers are complicated beasts, so there is lots to go wrong
- Interferometry isn't easy, and good interferometry is more difficult still
- Buts that's why we do it!