A Brief Primer to Optical Interferometry

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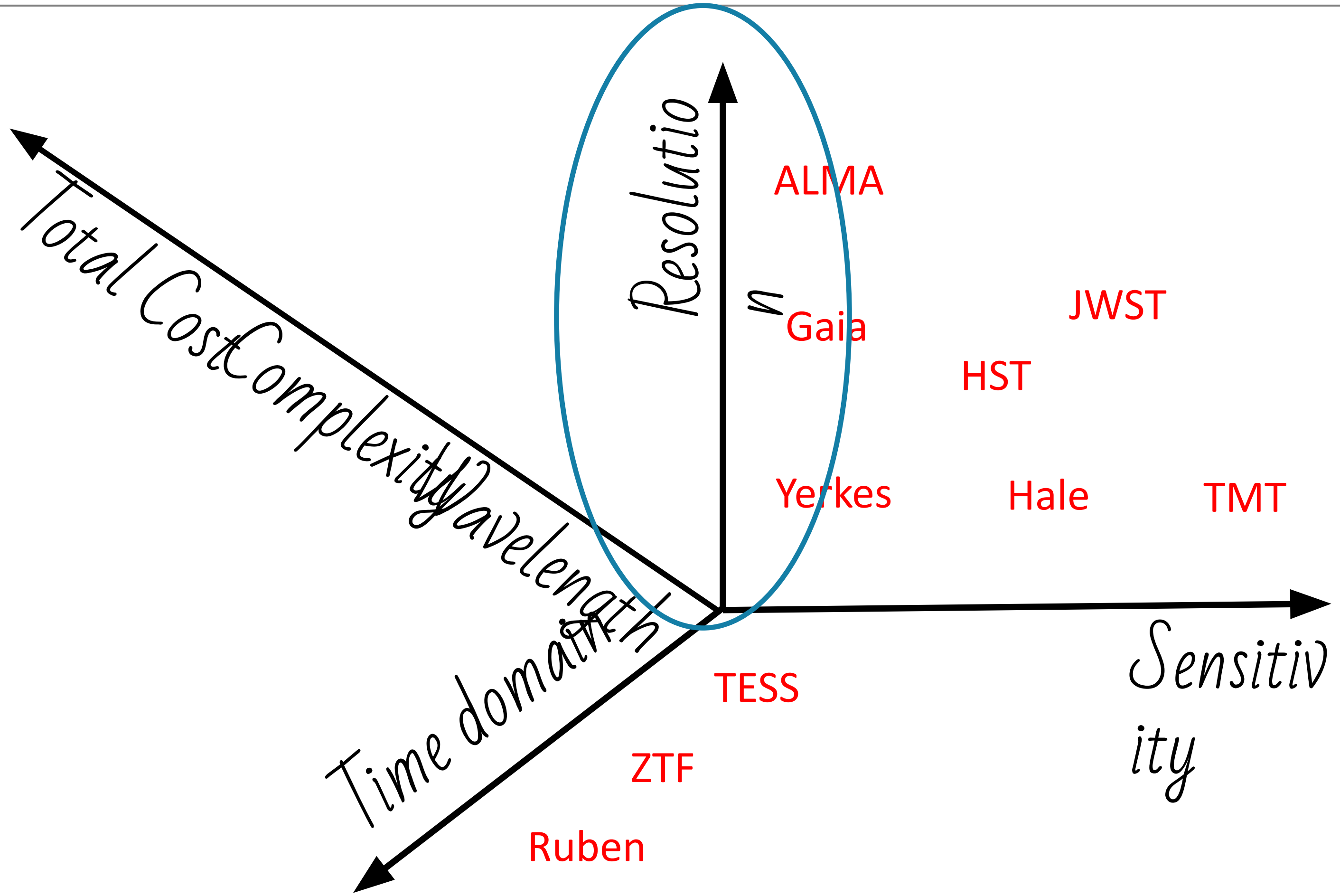
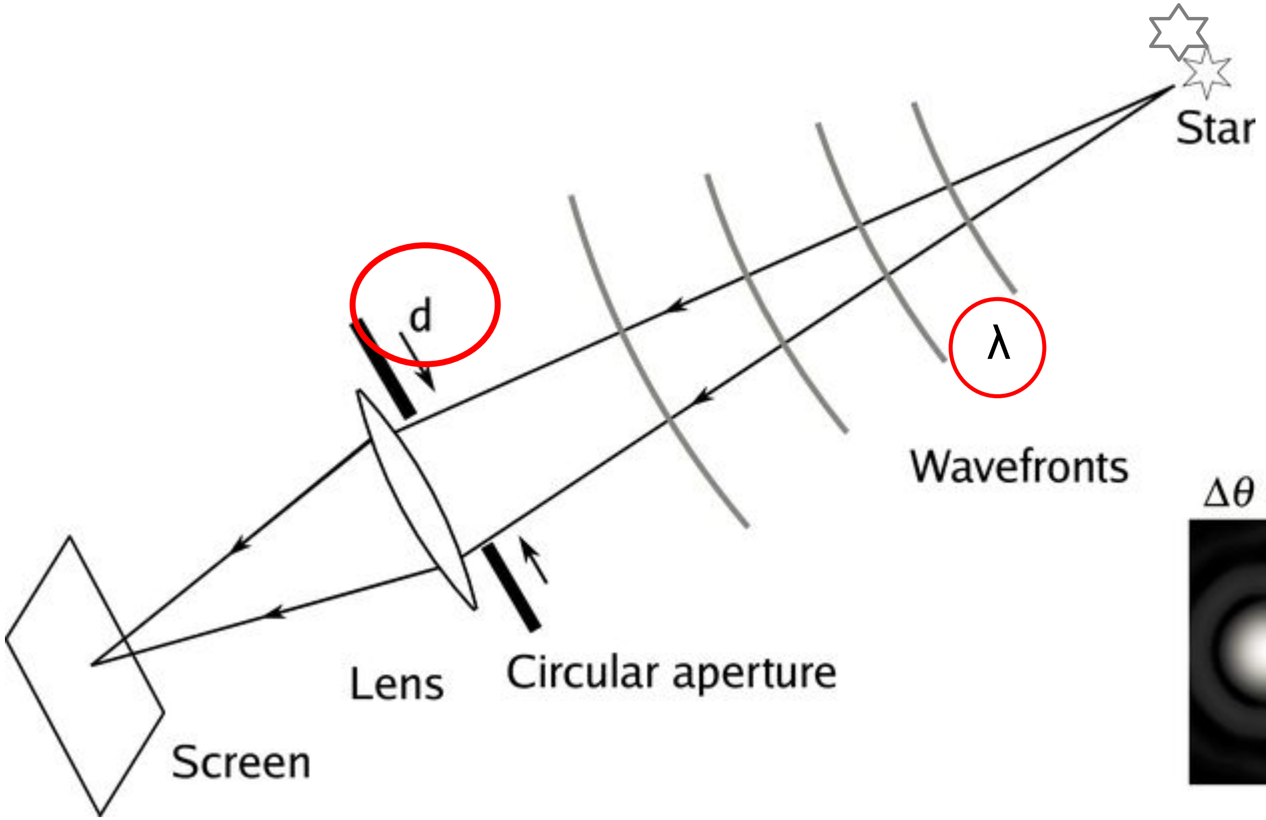
Outline of the Talk

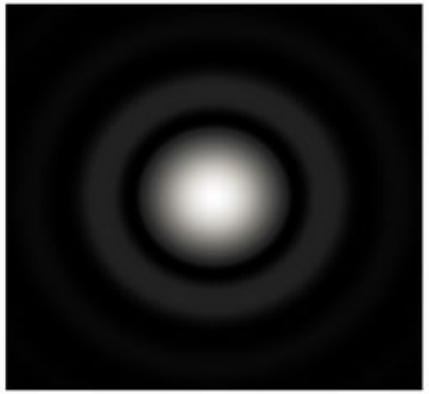
- Why use Interferometry? What is it?
- Basic Concepts and Language
- What types of things can an optical/infrared interferometer measure?
- What are some of the enabling technologies?
- Where can you go for more information?

Why Interferometry?

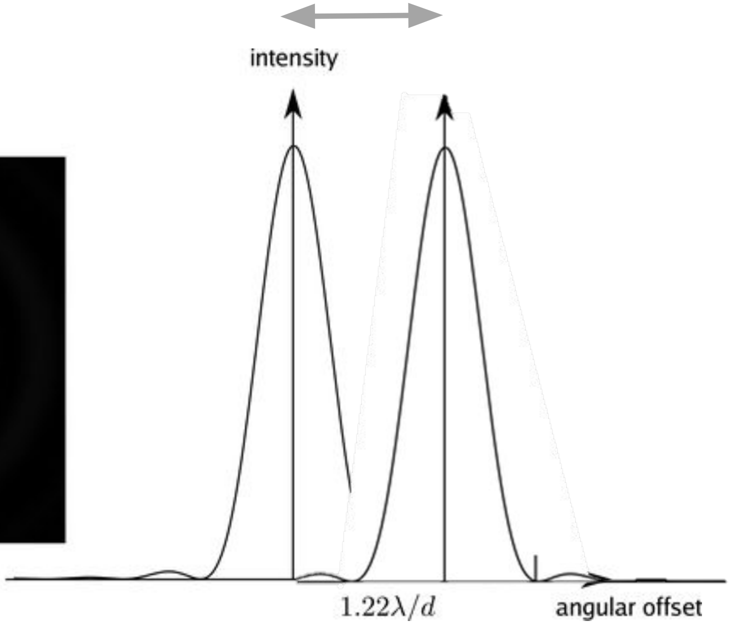


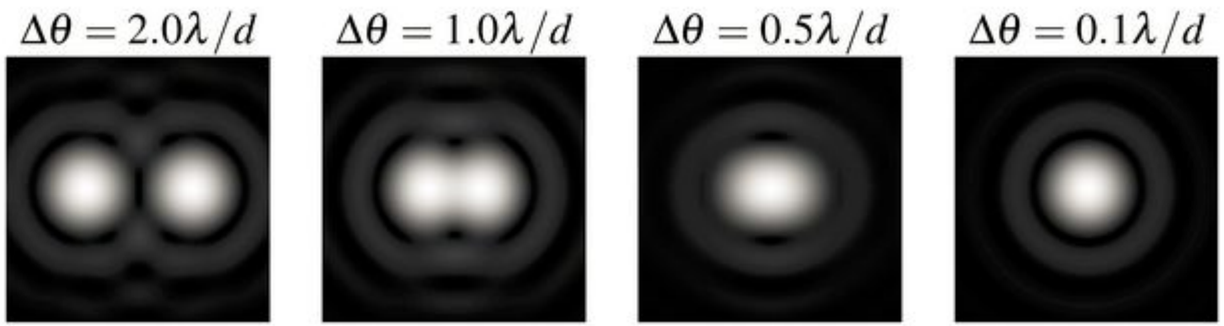
Why Interferometry?





Airy Disk

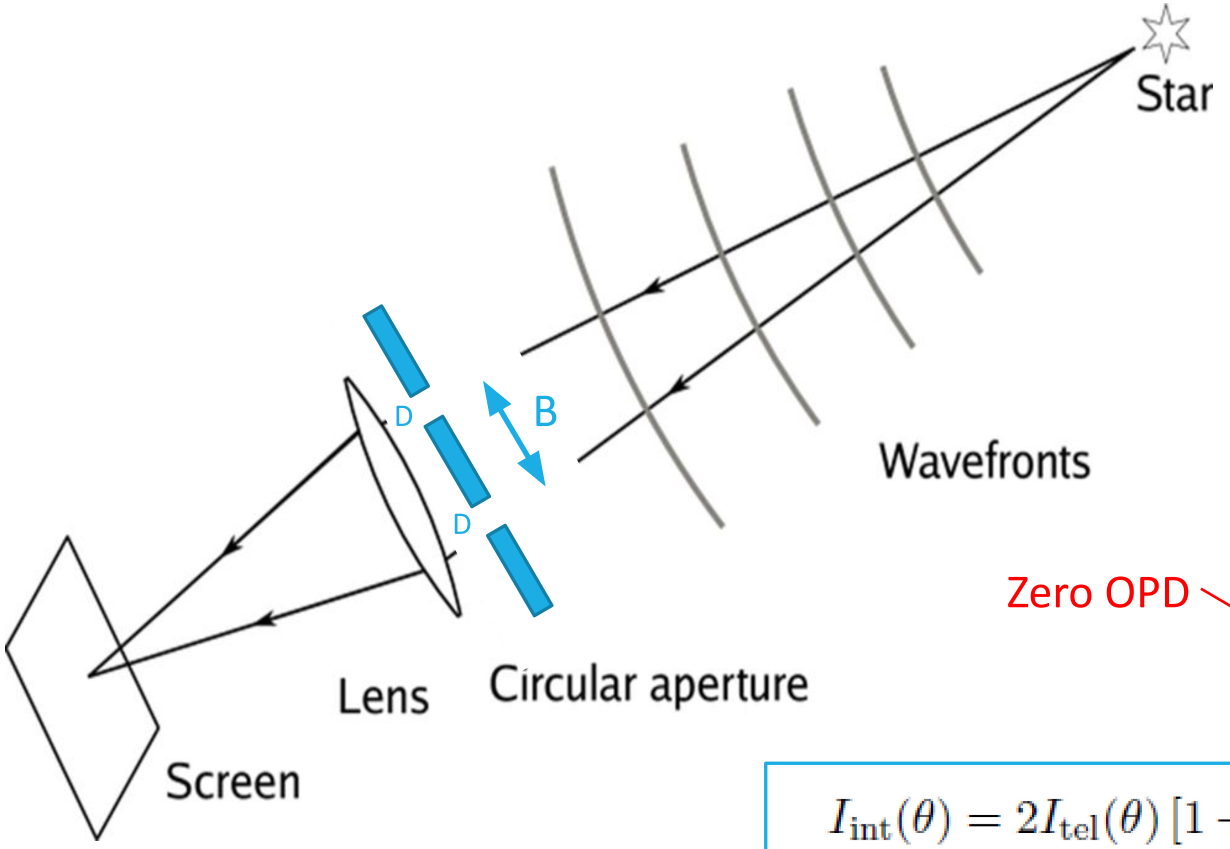


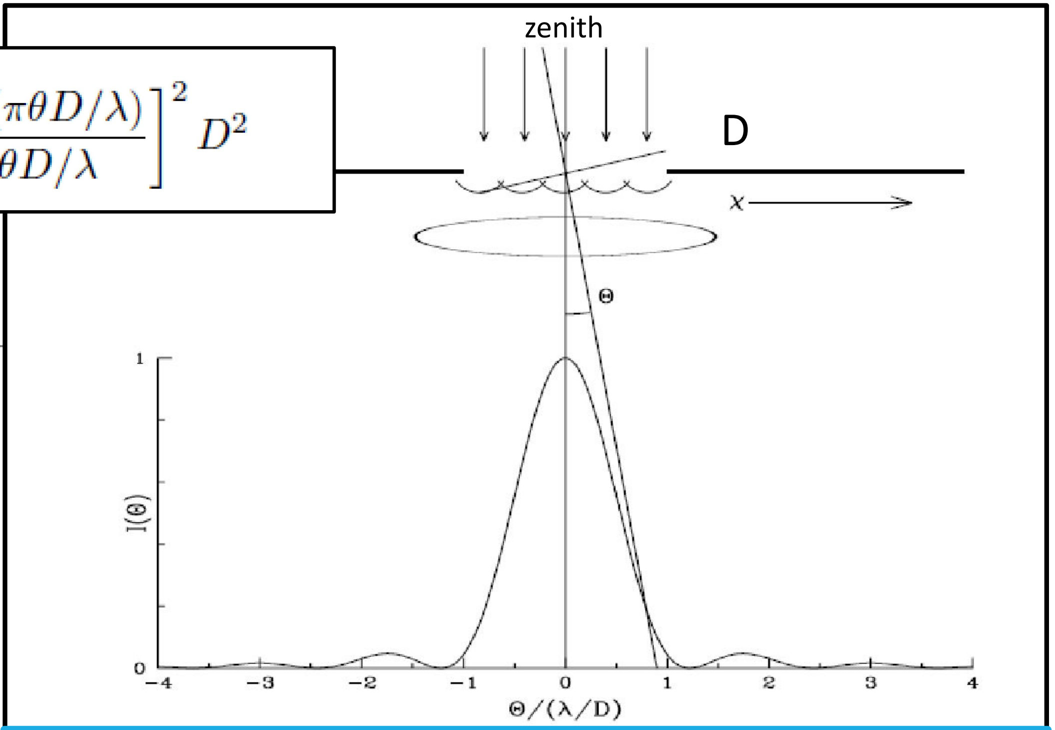


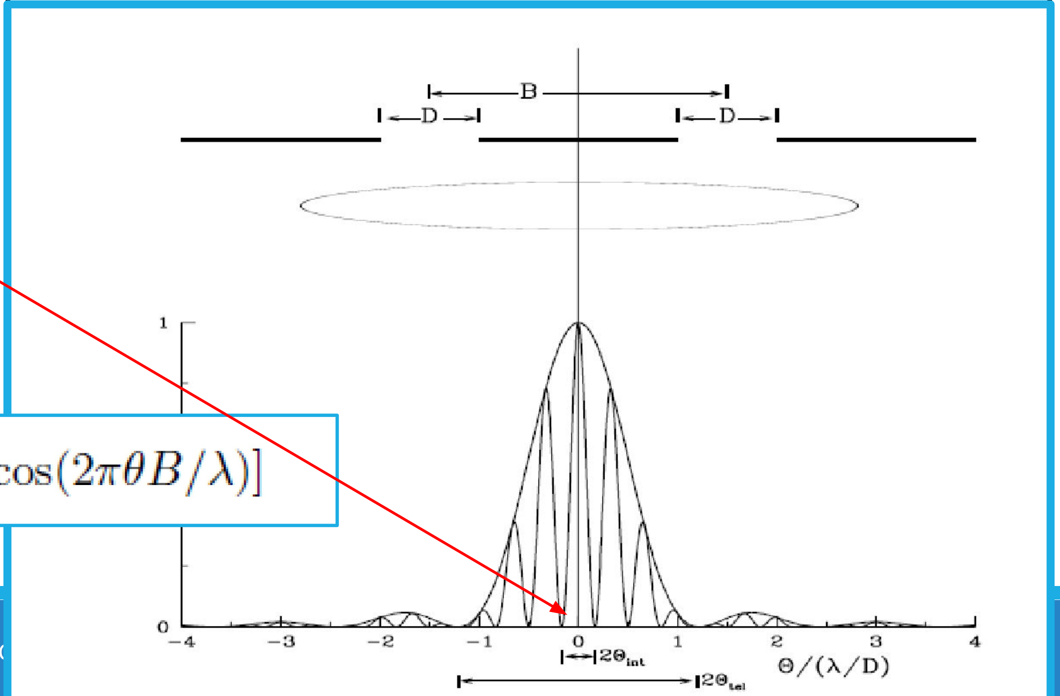
Resolution

Why Interferometry?

$$I_{\mathrm{tel}}(\theta) \;=\; \left[\frac{2J_1(\pi\theta D/\lambda)}{\pi\theta D/\lambda}\right]^2 D^2$$





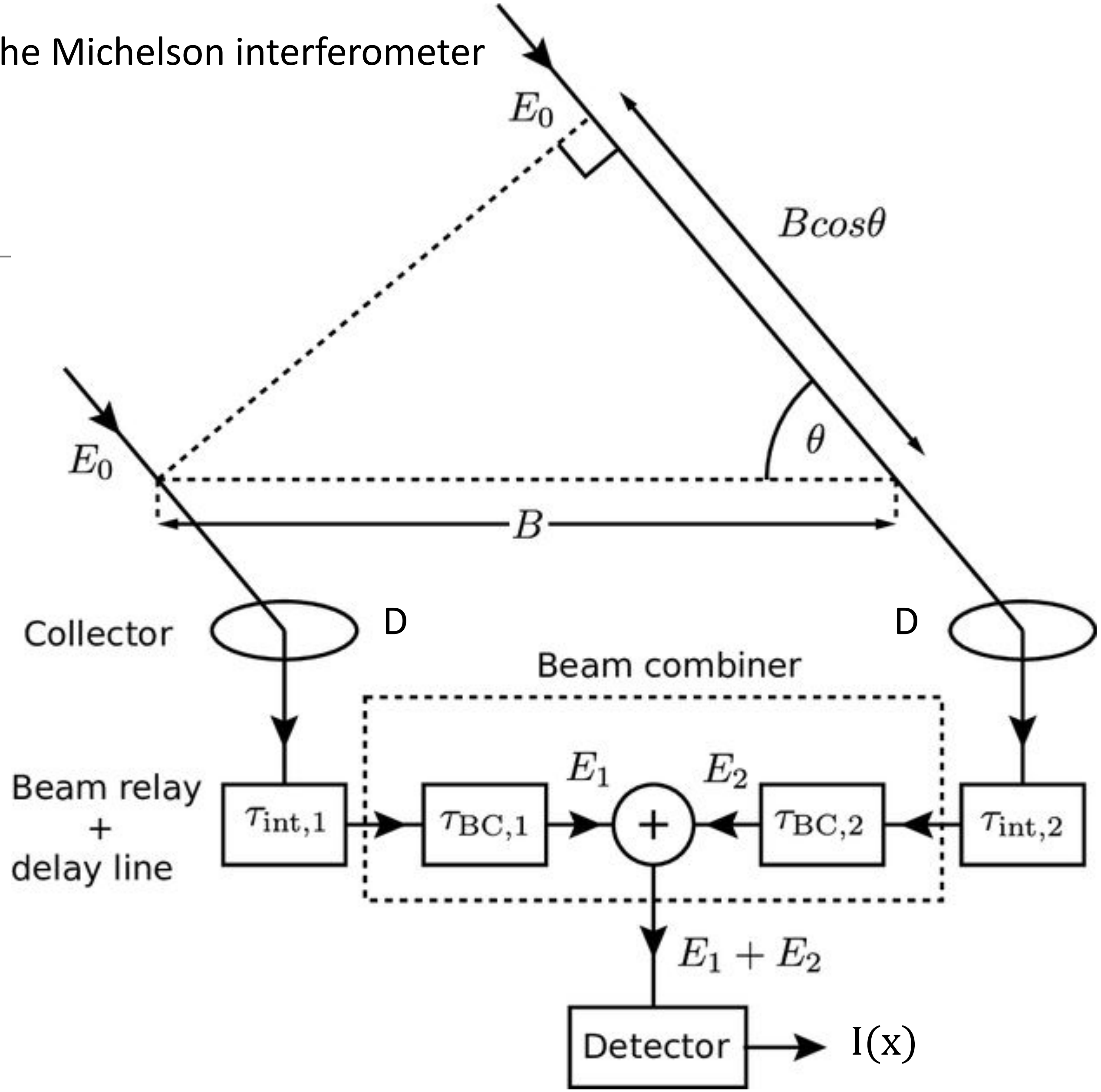


$$I_{\mathrm{int}}(\theta) = 2I_{\mathrm{tel}}(\theta)\left[1+\cos(2\pi\theta B/\lambda)\right]$$

The Michelson interferometer

The Basics

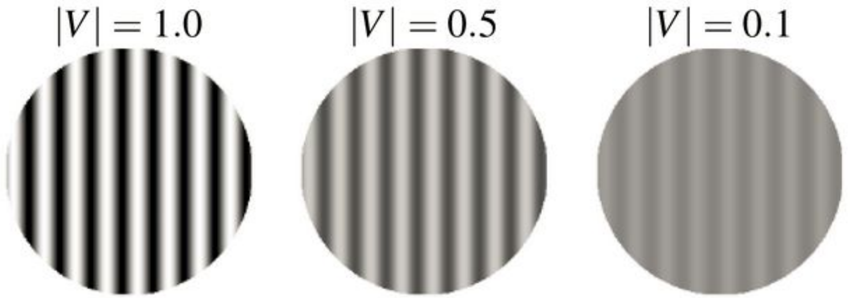
- Intensity ~ E^2 (a complex quantity)
- **Baseline = B**
- Telescope **Diameter = D**
- If you want to look anywhere in the sky, then you have to compensate for the geometric angle between the E field arrival direction and the locations of the collectors = **B cos Ɵ**
  - You could "time" this difference in arrivals
  - We call this extra distance the E field travels the **Delay**
- Because of the nature of optical/infrared light, we must account for this delay in physical space (not software)



The Basics

- In practice, detectors measure the power they receive which is related to the intensity of the light, we measure the **Visibility** of the fringes

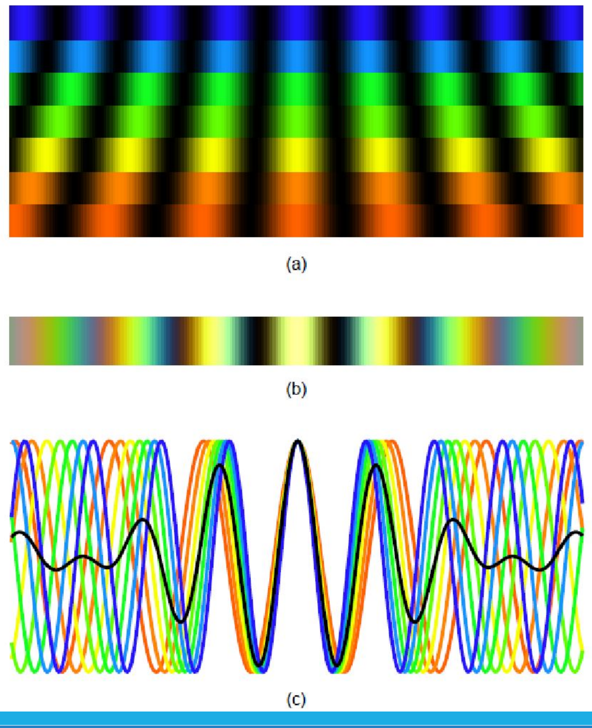
$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$



- Detectors also typically do not measure monochromatic light, they measure over a bandwidth containing multiple wavelengths of radiation

shortest wavelength

longest wavelength

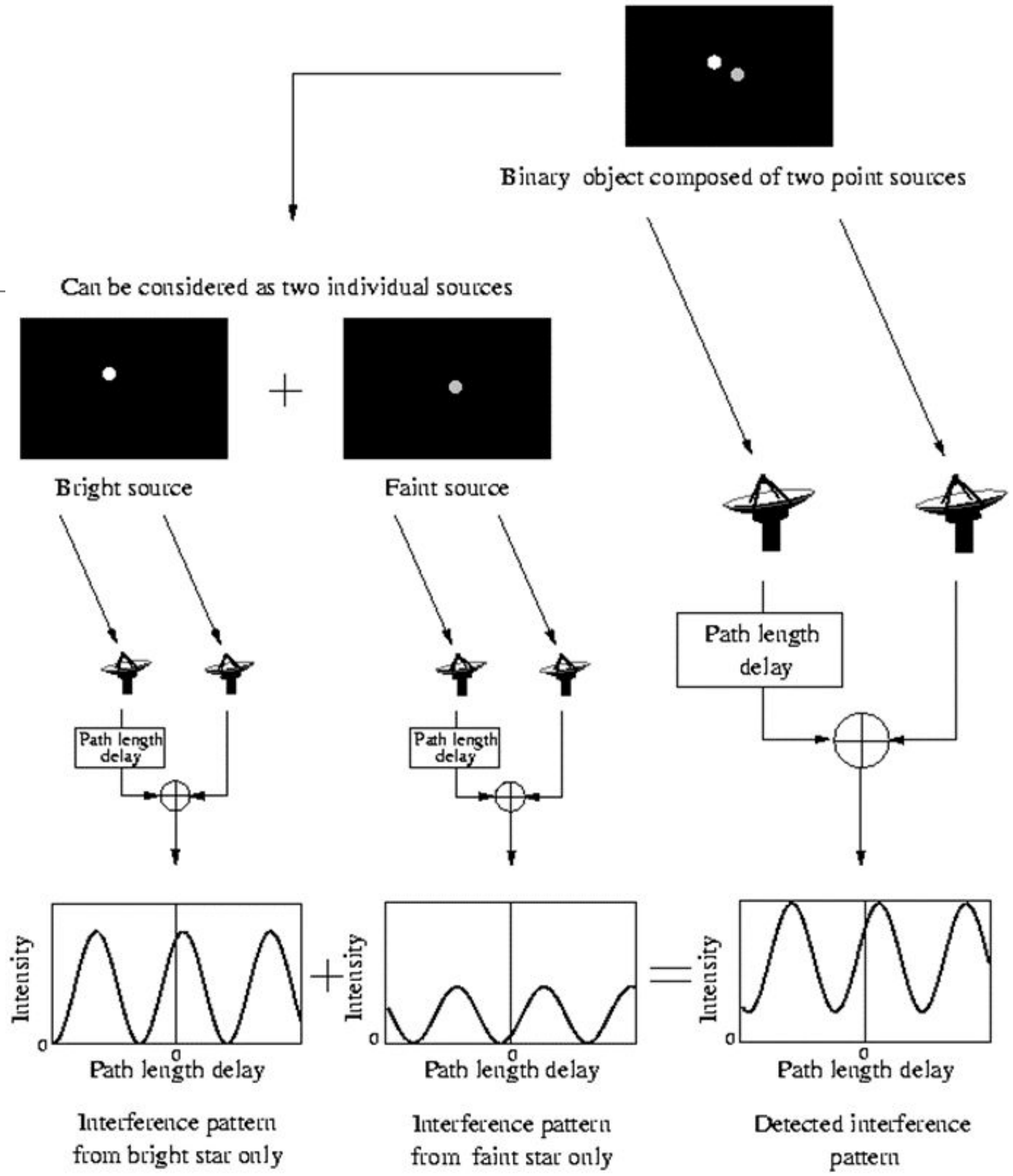


Intensities of multiple wavelengths for a point source

Sum of these intensities, creating a wavepacket

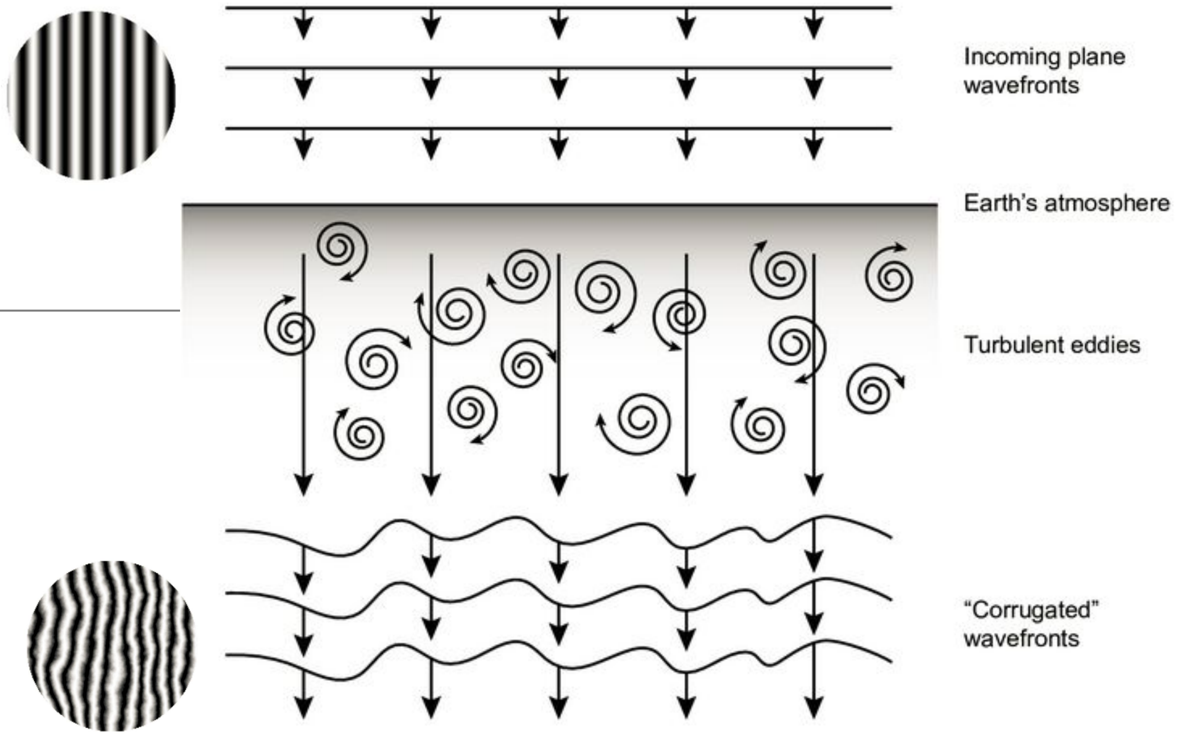
The Basics

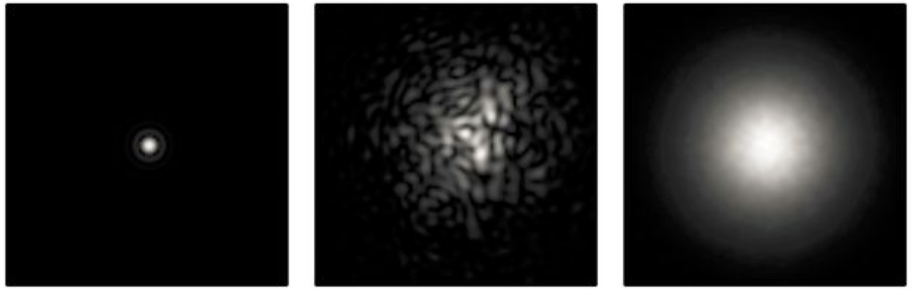
- Imagine your idealized two-element interferometer is looking at a binary star
- Without the presence of an atmosphere, you are able to encode the fringes from the object using convolution
- The incoherent brightness distribution on the sky from the astronomical object we wish to measure with a complex visibility is explained by the van Cittert–Zernike Theorem (it has several important assumptions)
- The phase information is as important as the amplitude of the fringes for what we need to measure – i.e. a complex visibility
- The Fourier transform of our measurements will allow us to recover the spatial information and brightness distribution of our source



A Word about the Atmosphere

- On Earth, the atmosphere acts as a fluid flowing over the telescopes and disturbs the planar wavefronts coming to us from the sky
- The scale size of this turbulence affects how disturbed the wavefronts become
  - Kolmogorov scale
  - Isoplanatic patch size
  - How quickly you have to make measurements with the interferometer
  - Use of adaptive optics (or not)
- The Moon does not have atmosphere, but anything that disturbs your wavefront may cause you to need similar interventions





Airy disk | speckle (short) image | long integration

Diffraction limit | Seeing limit

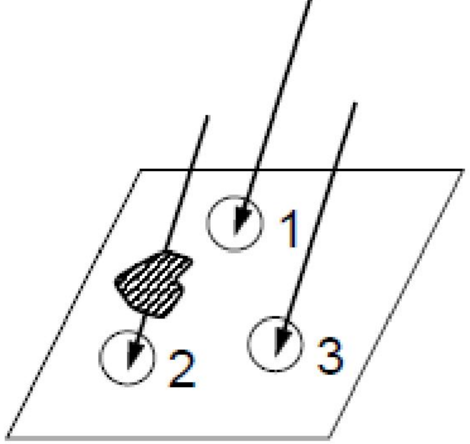
$$\binom{N-1}{2} = \frac{(N-1)(N-2)}{2},$$

Number independent closure phase triangles with N collectors

The Basics

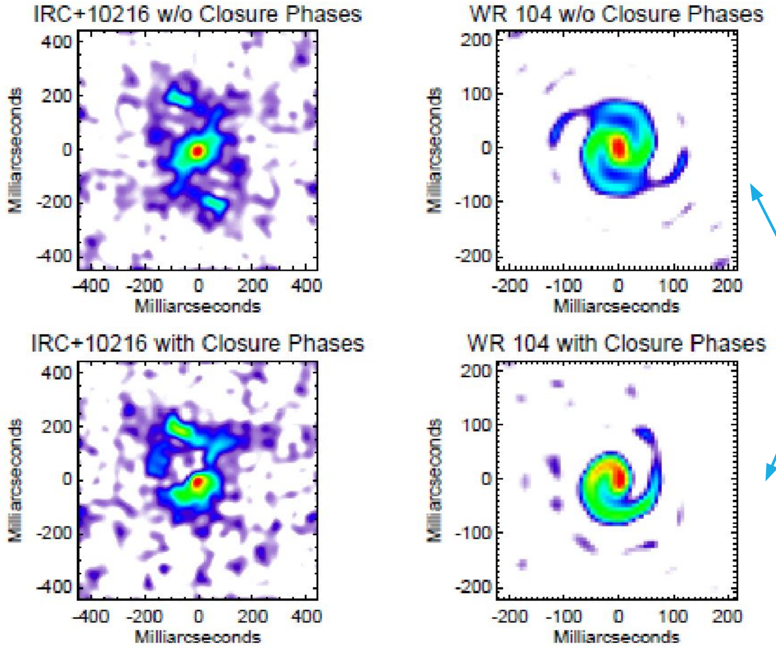
- Closure Phase – measuring the phase on each baseline in a closed triangle of three collectors together allows us to remove the atmosphere dependent terms
  - Uncorrupted by individual "telescope-dependent" phase errors
  - Very sensitive to asymmetric features
  - Powerful constraint in image reconstruction
  - Required for several techniques

Number of Telescopes	Number of Fourier Phases	Number of Closing Triangles	Number of Independent Closure Phases	Percentage of Phase Information
3	3	1	1	33%
7	21	35	15	71%
21	210	1330	190	90%
27	351	2925	325	93%
50	1225	19600	1176	96%



Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	=	$\Phi_0(1\text{-}2)$	+	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	=	$\Phi_0(2\text{-}3)$	+	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	=	$\Phi_0(3\text{-}1)$	+	$[\phi(1)-\phi(3)]$

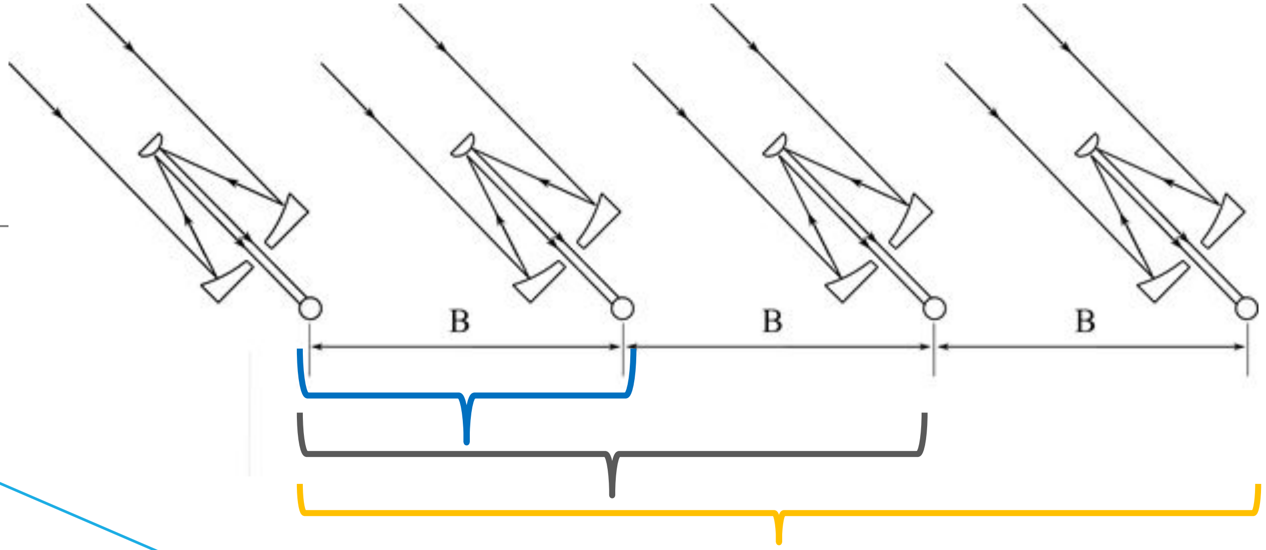
$$\begin{aligned}\text{Closure Phase}\,(1-2-3) &= \Phi(1-2)+\Phi(2-3)+\Phi(3-1)\\ &= \Phi_0(1-2)+\Phi_0(2-3)+\Phi_0(3-1).\end{aligned}$$



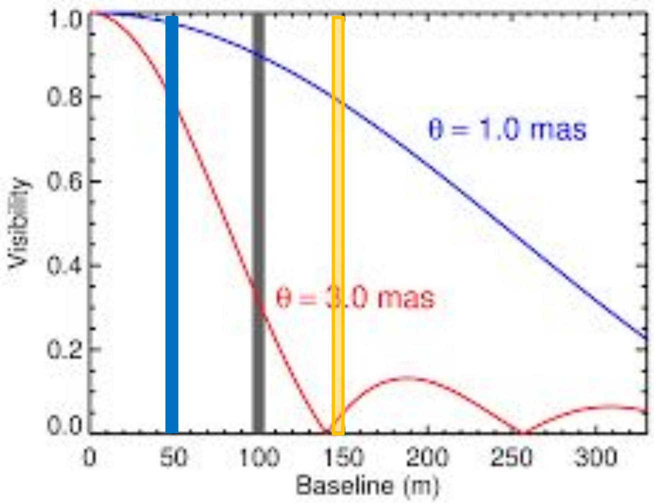
Keck Aperture masking images without and with closure phase

The Basics

- SNR for an interferometer depends on the square root of the number of photons and the visibility
  - More closely spaced telescopes sample higher visibilities for a given object angular diameter
  - More distantly spaced telescopes sample lower visibilities but smaller spatial scales which may be more interesting astrophysically
- Concept of building up longer baselines with many intermediately spaced shorter baselines is called Baseline Bootstrapping
  - There is an analogous Wavelength Bootstrapping using shorter and longer wavelenghts

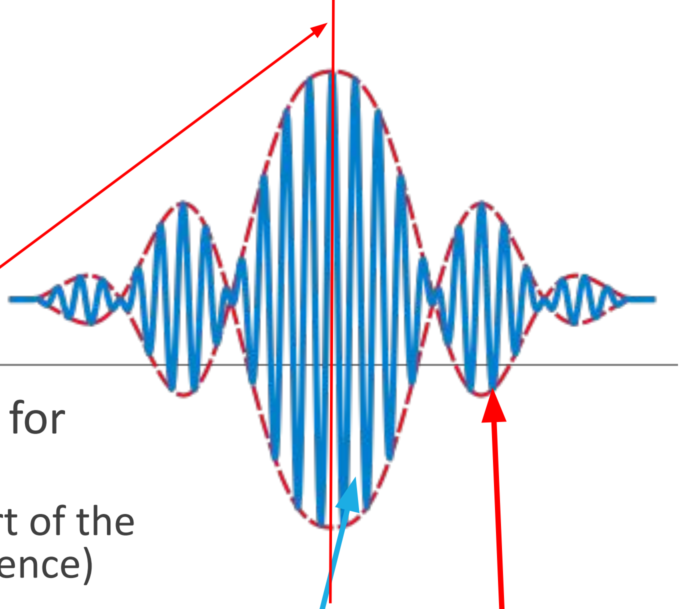


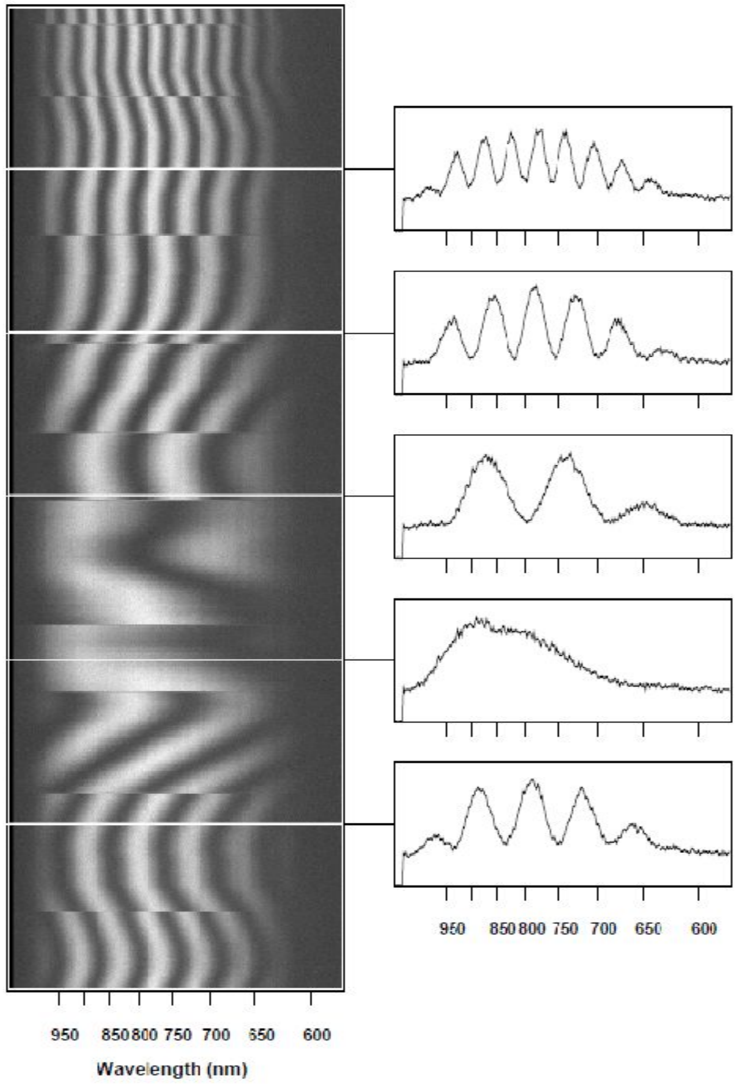
1 milliarcseconds
= 1 mas
= 1E-3 arcseconds
= 4.8E-9 radians



The Basics

- Fringe Tracking is the heart of the matter for interferometry
  - Phase tracking – staying on the central part of the fringe closest to 0 OPD (optical path difference)
    - May be required for certain techniques
  - Group delay tracking – staying on the group delay envelope within several fringes of 0 OPD
- Always accomplished in concert with the Delay Lines in “hard real time” – typically faster than the atmosphere changes
- Charles Townes has nice calculation in Lawson’s book for the SNR cutoff between homodyne and heterodyne fringe tracking approaches – right around 10 microns is the tipping point for “room temperature”





COAST interferometer group delay tracking at various optical wavelengths

How Do You Measure It?

- The keys are measuring visibility amplitude and phase of the target
- The ability to calibrate each measurement is critical
  - Calibration tells you how far from an ideal model your interferometer is performing
  - This can change on fairly short (minutes) timescales for Earth-based systems
- What types of measurements can be made?
  - Imaging
  - Spectroscopy
  - Differential Phase
  - Astrometry
  - Nulling

What Can Y
Imaging

- Imaging interferometry is th
many visibility amplitudes a
ideally on as many non-redu
possible, in order to reprodu
astronomical object's image
  - The speed that the image is
the number of independent
triang
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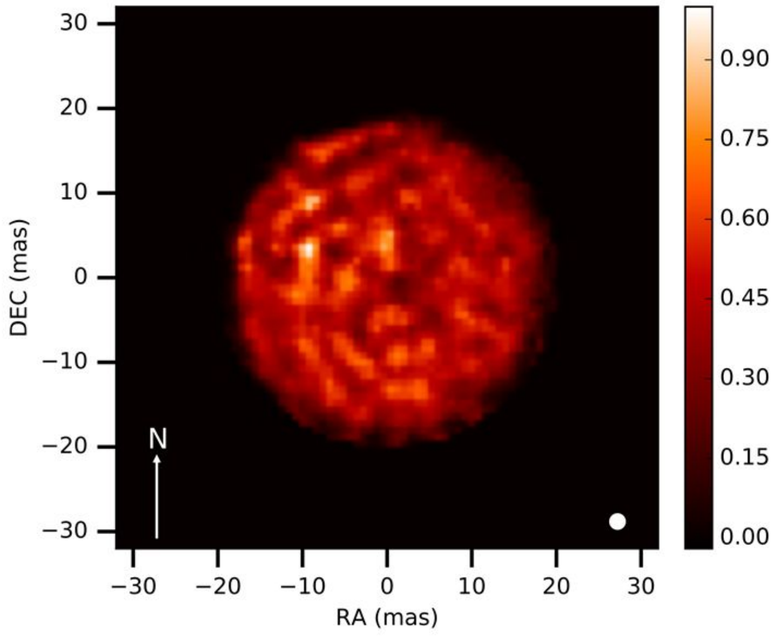
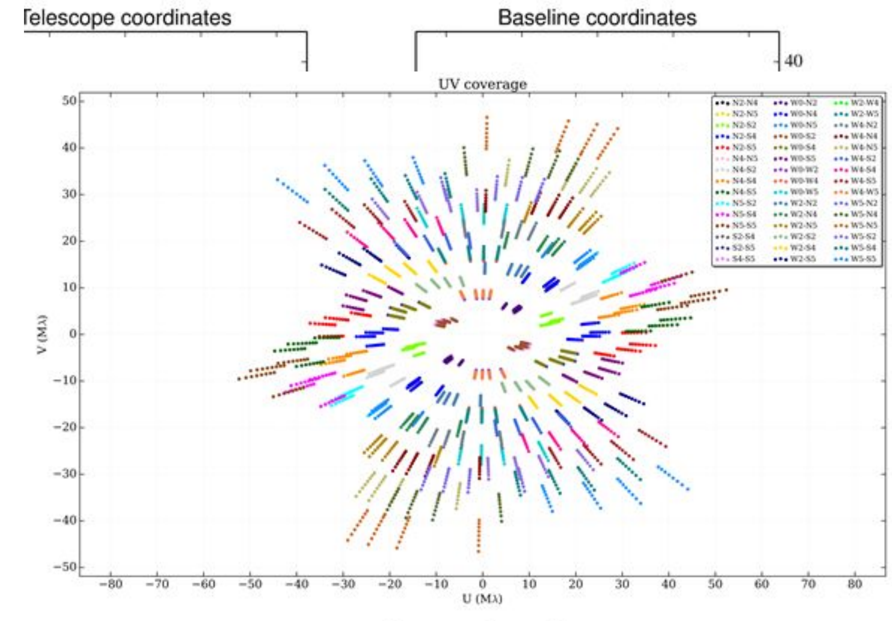
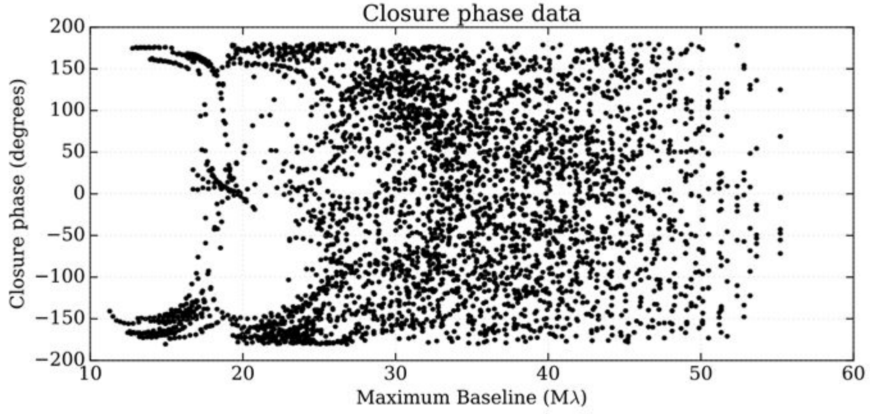
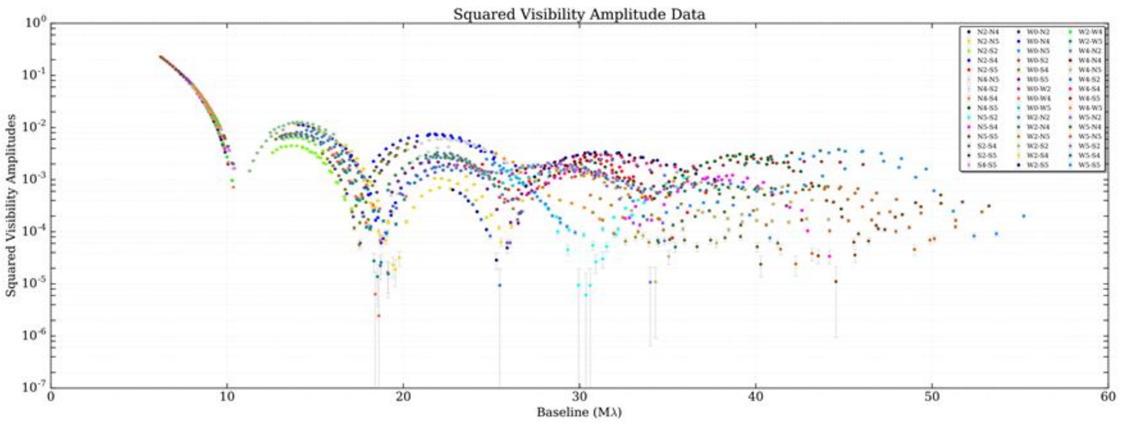
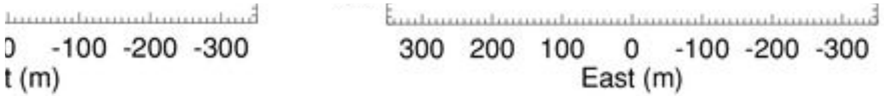






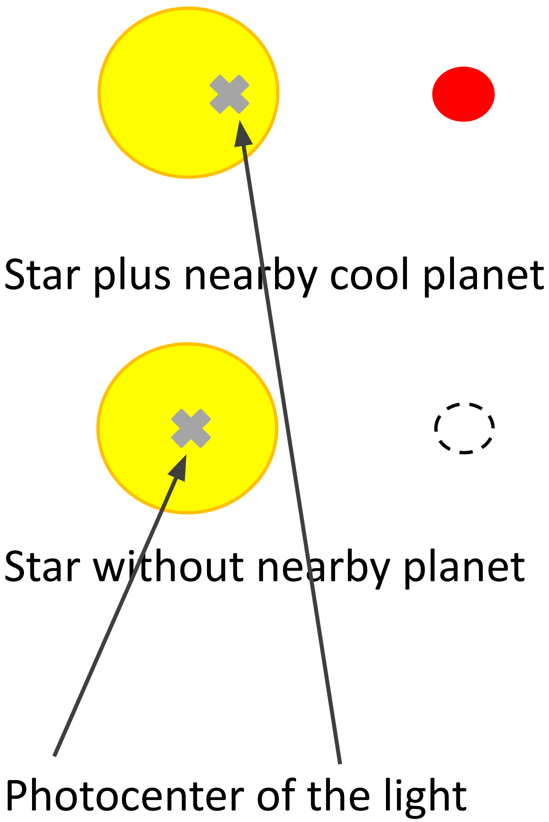


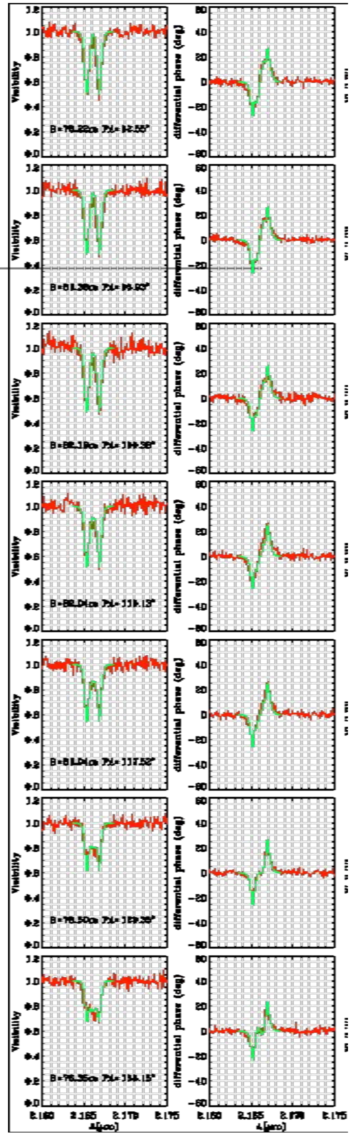


CHARA Earth-synthesis rotation tracks for 2 different stars

What Can You Measure? – Spectroscopy/Differential Phase

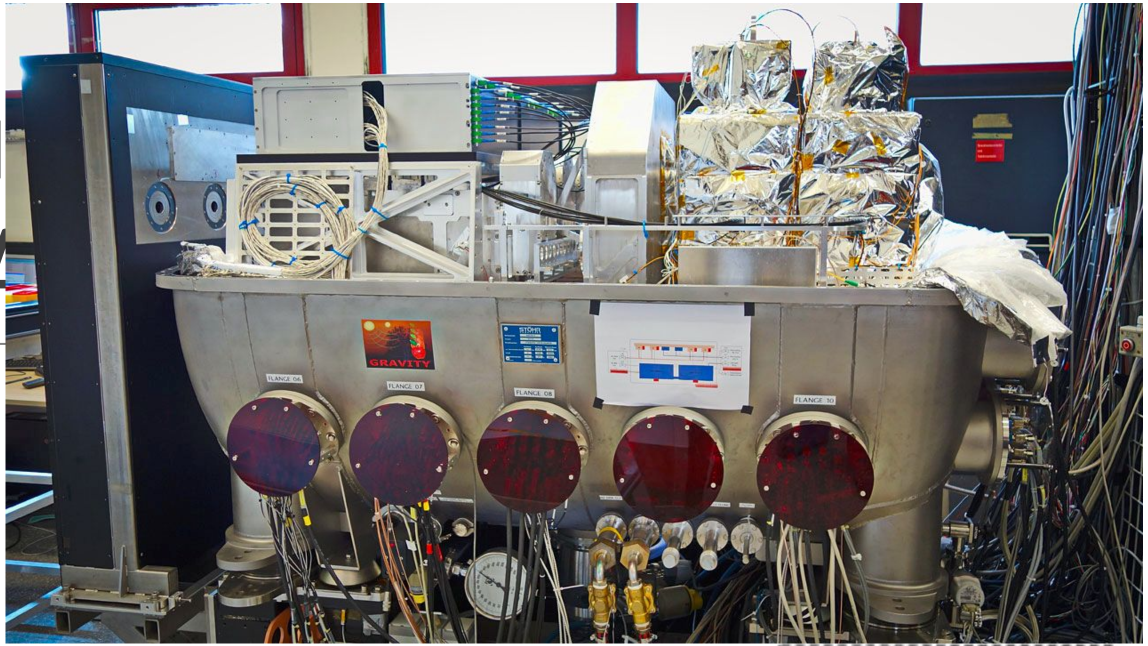
- Spectroscopic interferometry relies on measuring visibility amplitudes and phase, with some amount of spectral dispersion
  - Designs in your interferometer that make this easier include:
    - Separate fringe tracking and science combiners
    - Bright targets
    - The ability to integrate on the target as long as possible with the spectrally dispersed instrument
- With very good precision on your (closure) phase information, you can detect photocenter changes (or look for differences at different wavelengths)



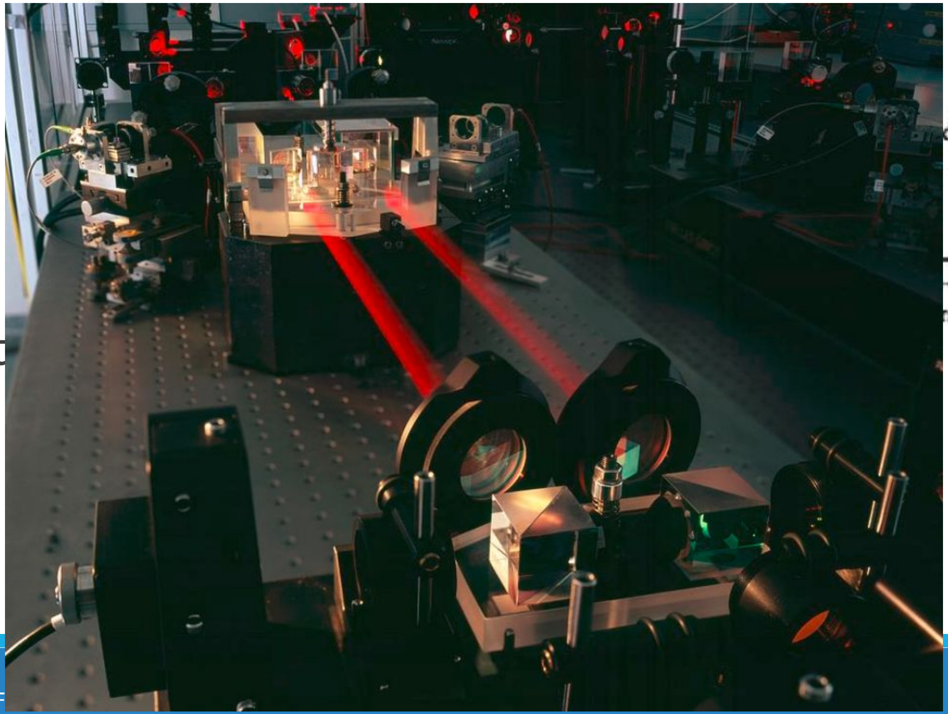


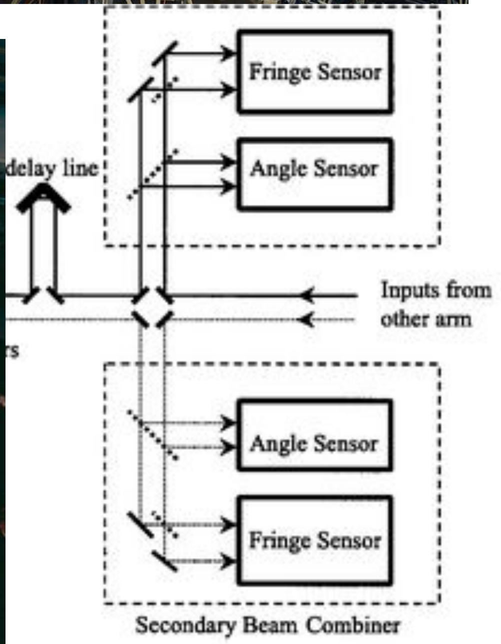
Meilland et al. (2012)

What Can you Measu
Astrometry (Narrow A



- Astrometry is the high precision measurement of the position of two objects in the sky
- In interferometry, this is tracked by carefully measuring the phase on two simultaneously tracked objects
  - Requires redundant beamlines
  - Uses constant term metrology
  - Switching between two nearby targets within the isoplanatic patch
- Wide-angle astrometry with a highly calibrat system might be possible without redundant beamlines (e.g. NPOI)



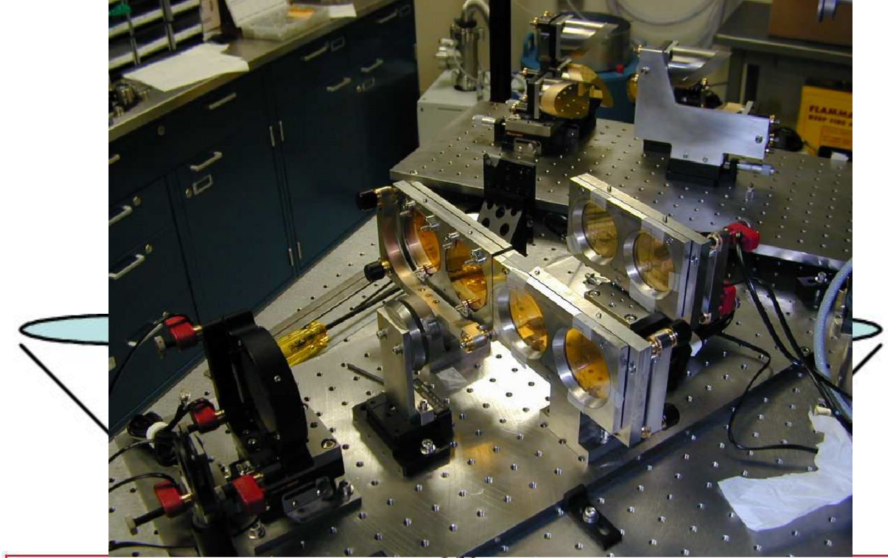


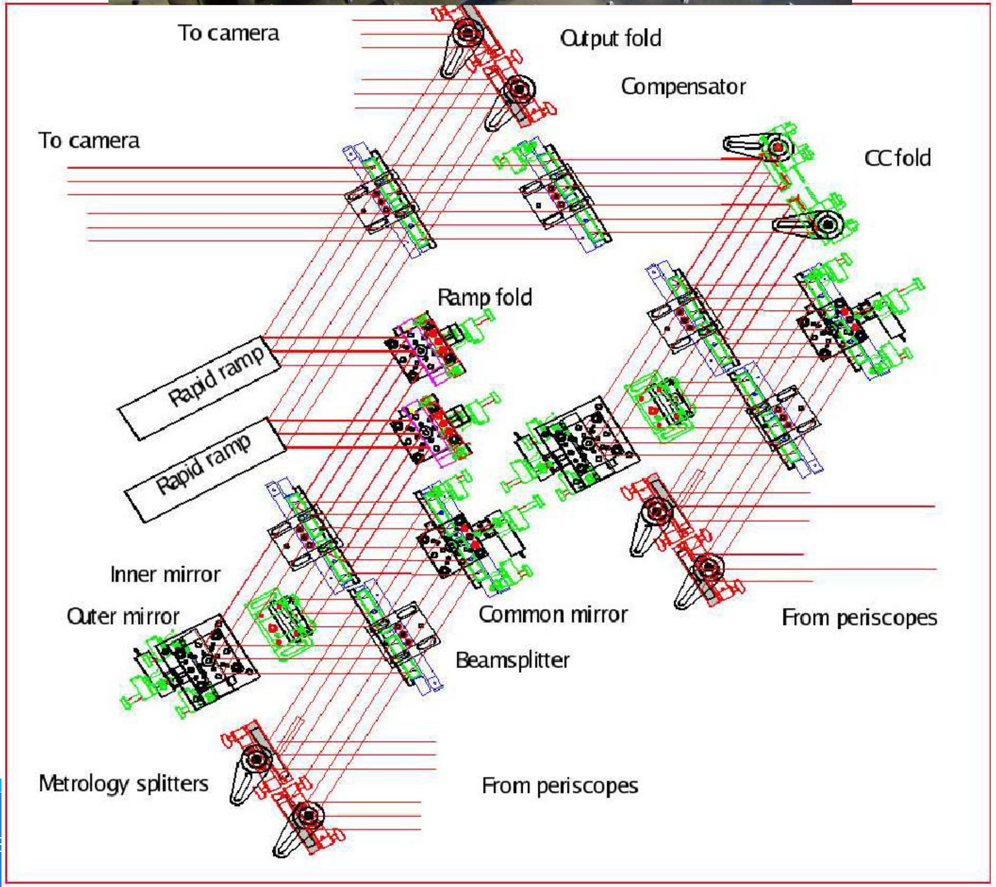
VLTI's PRIMA instrument in GRAVITY

What Can you Measure? Nulling

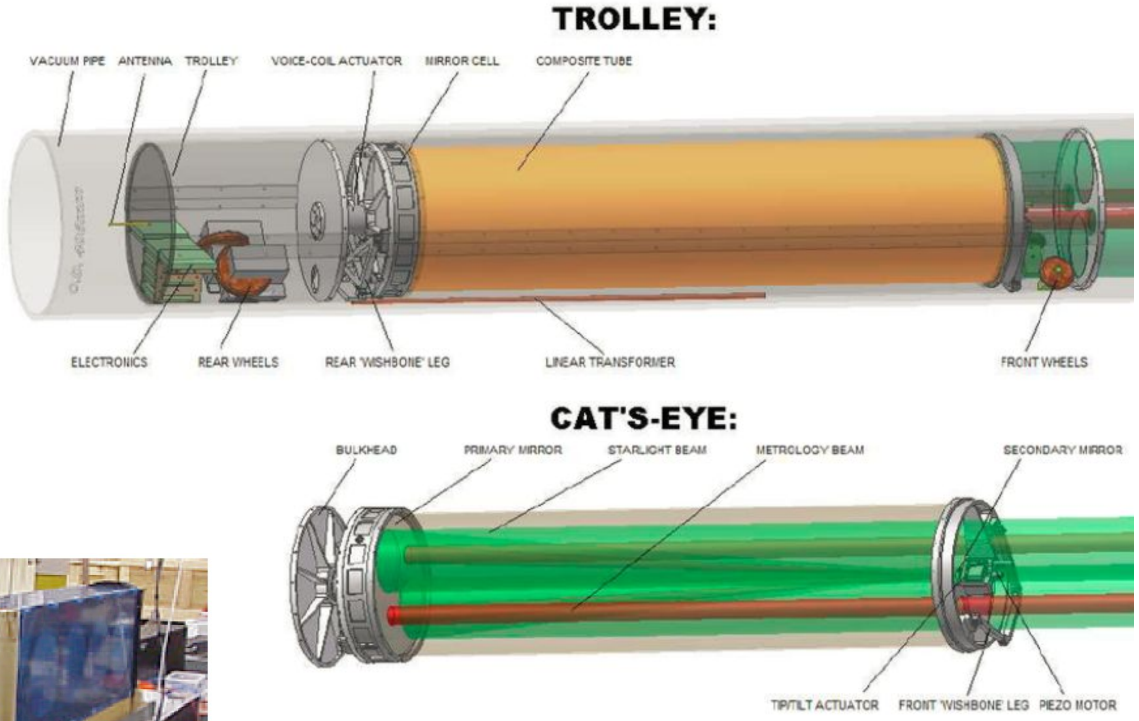
- Nulling concept (Bracewell) is analogous to coronagraphy
  - Use careful control of phase in one “arm” of the interferometer to “null” the fringe at the location of the bright target
  - If fainter companions are well-placed with respect to the fringes, you can detect them
- Challenging technique for several reasons
  - Star-exoplanet systems are easier to measure at longer wavelengths
  - Stable, deep nulls (10^3-10^6) over broad bandpasses are optically challenging
  - Calibration schemes are intricate

Keck Interferometer Nulling Beam Combiner and one arm of Modified Mach-Zehnder beam combiner

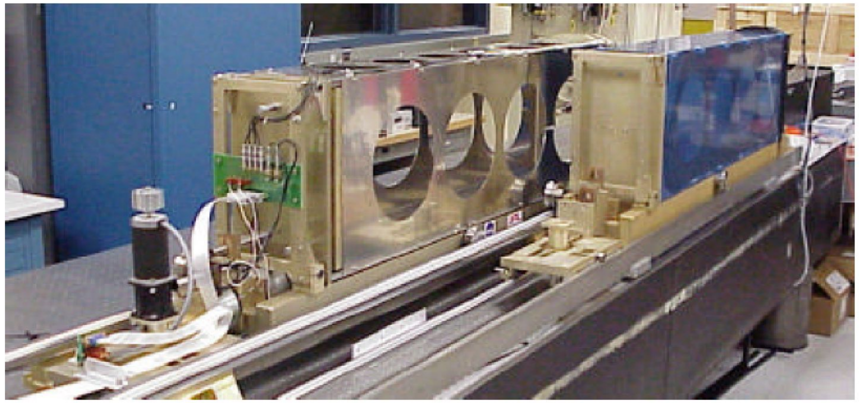




How Do You Measure It?

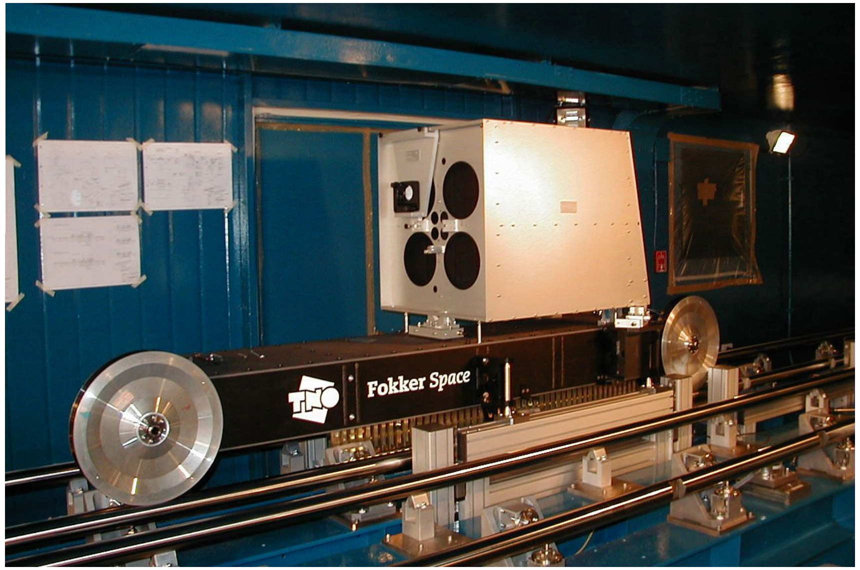


- Delay Lines – Cat's Eye style retroreflector that moves on precision rails and possibly in vacuum – one per telescope
  - Use laser metrology to track p
    fraction of the wavelength of
  - Compensates for both siderea
    and possibly some seeing (voi
  - "Hard real time" with fringe tr
    follow the fringes
  - Length of tracks determines h
    sky you can observe without r



- Only 2 design types have been deployed in working interferometers today

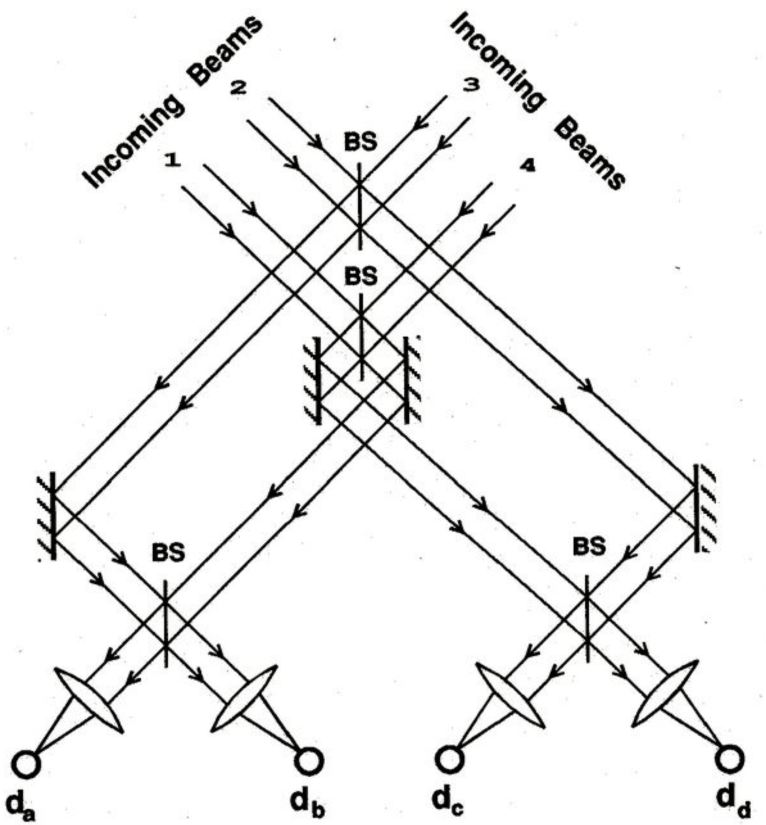
MROI, JPL/PTI/CHARA, and VLTI delay trolleys

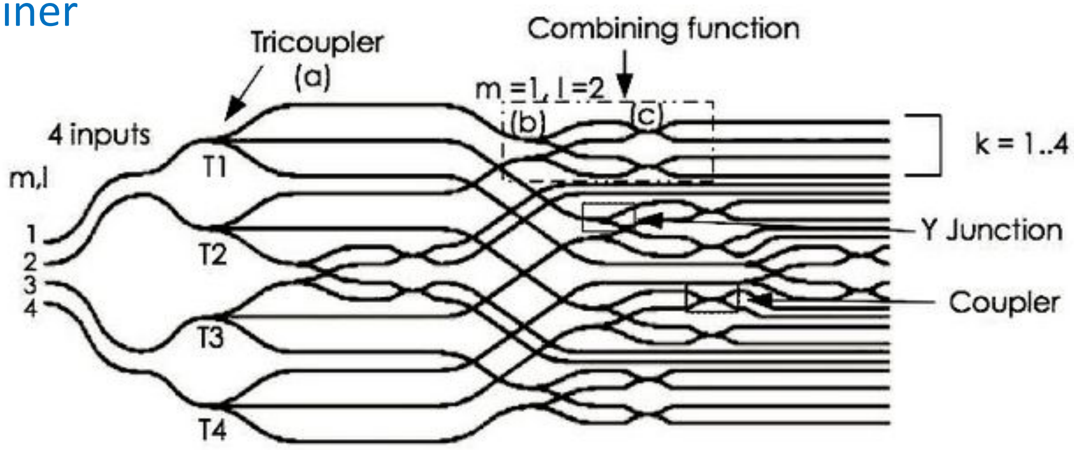


How Do You Measure It?

- Beam Combiners – Make the interference fringes on either a beamsplitter or directly on the detector
  - Can use bulk optics or integrated photonics (optical and NIR)
  - Different schemes to encode and measure the fringes depending on application
  - Because this step is done after delay compensation, it is typically very geometric with precise spacing
  - Because this step often includes many optics, and will be recorded on an even smaller detector, the beams are usually small (<50mm)

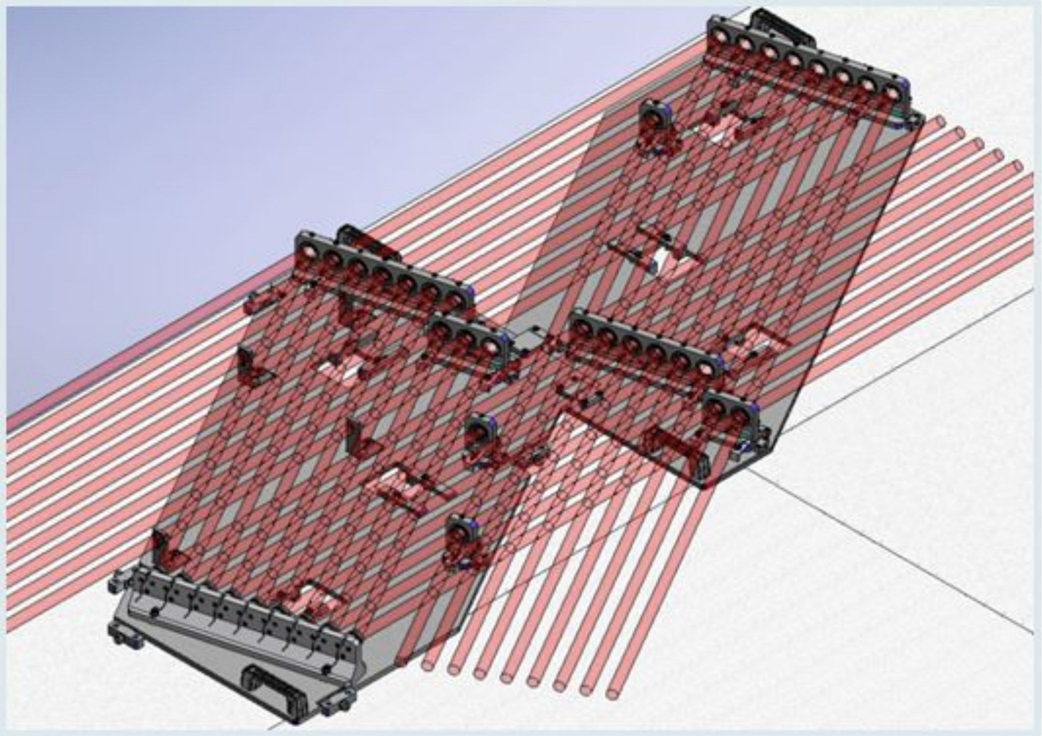
COAST 4-way bulk optics BC and a similar application PIONIER photonic combiner

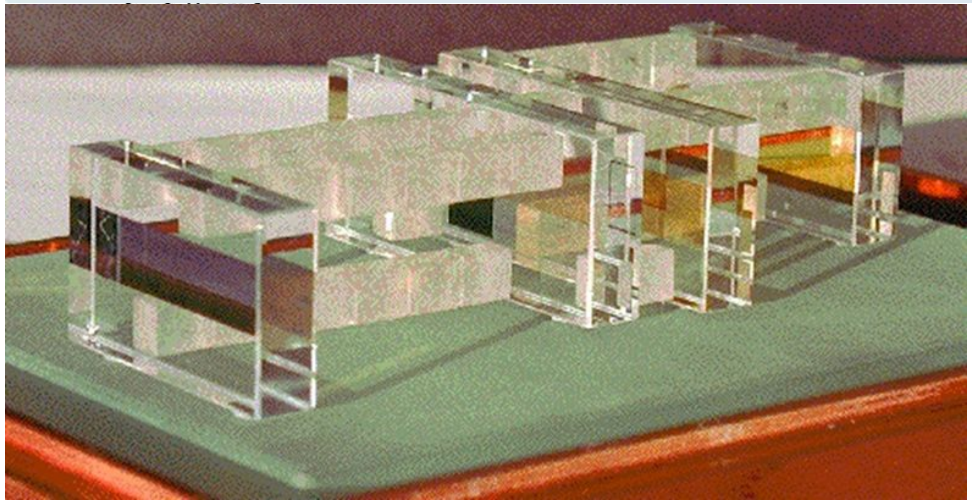




How Do You Measure It?

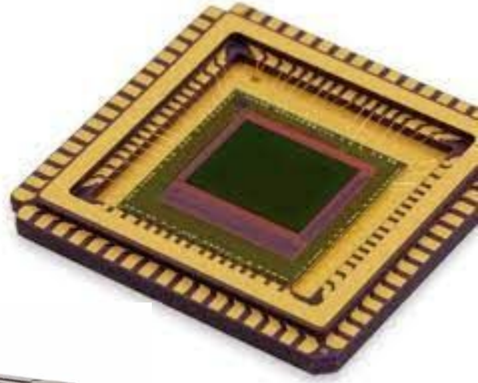
MROI nearest-neighbors 10-way combiner and COAST 4-way optically contacted combiner





- Beamcombiners can be used for fringe tracking or science, or both
  - Trade-off in spectral resolution versus number of photons collected
  - May be a preference for one type over the other
    - SNR considerations
    - Physical space to combine beams
    - Ability to calibrate
    - Wavelengths of observation (glasses being available)
    - Cost

How Do You Measure It?



- Detectors
  - Many improvements in recent years in terms of noise and background suppression
  - Need to read very quickly (coherence time of the light)
  - Small format or linear arrays have advantages over large detector arrays used in astronomy

- Packaging for detectors
  - Off-the-shelf package and detector – constrained by what is available
  - In the infrared you need to cool detectors, so often build custom systems

We Are Going to Build….

A HOUSE

- Walls, Roof, Foundation, Doors
- Power, Water, HVAC
- Critical Rooms – Kitchen, Bathroom, Bedrooms
- Other Rooms – Music Room, Entertainment Room, Wine Bar, etc.
- Other considerations: Garage, How Many Floors, On a Cliff, Color/Siding/Roof

AN OPTICAL INTERFEROMETER

- Light Collectors
- Beam Transport
- Delay Compensation/Metrology
- Beam Combiners/Detectors
- Software Control/Automation
- The types of science you wish to do govern which extra features you need
- Do you have to worry about atmosphere or vibrations?

References

- "Practical Optical Interferometry" D. F. Buscher, 2015, Cambridge Press

- "Principles of Long Baseline Stellar Interferometry (course notes)" P. R. Lawson, 1999, Michelson Fellowship Program, NASA-JPL/Caltech

-- "Principles of Optics", M. Born & E. Wolf, 1999, Cambridge Press.

- CHARA, VLTI, NPOI, LBTI, Keck Interferometer and MROI websites

Articles/Other:

Meilland et al., 2012, Astronomy & Astrophysics, 538, 110.

MROI Imaging Simulation of Betelegeuse – R. Norris, F. Baron and J. Young

Special Thanks to the KISS Organizers and all the people who've trained me over the years.