Interferometer Design for Synthesis Imaging

David Mozurkewich

Naval Research Lab – NPOI

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Outline of Talk

- Preliminaries
- Strategies for Imaging Complex Sources
- Array Design for Synthesis Imaging
- Beam Combination and Fringe Detection

How Does Interferometric Imaging Work?

- Combine Light from Two telescopes
  - Adjust Beam overlap and tilt
- Adjust Delay until we see Fringe
- Measure Fringe Amplitude and Phase

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- Combine Light from Two telescopes
  - Adjust Beam overlap and tilt
- Adjust Delay until we see Fringe
- Measure Fringe Amplitude and Phase
- These are the Amplitude and Phase of a Fourier Transform of the Image at a Wavenumber equal to the Projected Baseline Divided by the Wavelength

u,v Plane

- u and v are the coordinates of the wavenumber (Baseline/wavelength)

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- Missing the longest baselines implies our image will be missing the high spatial frequencies.
- But there will always be holes in the Measured portion of the u,v plane.

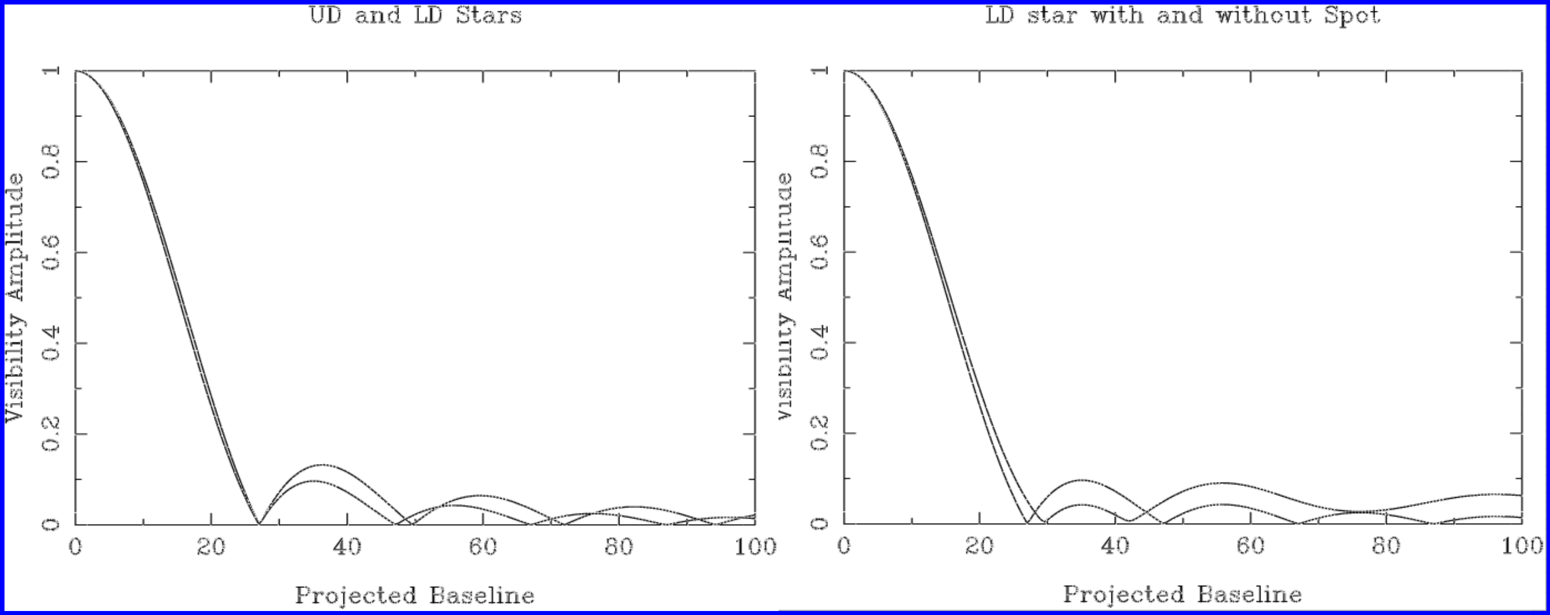
Why Does Interferometric Imaging Work?

- The Key
  - We Assume the Source is Compact
    - (finite spatial extent)
- We try to fill the u,v plane as uniformly as possible.
- If the Largest Hole is smaller than 1/spatial extent of the source, the image is Unique.

II. Strategies for Imaging

- Examples of Visibility Functions
- Statement of the Problem
- Implications for Array Design

Visibility Functions Of Stars



Uniform Disk and
Limb Darkened Disk

Clean, Uniform Disk
and a Star with Spot

General Properties of Interesting Sources at Visible Wavelengths

- Most Power is at Low Spatial Frequencies
- Most Interesting Structure is at Higher Spatial Frequencies
- The Baselines that Contain Interesting Information also Contain Very Low Signal to Noise
- But the Atmosphere Forces us to Fringe Track
  - We cannot use longer integration times

The Hard Choice

- Either
  - Record Useful Data

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  - Look at Interesting Sources

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- Fortunately, there are Alternatives
  - I know of 5

Alternative 1
Integrate Forever

- Integration time at high Signal to Noise

$$t_{\text{int}} \sim NV^2$$

  – V=0.1 costs us 5 Magnitudes Sensitivity
- At low Signal to noise

$$t_{\text{int}} \sim \left(NV^2\right)^2$$

- This Really is Integrate Forever

Alternative 1
Integrate Forever

- But it’s Worse, on Long baselines, we don’t know where to look for the fringes.
- The Atmosphere moves the fringe around

$$\sigma^2 = 6.88\left(\frac{B}{r_0}\right)^{5/3} radians$$

- 50 to 100 um rms fringe motion
  – Use a narrower band pass
  – Scan over lots of delays where there is noise but no signal

Alternative 2

- Observe Only those Sources with High Visibility on Long Baselines

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- Assert with Great Confidence and Fanfare that These are Indeed Interesting Sources!

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- Observe Only those Sources with High Visibility on Long Baselines
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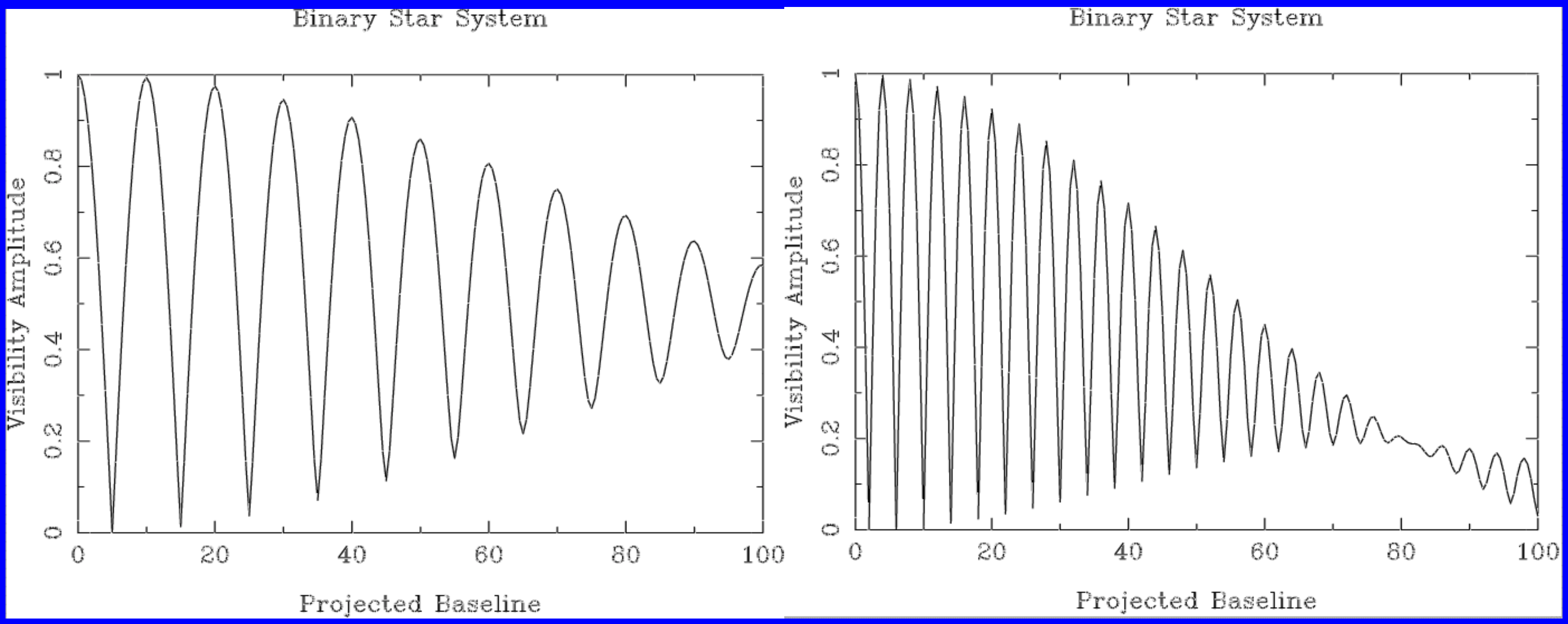
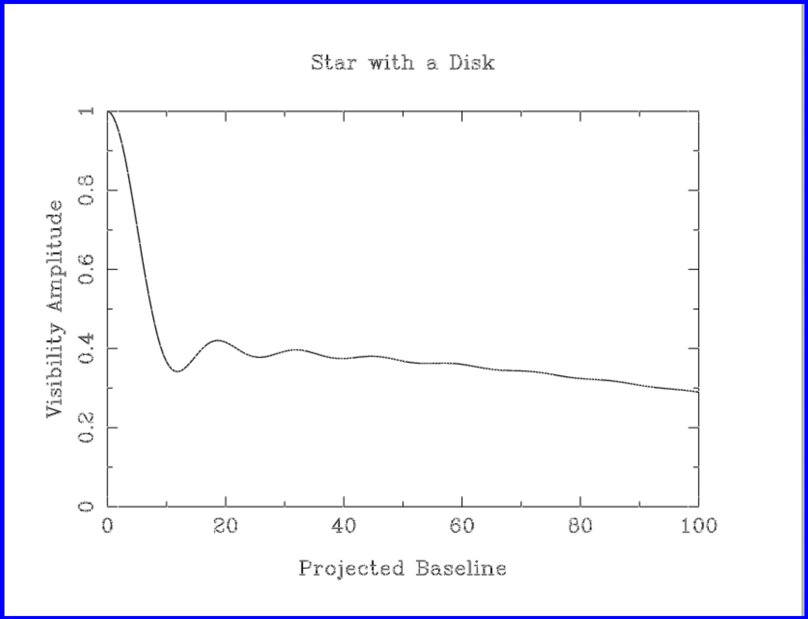
- This Really is a Viable Alternative

Binary Stars



A Star with a Disk



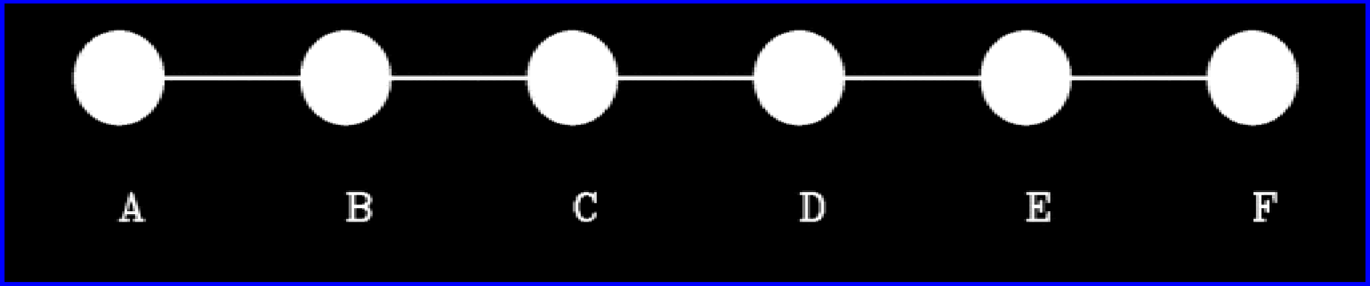
This Space For Rent

Alternative 3
Wavelength Bootstrap

- Track the Fringe at a Long Wavelength while also Recording Data at Shorter Wavelengths
  - This is the Most Widespread Technique used to Date.
- Pro
  - An Interferometer with a Wide Bandpass is a good thing
- Con
  - It is Difficult to use More than a factor of 2 to 4 in Wavelength. This limits the Maximum resolution to a few pixels across a source.

Alternative 4
Baseline Bootstrap

- Use Redundant Arrays
- Fringe Track on Short Baselines
- Record Data on Long Baselines



Alternative 5
Guide Star Methods

- Observe Two Objects in the same FOV
  - Track Fringes on Guide Star
  - Passively Observe on Target Star

Alternative 5
Guide Star Methods

- Pros:
  - Potentially Very Powerful in the Thermal Infrared
  - Should Produce Some Interesting Science in the near IR
- Cons:
  - Requires Large Telescopes
  - Amount of Phase Noise on Target star is a strong Function of seeing and angle between target and guide
  - The FOV is too small to be useful at Visible Wavelengths using natural guide stars

III. Array Design for Synthesis Imaging

- Geometric issues
- Imaging issues

Beam Rotation and Retardation

- Light cannot always be treated as a scalar.
- Even when there is no net polarization, the instantaneous orientation of the E-vector can cause a reduction in Visibility amplitude.
  - Orthogonal components of the E-vector do not interfere.

Beam Rotation

- If the E-vector is rotated between two arms of the interferometer, there is a net loss in System Visibility Amplitude
  - $V = \cos(\theta)$
- Most Easily controlled by making the optical path from each telescope to the beam combiner as identical as necessary
- In plane reflections commute, out of plane do not.

Polarization Effects

- Mirrors are Wave plates
  - Rotate E-vector
  - Add phase shift between S and P polarizations
- If two orthogonal polarizations are phase shifted by ϕ radians

$$I = I_0 + V[\cos(2\pi d/\lambda) + \cos(2\pi d/\lambda + \phi)]/2$$

$$= I_0 + V\cos(\phi/2)\cos(2\pi d/\lambda + \phi/2)$$

- Even if the optics do not introduce any net polarization, they can reduced

Polarization Effects

- These Effects are LARGE
  - It is Easy t o get s-p shifts of many Radians
  - Silver and Gold are Best
  - Dielectrics are Amazingly Bad
- Fortunately, the Visibility Amplitude Depends only on the Difference between the two Arms being Interfered
- Matching all Reflections in the Interferometer Arms Should Prevent any Problems.

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- You Can often get the Correct Answer without Thinking Too Hard.
- But If You Think a Little Harder, You will often get the Wrong Answer.
- Once You have the Wrong Answer, it's a lot of Work to get back to the Right Answer.

Cross Terms

- When both retardation and beam rotation are present, there is a cross term proportional to the Beam rotation times the *Total* s-p phase shift.
- This term always reduces the visibility amplitude of polarized light.

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Cross Terms

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- This term always reduces the visibility amplitude for polarized light.
- But unpolarized light sees no net reduction due to this term.
- BEWARE, light cannot always be simply treated as a vector.

Optimal Design of Interferometric Arrays

- Tremendous Amount of work at Radio Wavelengths
  - Random Arrays
  - Cornwell Circles
  - Reuleaux Triangles
  - Non-redundant Y
  -

Optimal Design of Interferometric Arrays

- Tremendous Amount of work at Radio Wavelengths
  - Random Arrays
  - Cornwell Circles
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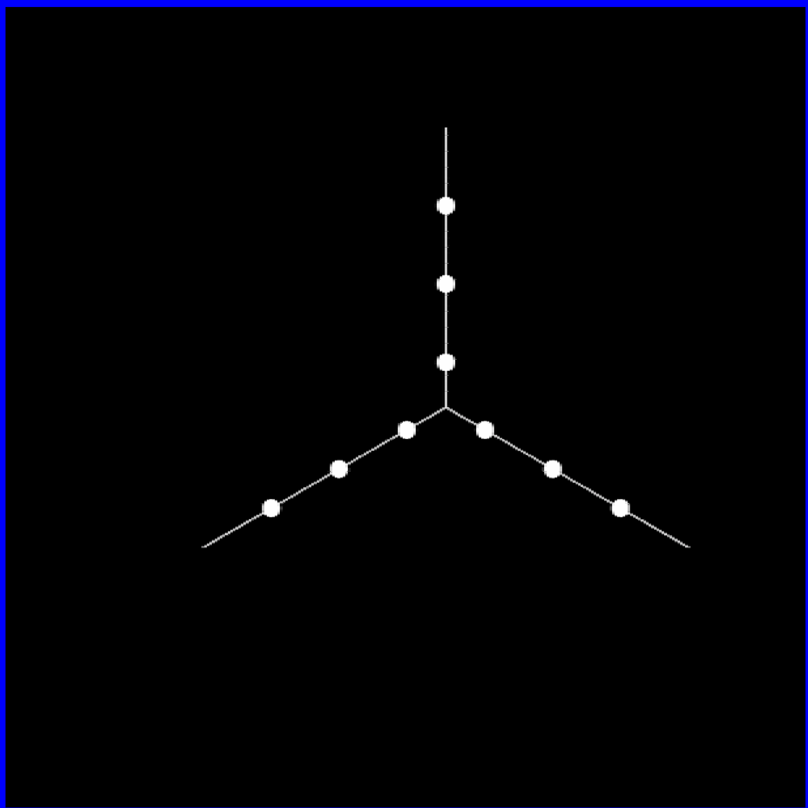
  - Non-redundant Y
- Probably none of it is applicable at Visible Wavelengths
- Optimal Usually means most uniform (u,v) Coverage

Optical Interferometric Array Layout for Imaging

- Imaging Requires Redundant Arrays
  - For Baseline Bootstrapping
- Optical Interferometry Requires Vacuum Feed System
  - For a wide Spectral Bandpass
- A Partially Redundant Y seems to be the Only Reasonable Choice

A Partially Redundant Y



- Not as Redundant as it looks
- 2 per arm
  - 0 of 15 redundant
- 3 per arm
  - 3 of 36 redundant
- 4 per arm
  - 9 of 66 redundant

IIII. Beam Combination and Fringe Detection

- After Combining the light, we Need to Know
  - If a Fringe is Present
  - It's Amplitude and Phase
- The Type of Detection technique Depends on the Type of Beam Combination Technique
  - Fringe Detection Schemes
  - Beam Combination Strategies

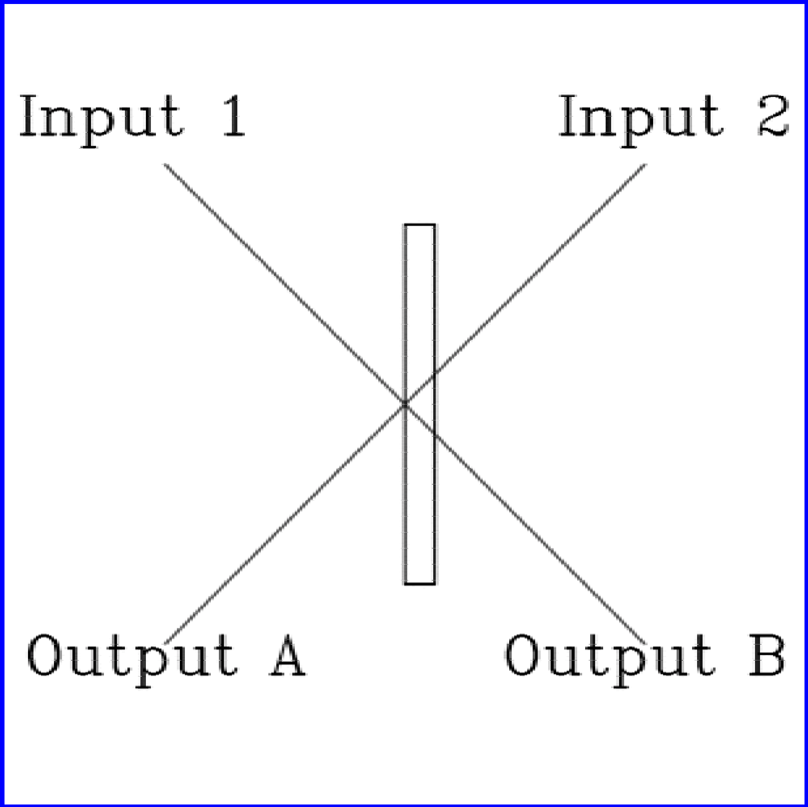
Type of Beam Combiners

- Pupil Plane
  - Each Point in Aperture 1 is Combined with a Point in Aperture 2 Separated by exactly the same Baseline vector B
  - V measured at a Delta Function in the u,v Plane

Type of Beam Combiners

- Pupil Plane
  - Each Point in Aperture 1 is Combined with a Point in Aperture 2 Separated by exactly the same Baseline vector B
  - V measured at a Delta Function in the u,v Plane
- Image Plane and Spatially filtered
  - Each Point in Aperture 1 is Combined with ALL points in Aperture 2
  - V is an average over Baselines B-A to B+A

Fringe Detection
Passive



$$\left\langle \frac{(A-B)^2}{(A+B)^2} \right\rangle$$

- Depend on atmosphere to move fringe
- Minimum of Detectors
- Not for multi Baseline
  – No Phase Information

Fringe Detection: Time Modulation

- Improve on Passive detection
- Modulate Path length Rapidly Relative to Atmosphere
- Detect Photons Synchronously with Modulation

Time Modulation – II

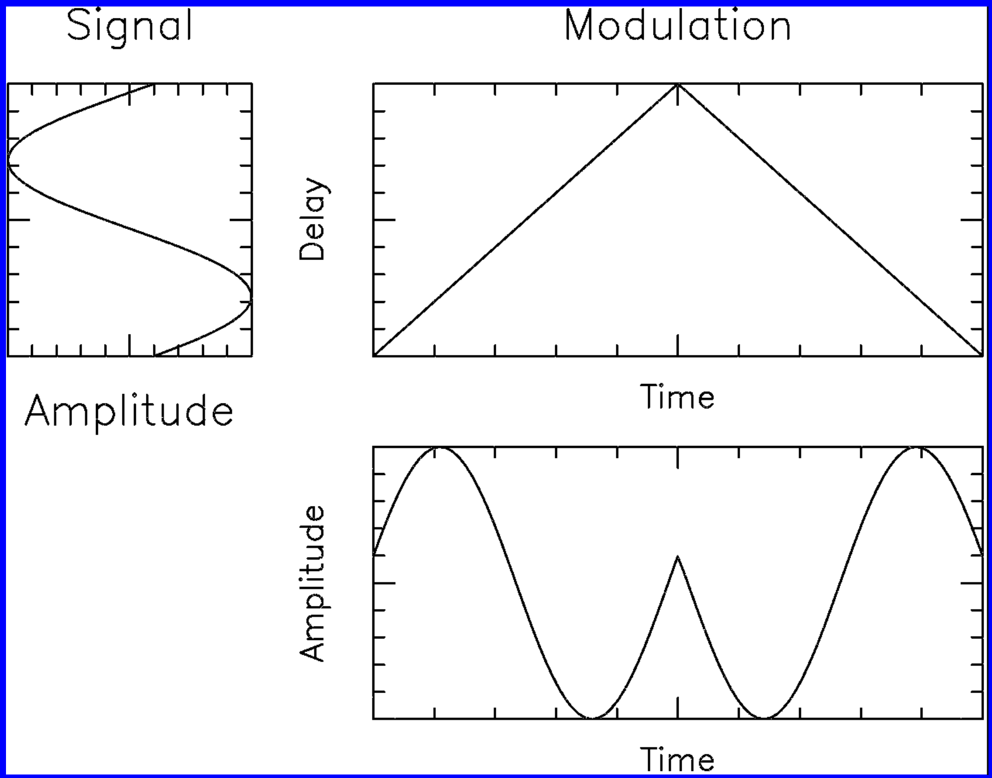
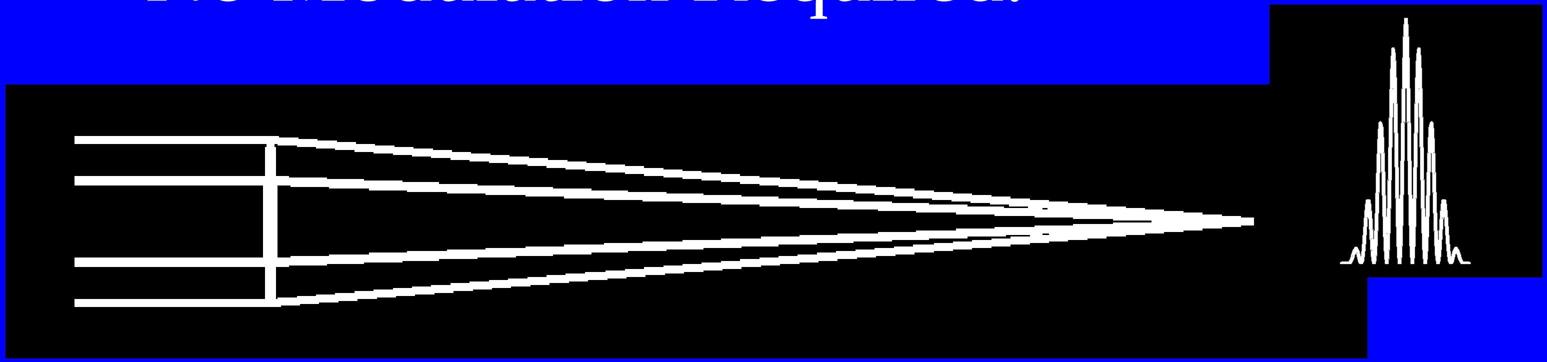
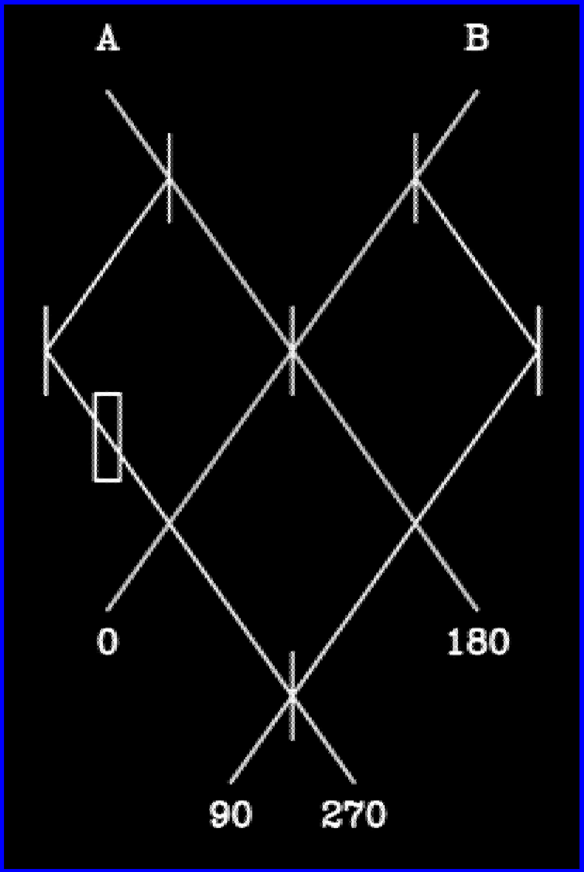


Image Plane: Spatial Modulation

- All Aperture Masking, I2T, GI2T
- Stuff beams through a single lens
- Diffraction pattern of a lens gives fringes
- No Modulation Required.



Quadrature Detection



- A Non-modulating combiner can also be built in the Pupil Plane
- 180 degree shift added between outputs of Beam Splitter
- Achromatic 90 degree shift added with air and glass paths.

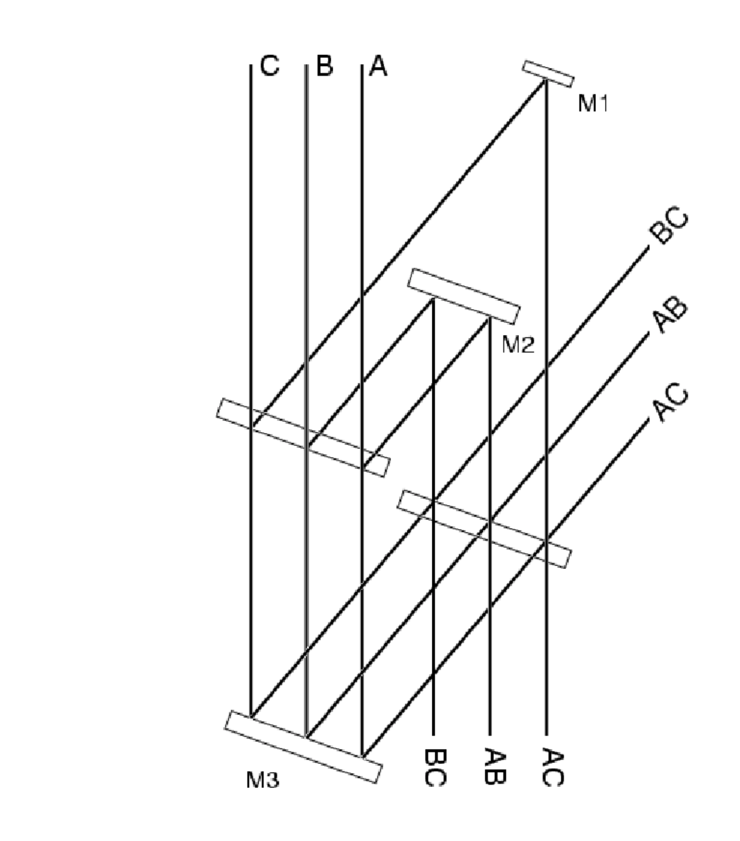
How to deal with Multiple Baselines

- What is the Best way to Combine Light from Multiple Telescopes?
  - Measure at least Three Baselines (One Triangle) at a Time for Closure Phases.
  - Pair-wise Combination (C_2)
    - One Detector for each baseline
  - All-on-one (C_N)
    - Each Detector Sees Light from all telescopes
  - Somewhere in Between
  - Somewhere else
    - Separate Fringe tracking and Science tasks

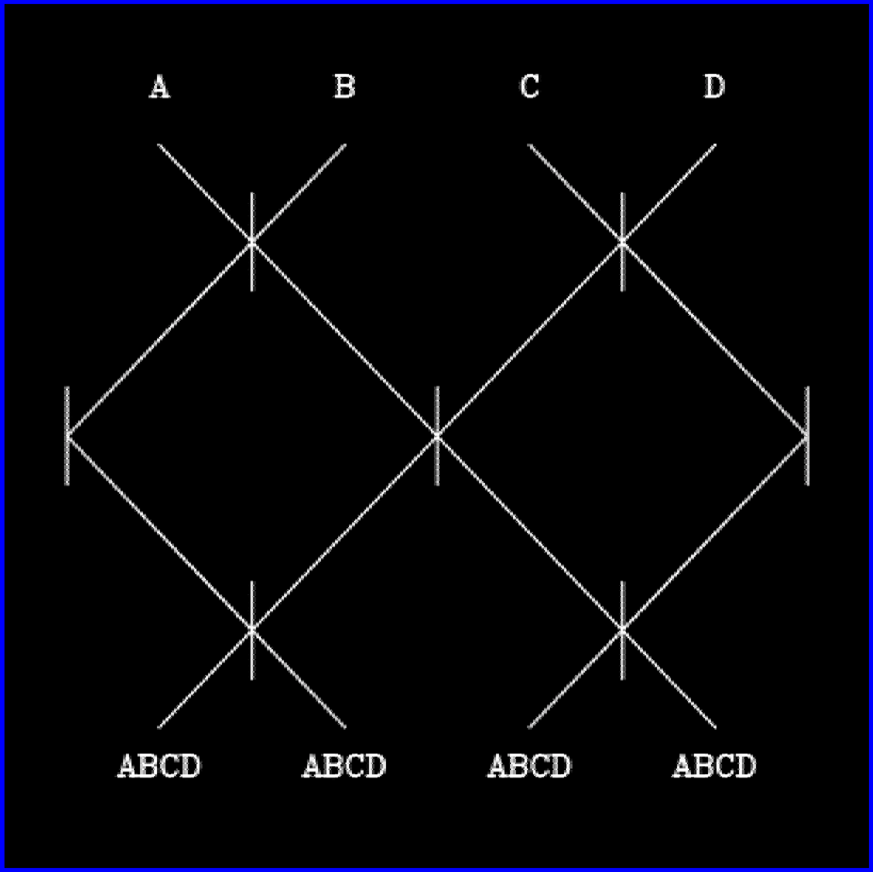
Signal to Noise

- SNR proportional to IV^2
- For N telescopes
- Pair-wise
  - I → N/[N(N-1)/2] V → V
  - SNR → 2/(N-1) IV^2
- All-on-One
  - I → N V → 2V/N
  - SNR → (2/N) IV^2
- All-on-One is better, but not by Much

Pair-wise Combination



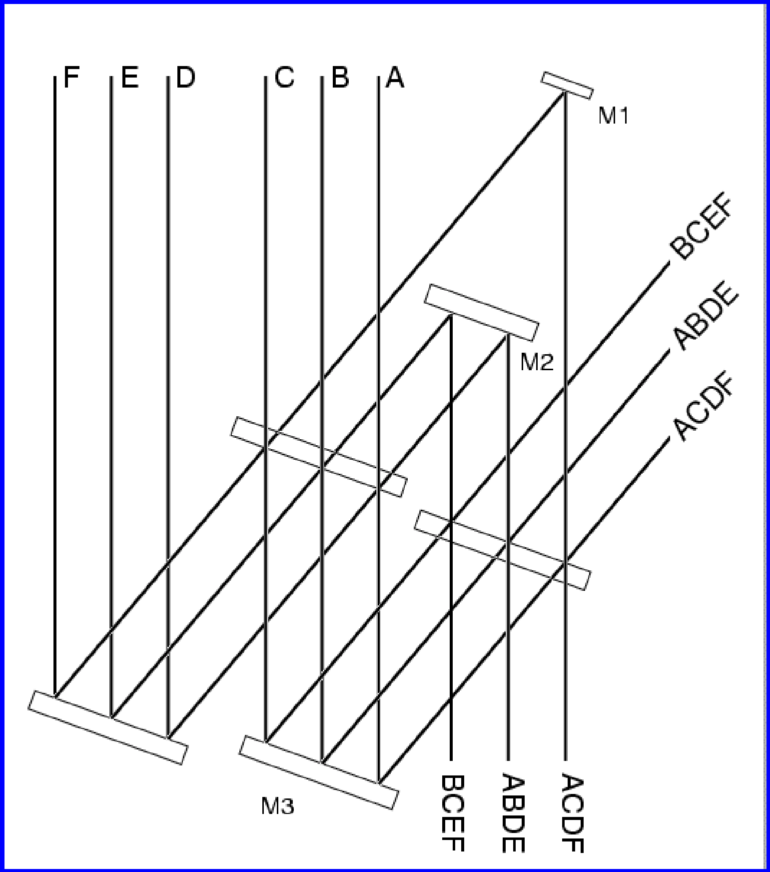
All-on-One-Combiner



Comparison

- All on One
  - Detectors grow as N
  - Modulation Amplitude grows as N squared
  - Better Signal to Noise
  - No Baseline-based phase errors
- Pair-wise
  - Detectors grow as N squared
  - Modulation Amplitude grows as N
  - Always has baseline-based errors
- Neither choice is any good

NPOI Beam Combiner



- Number of Detectors
  - Pair-wise 15
  - All-on-One 4
  - NPOI 6
- Modulation Amplitude
  - Pair-wise 6
  - All-on-One 17
  - NPOI 8

The Best Approach

- Separate Fringe Tracking from Science
- For Fringe Tracking
  - Measure minimum number of Baselines
  - A-B, B-C, C-D, D-E …
- For Science Tracking
  - Combine beams in groups of 3 or 4
  - Switch between combinations
- Detectors grow linearly with number of apertures
- Modulation Amplitudes independent of apertures