Ground vs. Space Interferometry

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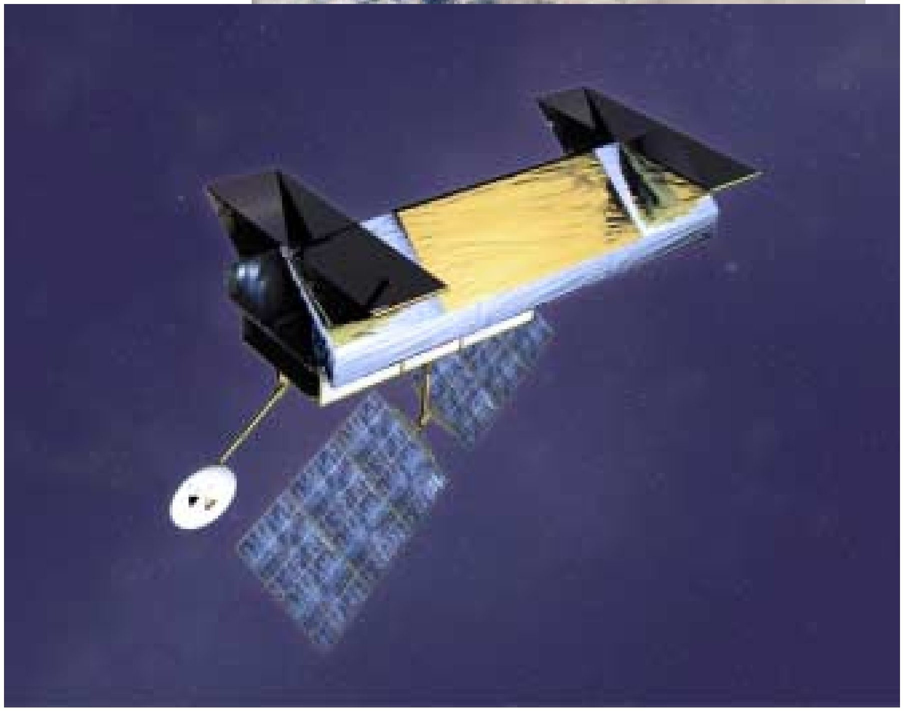
Overview

- Some obvious advantages to both ground and space
- How the atmosphere limits ground-based measurements
- Astrometry: ground limitations
- Astrometry in space
- Imaging: SNR for point source detection
- Dilute aperture imaging
- Nulling
- Some space interferometer examples

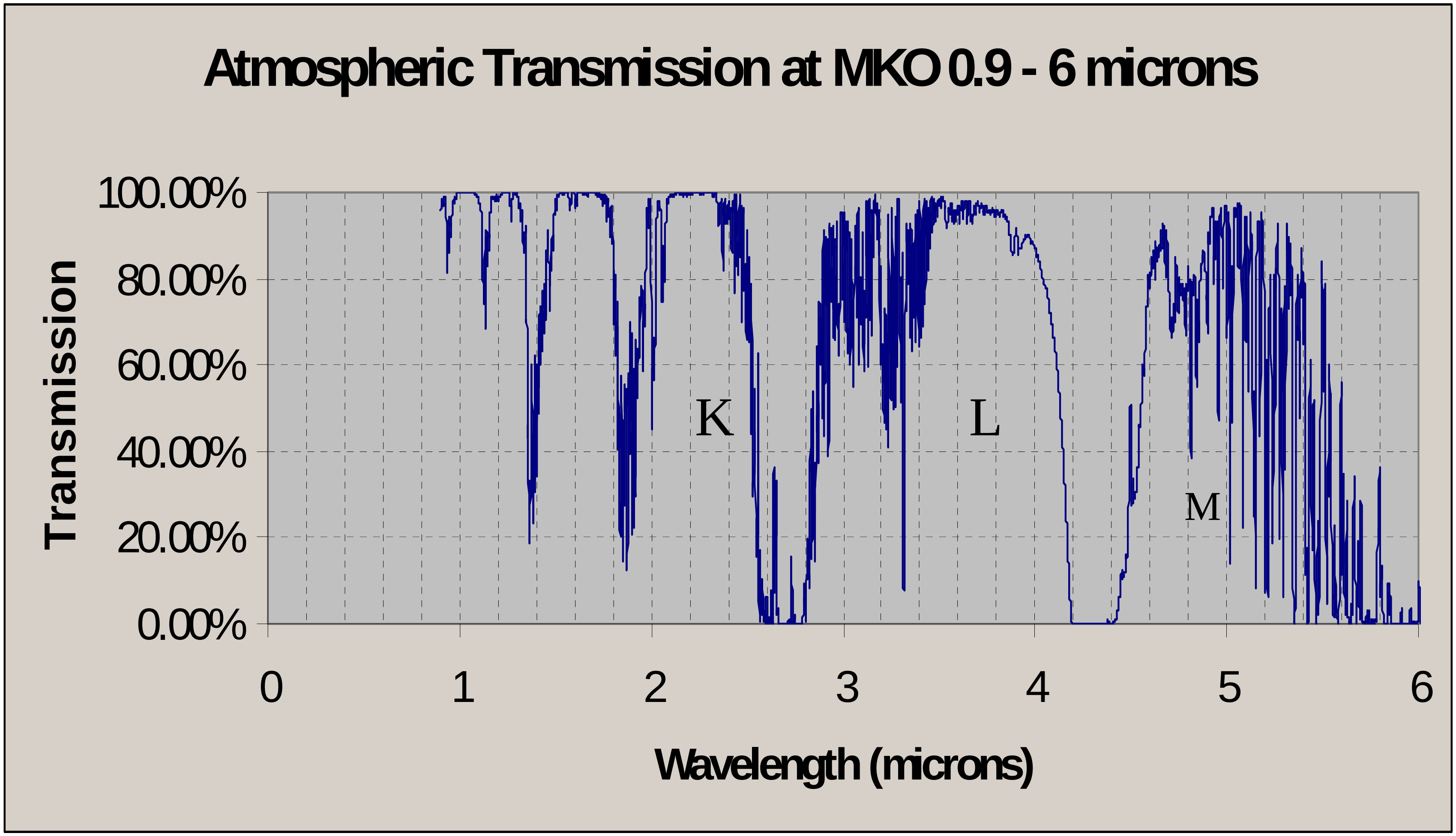
Space Advantages

- Atmospheric transmission:
  - X-ray
  - UV
  - NIR bands between 1-10 microns
  - Sub-millimeter
- Lack of Turbulence
- Easily reconfigurable u-v coverage (spinning the spacecraft)
- Easy to reduce background in thermal infrared

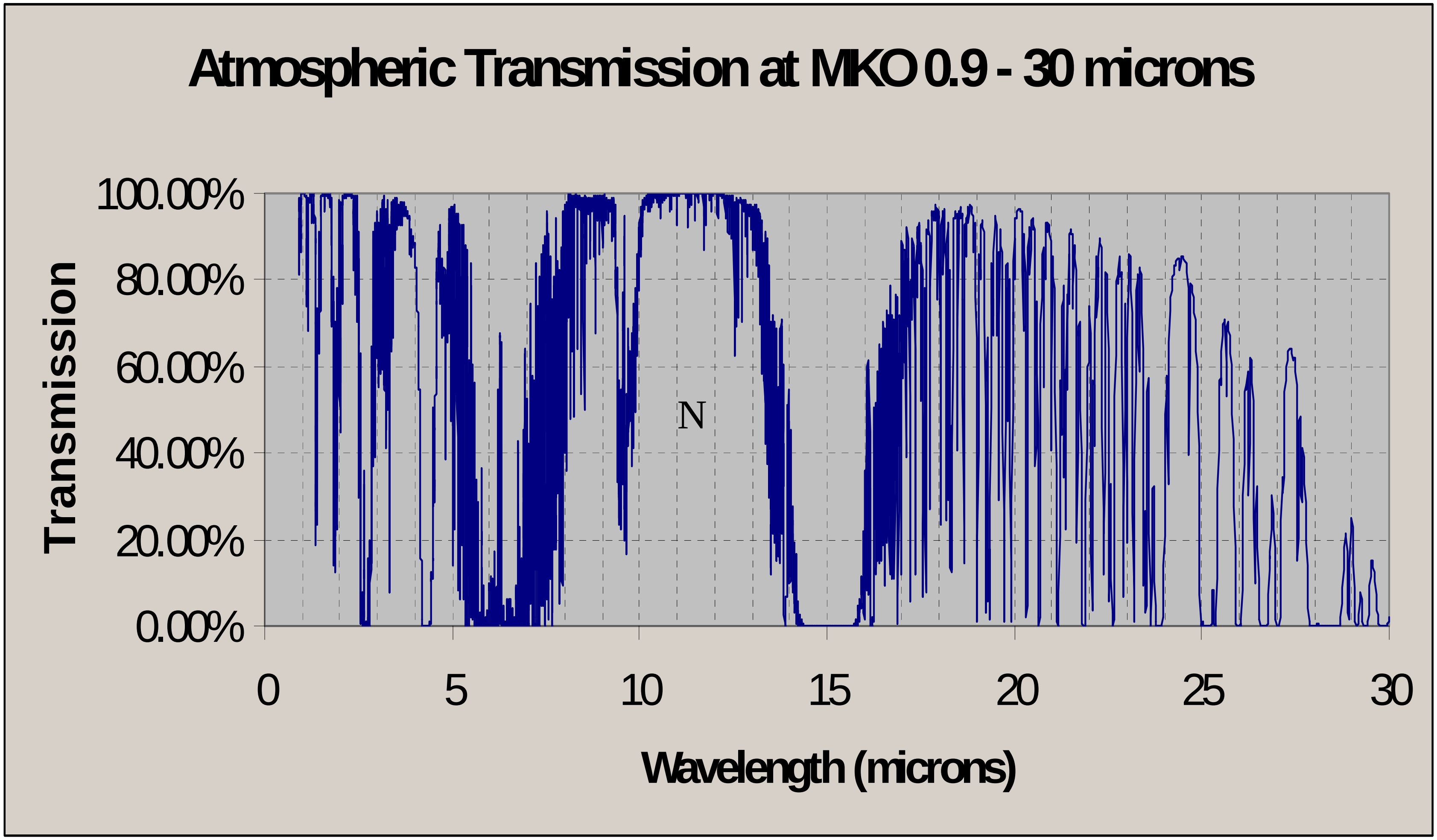


Ground Advantages

- Longer baselines (up to a point)
- Larger apertures
- Upgrades, lifetime
- Cost



These data, produced using the program IRTRANS4, were obtained from the UKIRT worldwide web pages.



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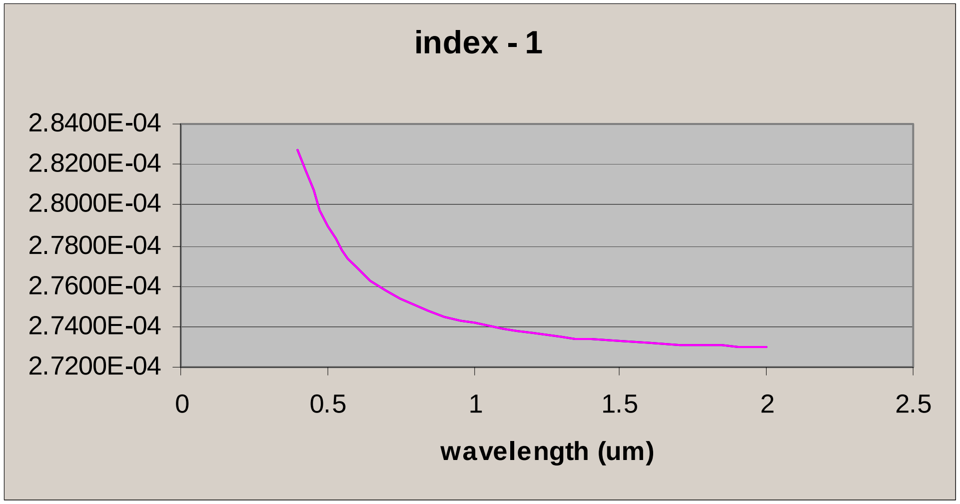
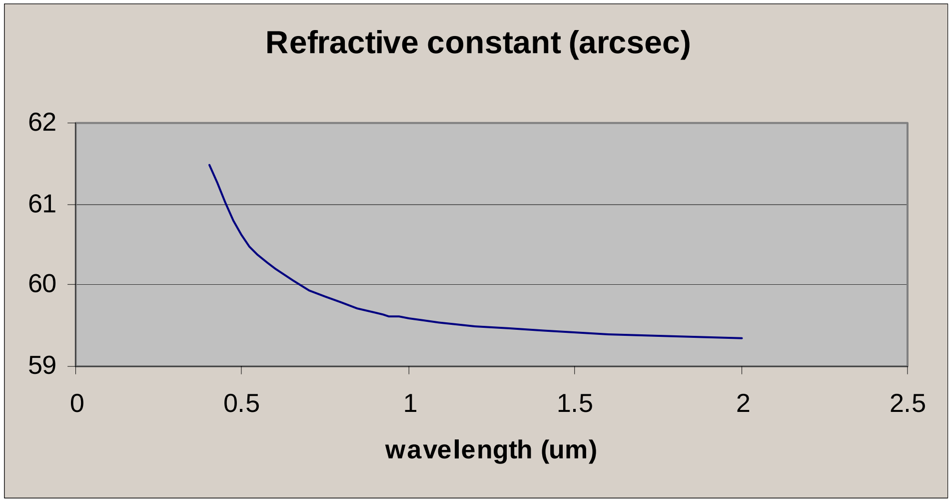
Dispersion

- "Wedges" in atmosphere lead to ~ 20 micron delays in Mark III measurement. 20 um = arcseconds!
- Measured phase is different in red and blue light by ~ 250 nm over visible spectrum at tan(z)=1.
  - Equivalent to 5 milli-arcsec
- Colavita 2-color technique: remove the atmospheric wedge contribution based on the difference in red and blue phases.
- Improvement of ~ 5 compared to single-color results.
- Limited by water-vapor turbulence

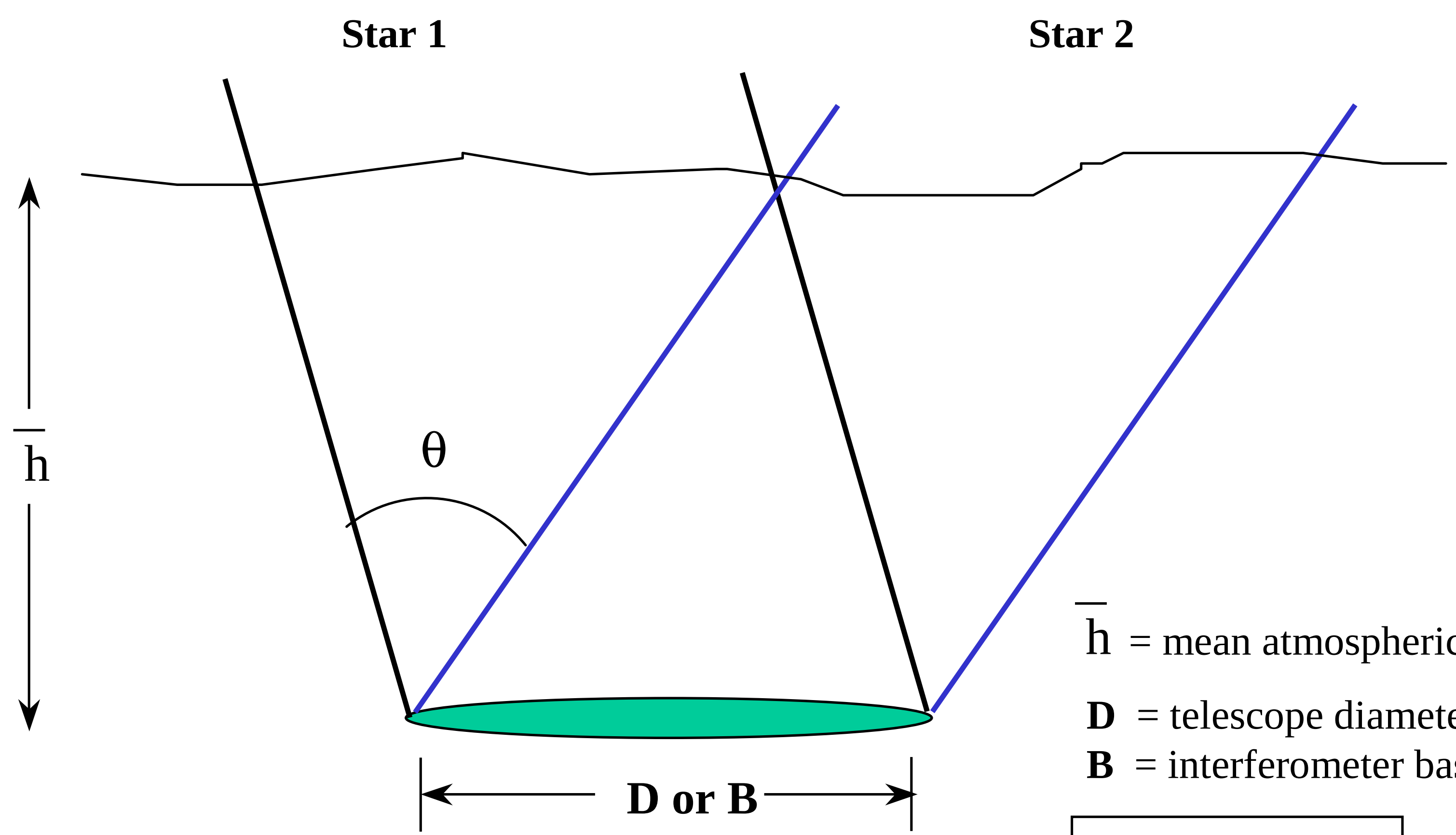




Turbulence

- Wavefronts blow across the instrument: hurts astrometry
  - Apertures: this is pretty fast, t_0 = 10-20 ms for a 10 cm aperture. Averages as $t_0^{-1/2}$
  - Baseline: large-scale wedges may be huge. The spectrum is not white. Averages as $t^{-1/6}$ (This is a big problem for astrometry.)
- Coherence scale: limits Adaptive Optics application
  - 1 arcsecond seeing, r0 = 10 cm in the visible
  - scales as lambda$^{6/5}$ (as does t_0)
  - "outer scale" may be hundreds of m
  - Isoplanaticity: region around the target where wavefront r.m.s. difference is < 1 radian
    - This region is a few arcseconds across
    - It limits the useful field for an adaptive optics system.

Isokinetic Angle



$\bar{h}$ = mean atmospheric height

D = telescope diameter

B = interferometer baseline

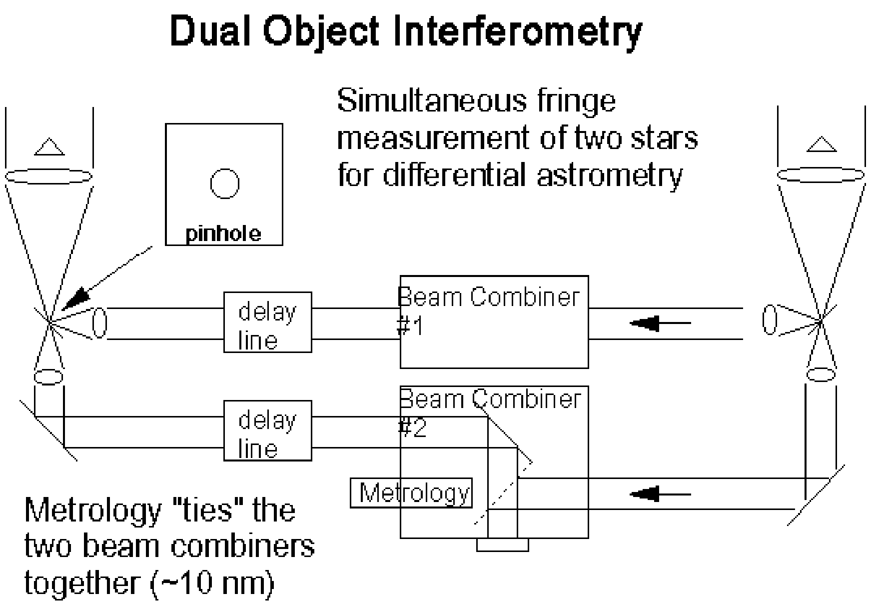
$$\theta = \frac{\mathbf{B}}{\bar{h}}$$

The isokinetic angle defines the average height where the beams from two different stars no longer overlap.

'Dome seeing' does induce relative image motions within a field.

Narrow Angle (Differential) Astrometry

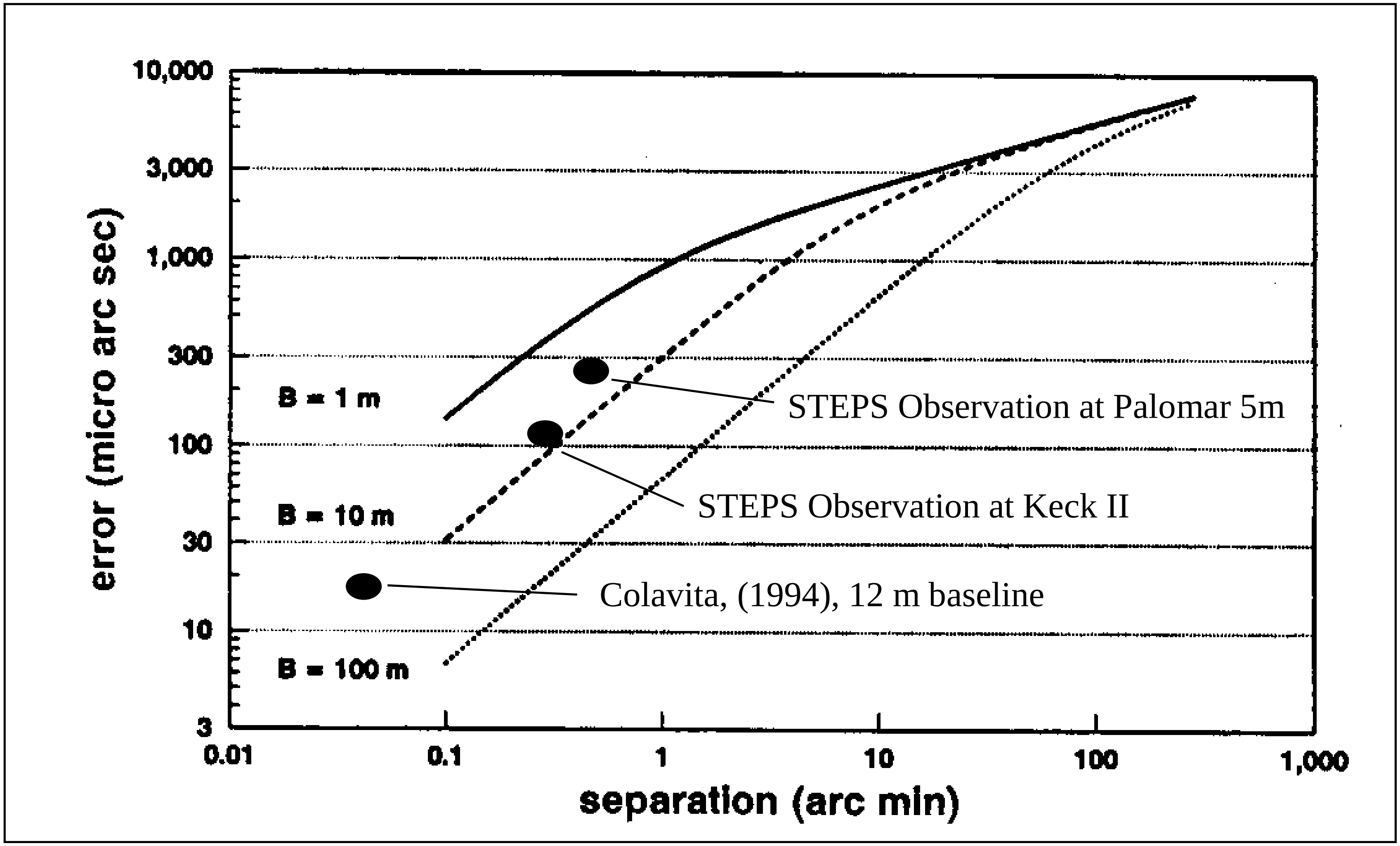
- Very narrow angle
  - Stars separation << isokinetic angle.
    - For 5 m telescope, 10,000 m turbulence, angle is 100 arcsec
  - accuracy proportional to star separation and B^(-2/3)
- Not-so-narrow
  - Stars separated by >> isokinetic angle
  - accuracy independent of baseline, proportional to star separation ^ 1/3



Picture downloaded from JPL PTI website

Narrow Angle Astrometric Precision

For a 1-hr long observation in 0.5 arcsec seeing



Shao and Colavita, 1992 A&A 262, 353

Ultimate Narrow Angle Limit on the Ground

- The Keck interferometer may be able to achieve 10 micro-arcsecond relative accuracy between stars.
  - Fractional sky coverage is small, few percent due to sparsity of bright nearby stars
  - This requires 5 nm metrology over 100 m baseline, relative to starlight path.
  - Note: Sun at 10 parsecs has 1 mas p-p motion due to Jupiter.
    - 10 uas sensitivity could detect a 0.01 Jupiter mass companion.
- The best single-aperture astrometry is ~ 200 micro-arcseconds for sources separated by > few arcsec.

Wide Angle Astrometry

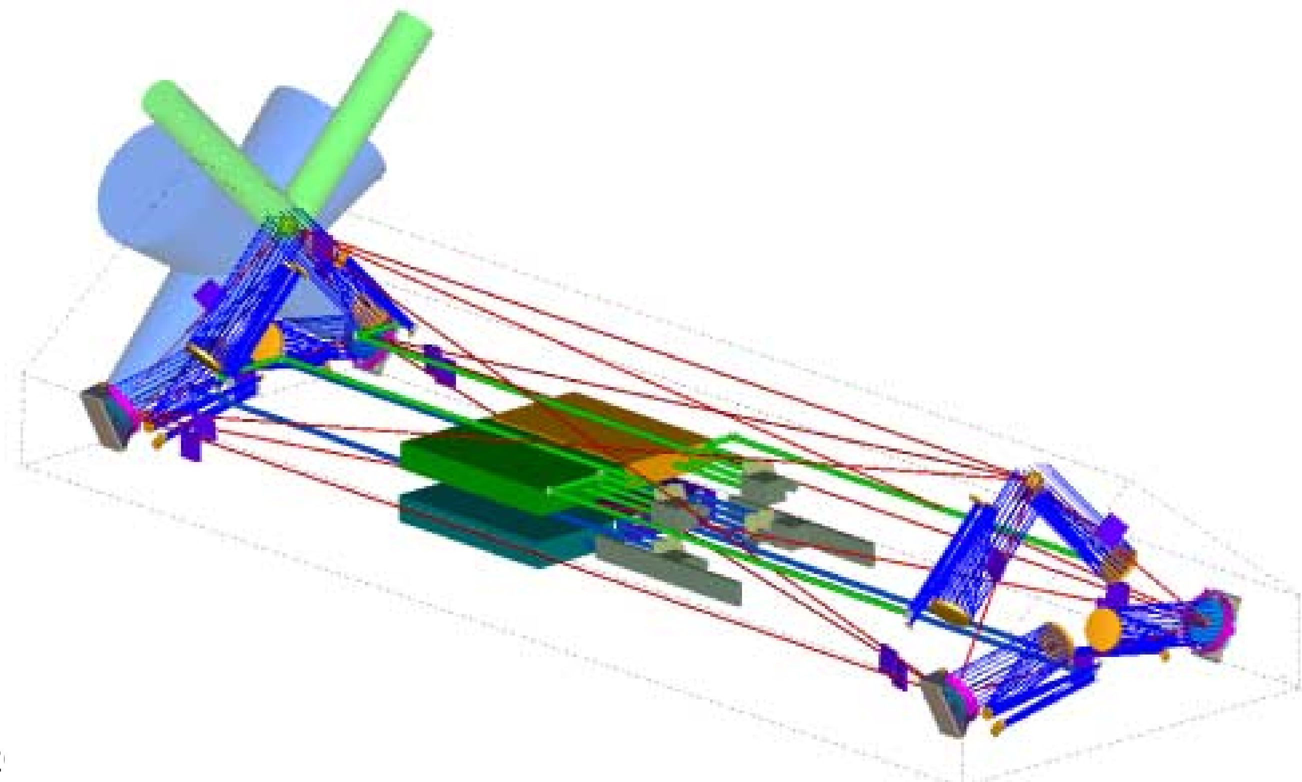
- Ground based: limited by slow drifts in the non-white atmosphere
  - averages as t^-1/6
  - The Mark III did ~ 5 milli-arcsec on stars with V<7
  - NPOI will go fainter but will have similar performance
- Baseline is stable: few microns/night at the Mark III.
  - Baseline solution is determined by fitting curves to stars using a priori positions.
- In space, the baseline moves
  - “Guide” interferometers are used to measure baseline motion
  - Various schemes link together patches or rings on the sky.

The Interferometer Baseline in Space

- Spacecraft drift because they can
  - Solar pressure, magnetic fields, gravity gradients
- Star trackers measure the angular drift
  - Typically good to better than 1 arcsec
  - Control is typically +/- 1 arcsec
  - Time scale is 10 – 100 sec.
- Hard to do better than this on an interferometer
  - Long thin structures are floppy
  - The end-points thermally deflect by micro-radians with respect to the star-tracker position
  - Joints in deployed structures are weak points.

Baseline phase referencing

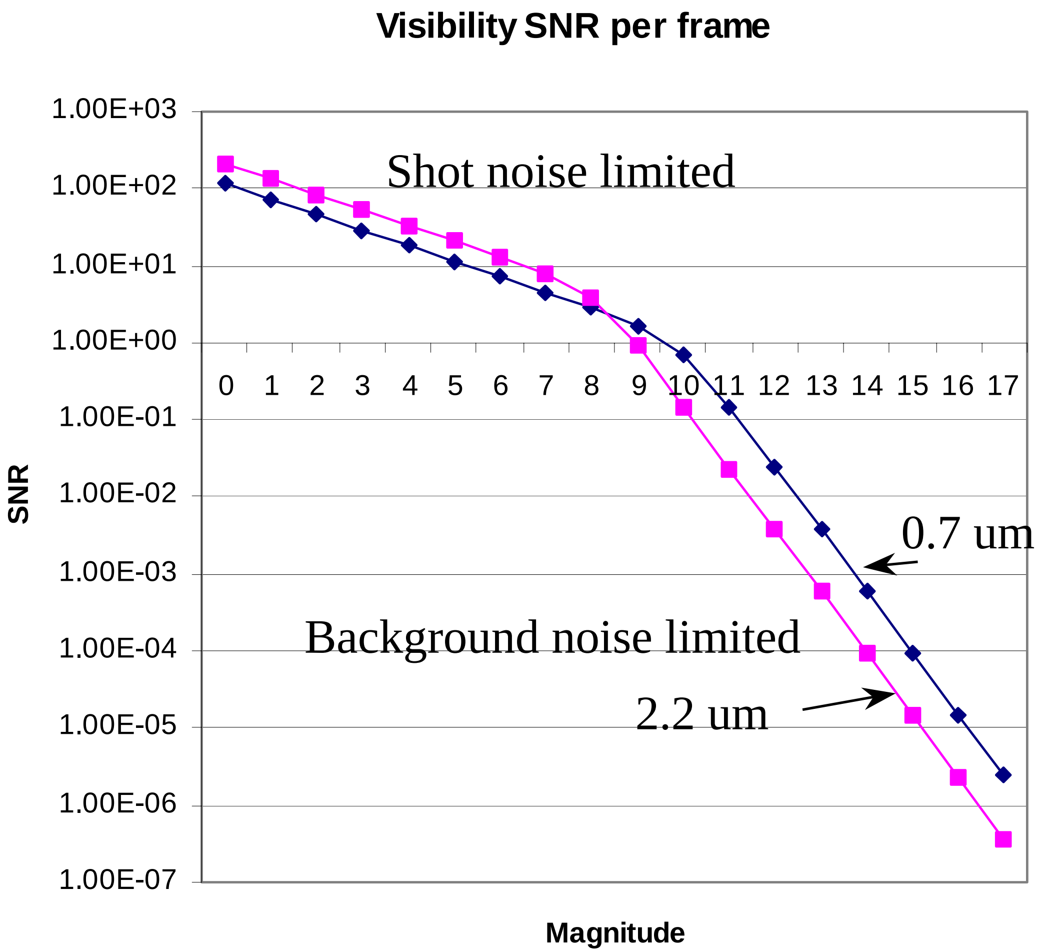
- Inertial motion of baseline must be controlled or known to 0.1*lambda/B radians
  - 1 mas for a 10 m baseline in the visible
- That's 10x better than HST
- Requires the development of dedicated star trackers, or
- On-board phase-referencing interferometers



So what if the Baseline drifts?

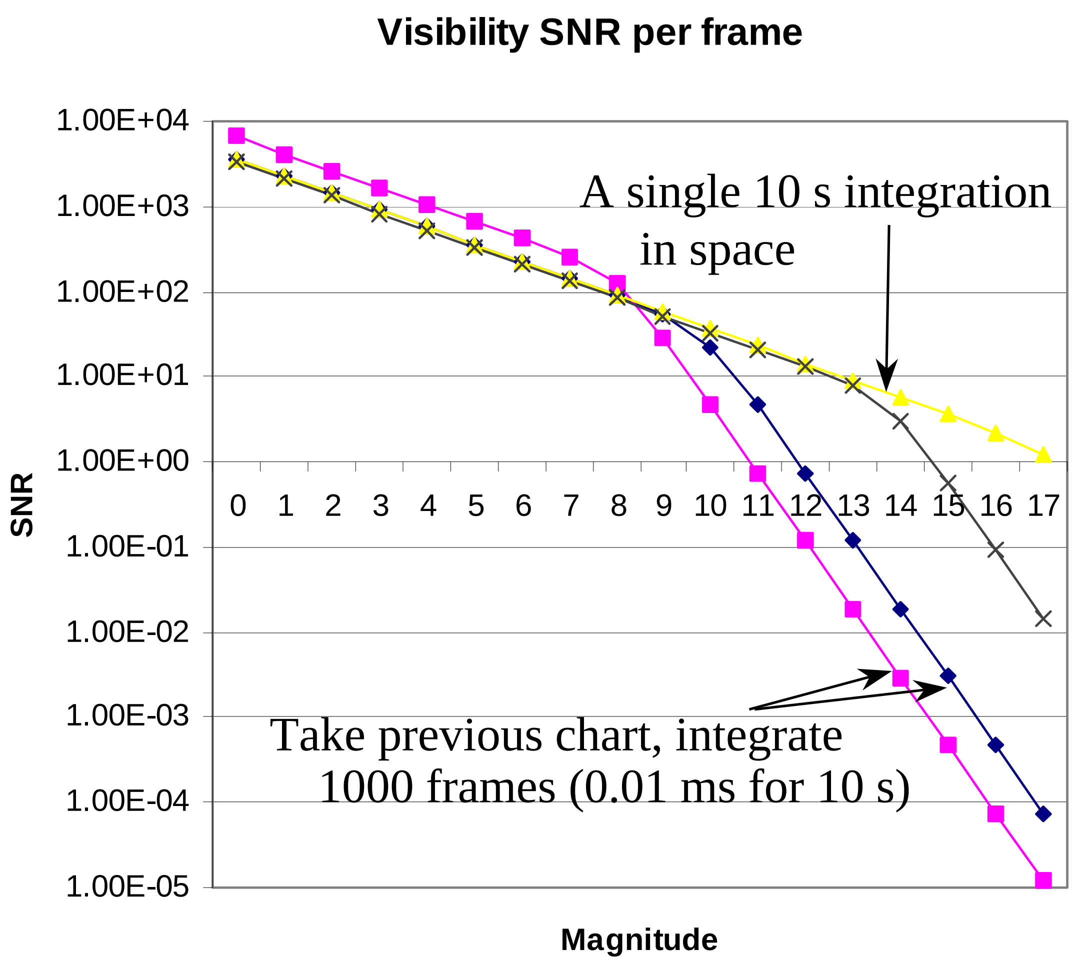
- Resolution is lambda/B = 0.01 arcsec for a 10 m baseline at 0.5 microns.
  - Drift of 1 arcsec smears 100 fringes!
  - This is comparable to the atmosphere
    - But it's measurable and somewhat predictable
    - Delay lines can be moved to compensate the motion
      - This is a new can of worms: dynamical changes in the S/C
- To the extent that the drift is not predictable (say 1% of 100 fringe motion), the spacecraft case is similar to ground-based
  - t_0 = 0.1 sec
  - r_0 is large, similar to adaptive optics case
- *Thus to have an advantage over the ground, a space interferometer MUST have a phase reference.*

SNR per frame in a ground-based interferometer



Assumptions:
seeing = 1 arcsec (r0 = 10 cm)
Aperture size = 10 cm (0.7 um)
40 cm (2.4 um)
Throughput = 0.1
Bandwidth = 10%
Visibility = 1.0
Integration time = 10 ms (0.7 um)
40 ms (2.2 um)
0.7 microns: 3 e- read noise/frame
2.2 microns: 25 e- read noise/frame

How does going to space help?

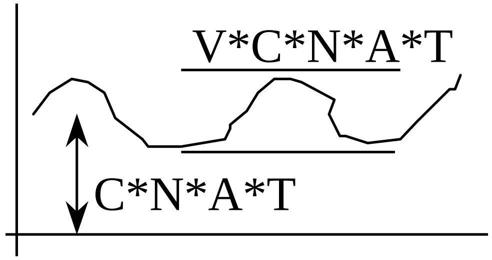


New Curve Assumptions:
seeing = perfect
Aperture size = 10 cm (0.7 um)
40 cm (2.4 um)
Throughput = 0.1
Bandwidth = 10%
Visibility = 1.0
Integration time = 10 s (0.7 um)
40 s (2.2 um)
0.7 microns: 3 e- read noise/frame
2.2 microns: 25 e- read noise/frame

Going to space improves the low SNR region by allowing coherent integration. It does not improve the high SNR region unless aperture size is increased.

SNR for a complex object

Shot-noise limit



Object complexity = C = number of resolved cells
Surface brightness = N = photons/cell/sec
Collecting area = A = effective area/u-v point
Integration time = T
Signal from object = S = C*N*A*T

Fringe visibility = V ~ 1/sqrt(C)

This can be thought of in terms of C vectors having random phases adding together in the focal plane.

Signal to Noise ratio per UV point is

$$SNR = \frac{V*S}{sqrt(S)} = V*sqrt(S) = sqrt(NAT)$$

INTEGRATION TIME IS INDEPENDENT OF OBJECT COMPLEXITY!

Example: Object 16 mag/arcsec^2
0.01 x 0.01 arcsec (one resolution element)

SNR = 10 per u-v point requires 8000 s per u-v point

(assumes nominal throughput of 29%, static V = 0.6, bandwidth = 500 A, central wavelength = 550 nm, and two 1 m apertures.)

Increasing the Number of Baselines

- More baselines increases collecting area
  - M apertures provides M times more light
  - 0.5*M^2 more baselines
- The light available (A) per baseline goes down as 1/M
- The integration time per u-v point increases as M compared to the single-baseline case.
- Example 1:
  - 16 mag/arcsec^2, 100 resolved points over 0.1 x 0.1 arcsec (10 m baseline)
  - Integrated flux is V=21
  - 15 apertures (107 baselines), each 1 m in diameter
  - Integration time (SNR=10) is 8000 * 15 = 120000 s (33 hrs) 10 x 10 map
- Example 2:
  - 16 mag/arcsec^2, 400 resolved points over 0.2 x 0.2 arcsec
  - Integrated flux is V=19.5
  - 30 apertures (435 baselines), each 1 m in diameter
  - Integration time is 8000 * 30 = 240000 s (67 hrs) 20 x 20 map
- Example 3:
  - same source as ex. 2, but two apertures move to 400 positions
  - Integration time is 8000 * 400 sec = a really really long time

Phase Referencing Summary

- SNR for extended, natural objects is not sufficient to support phase referencing.
  - Short baselines help (bootstrapping from short to long baselines is an old idea).
  - But for space to have an advantage over the ground, faint objects are observed.
- Bright reference stars are needed, V < 7-8.
- Separate interferometers (as with SIM) observe the reference stars and are tied to the rest of the interferometer by laser metrology.
  - Note that SIM reference stars are bright for stabilization at 10 nm. Their brightness is NOT driven by high precision astrometry requirements.
- Excellent Dissertation topic: Design considerations for an imaging space-based interferometer.
  - Optimum number of apertures, phase referencing, pointing control, structural rigidity, expendables….

Planet Detection by Nulling Interferometry

- The sky background is magnitude -2.1 arcsec^{-2} in the N band (10 microns)
  - This really doesn't limit things unless the optics train is cooled. Let's assume it's cooled.
- At 10 microns, the diffraction limit of the Keck aperture is 0.2 arcsec.
  - It thus sees the sky as a background of magnitude 1.4.
- An earth-like planet is ~ 15 magnitudes fainter than its star at lambda=10 um.
- It will thus be ~ 15 stellar magnitudes below the thermal flux of the sky.
  - The problem is that the flux is "everywhere."

Planet detection in space

- In space, the prospect of seeing an earth-like planet is very challenging, to say the least.
- But a nulling interferometer can effectively suppress the central star light because that light is localized.
- It does not suppress the zodiacal light
  - But the problem is many orders of magnitude easier than from the ground.
- Ref: Gene Serabyn's presentations at the summer school.

Maximum Baseline Length

- NASA has deployed a 60 m boom with an 800 lb mass. (SRTM 3-D Synthetic Aperture Radar)
  - 0.1 Hz boom
  - 100 m is probably the maximum extension of this technology for interferometry
- Separated spacecraft are required for longer baselines

Picture downloaded from JPL SRTM web site.

DLI: a lens-like configuration

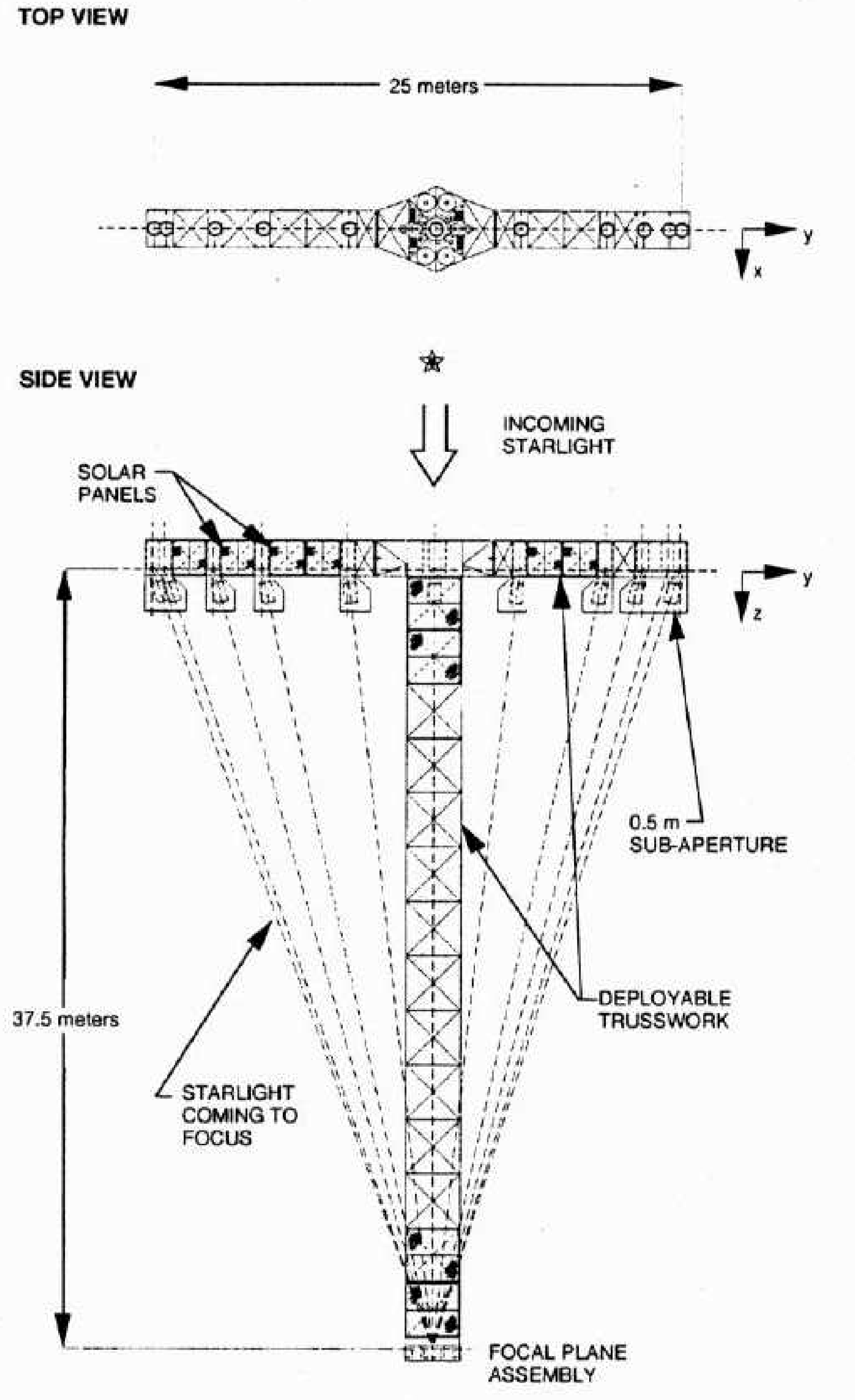


Figure 3. The Dilute Lens Imager

MUSIC:

Multiple Space-craft Interferometer Constellation

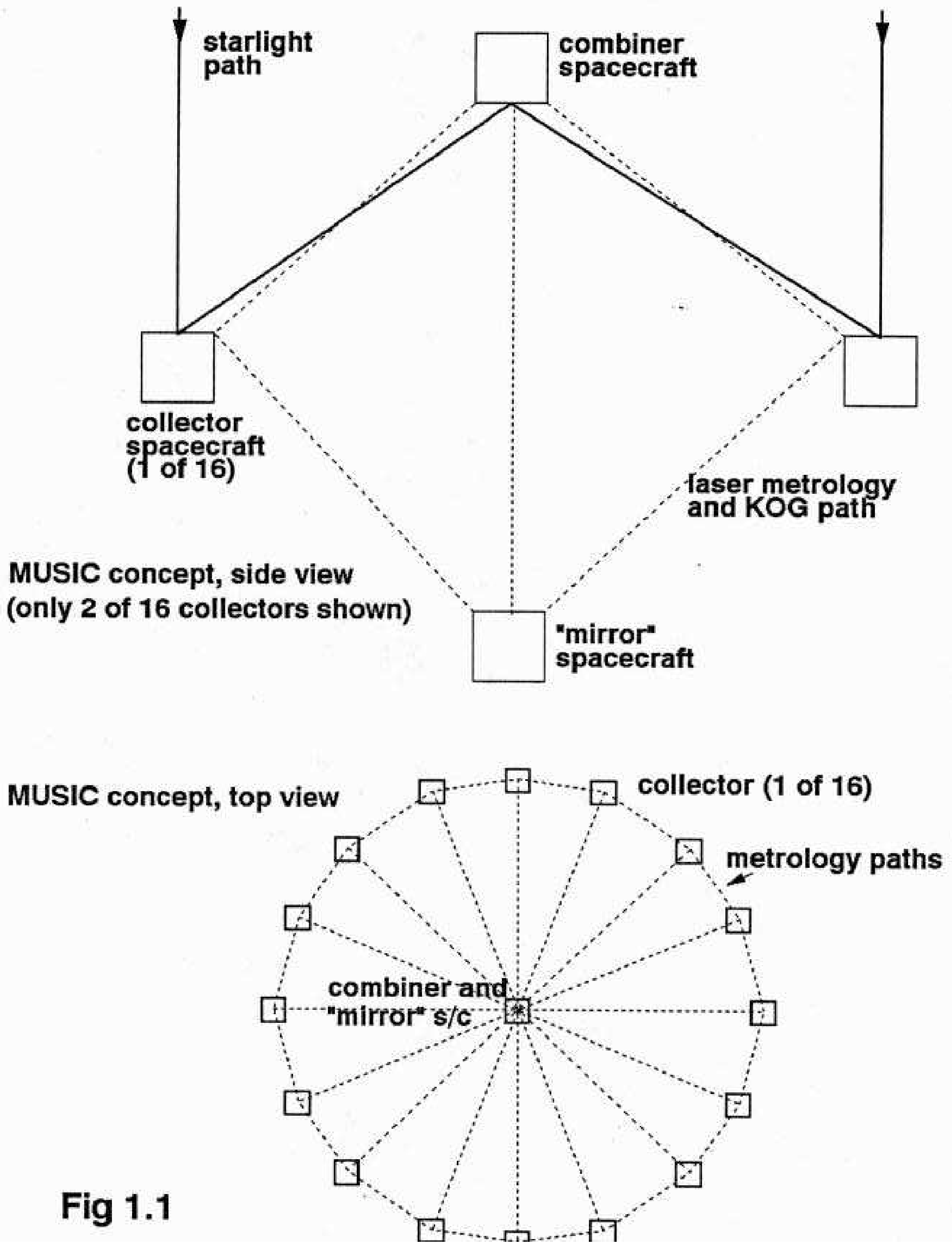
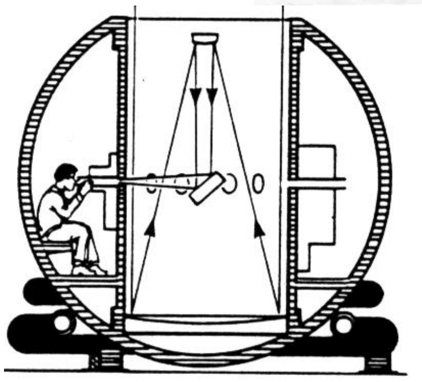
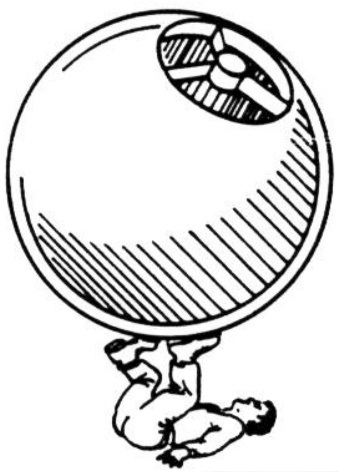


Fig 1.1

SONATA

OVLA





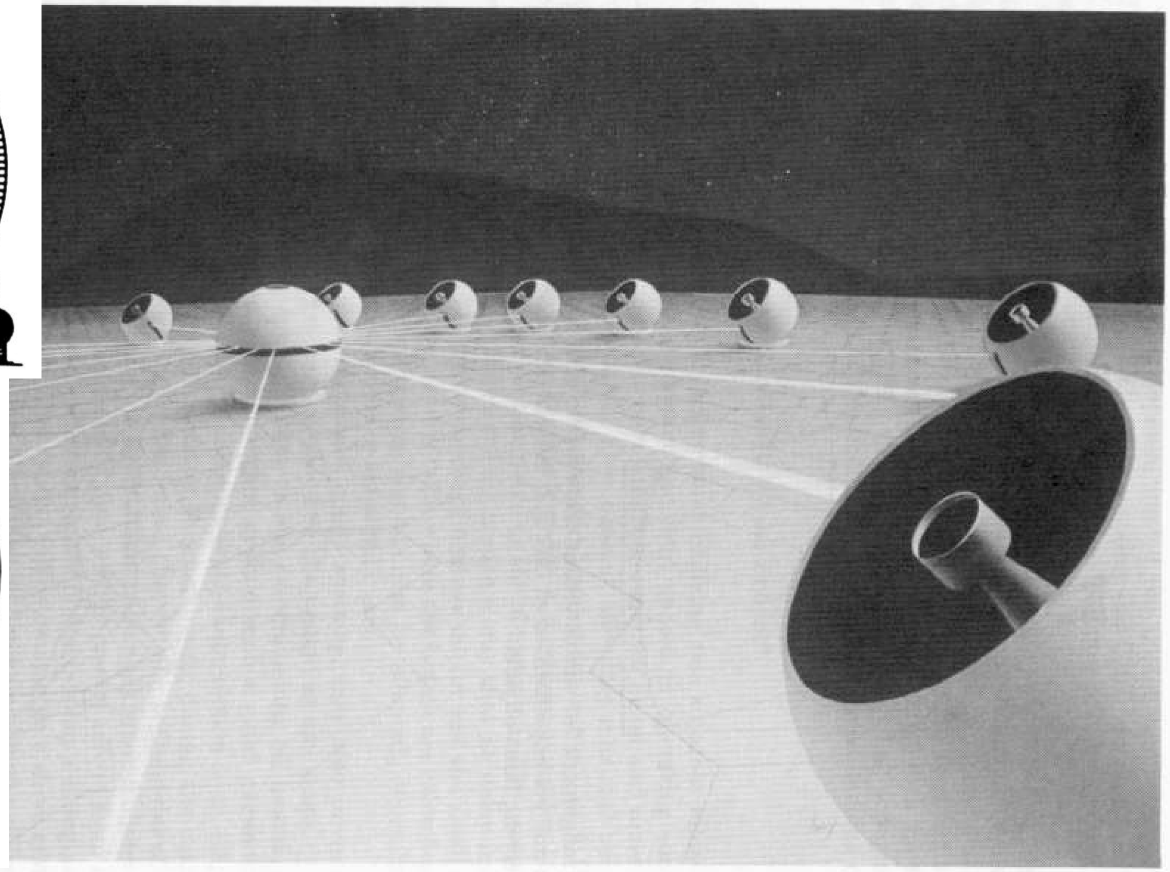
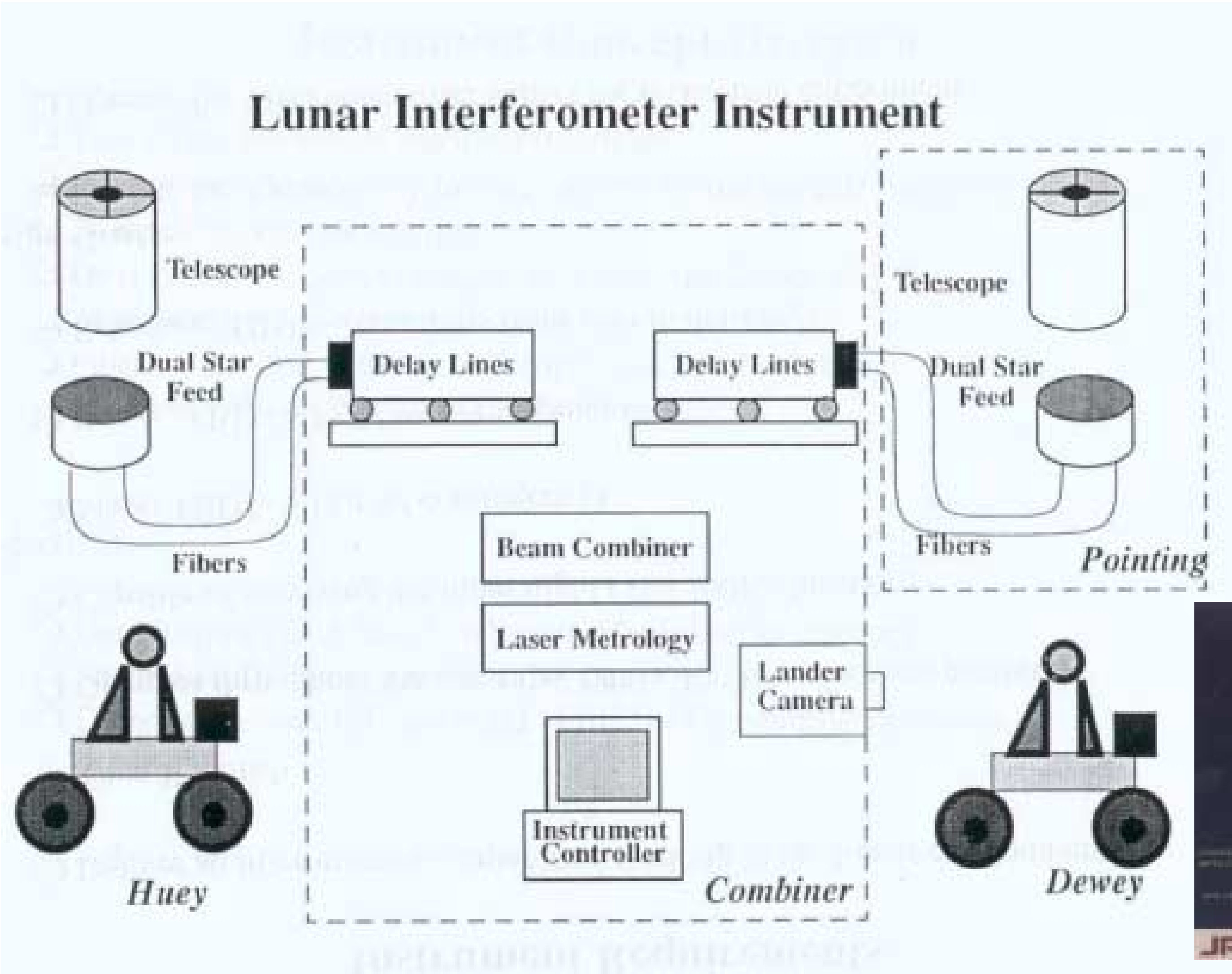
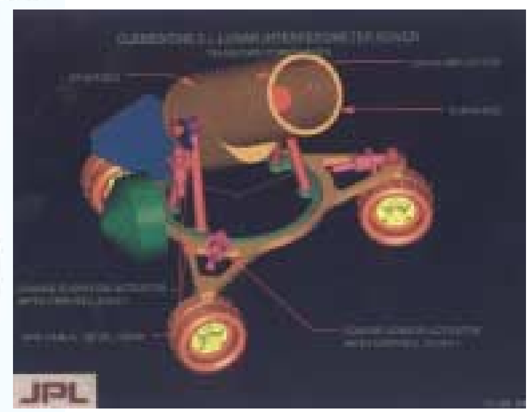


Figure 3: The Optical Very Large Array consists of many compact telescopes movable on a platform. The beams are recombined in a central station, using one of several interchangeable optical tables with different beam recombination systems. The telescopes move during the observation, so that delay lines be unnecessary. A sensitive system of laser beams keeps track of the telescope positions in three dimensions.

Clementine II Interferometer





Conclusions

- A space-borne interferometer need a phase-reference to monitor baseline motion
  - Without it, integration times will be short. The situation is similar to fringe smearing by turbulence on the ground.
- Wide angle astrometry:
  - Space is required to improve on Hipparcos. A few-micro-arcseconds may be achievable.
- Narrow angle astrometry
  - Potential on the ground to see large terrestrials.
  - No chance to detect Earths using interferometric techniques
- Imaging
  - Large (> 1 m class), multiple collecting apertures are required to image low-brightness complex objects.
- Nulling
  - Atmosphere severely limits effectiveness of nulling
  - Need to be above the atmosphere for terrestrial planet detection
- Let's do both!!