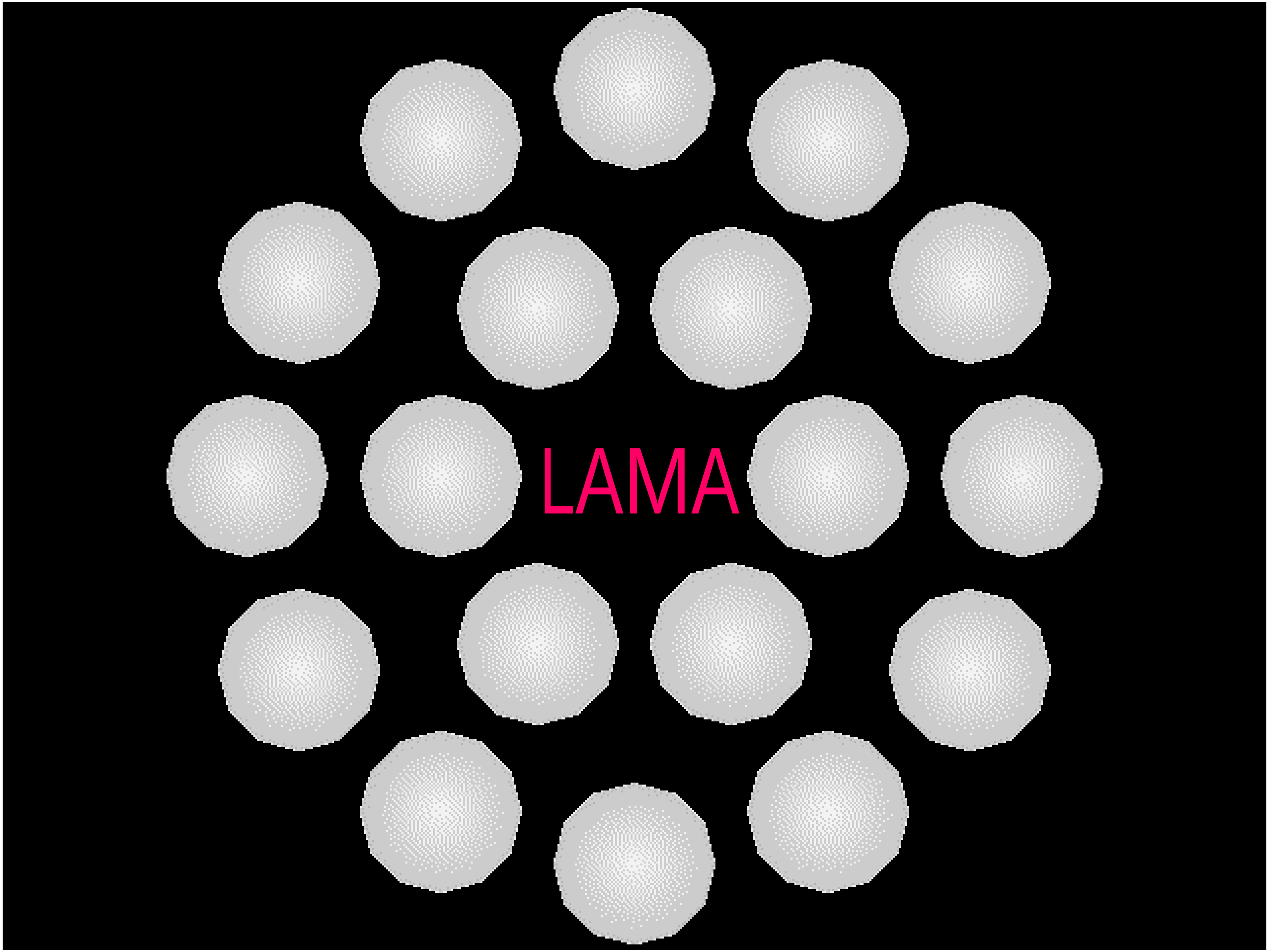
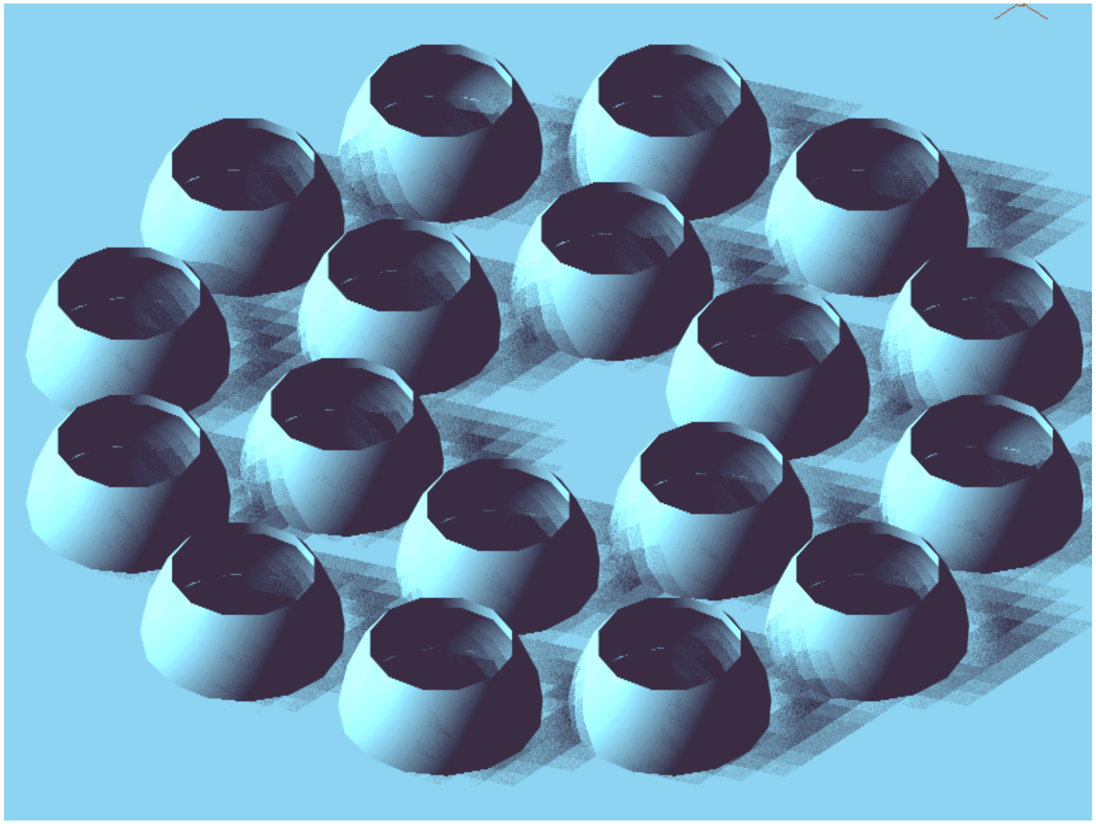

LAMA

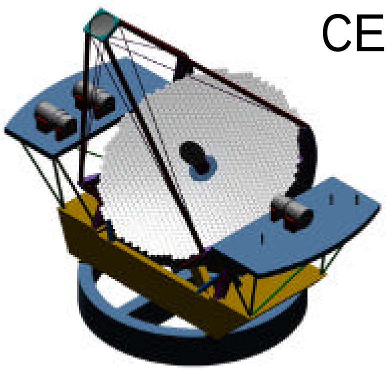
Outline

- LAMA concept
- Technologies
- Feasibility



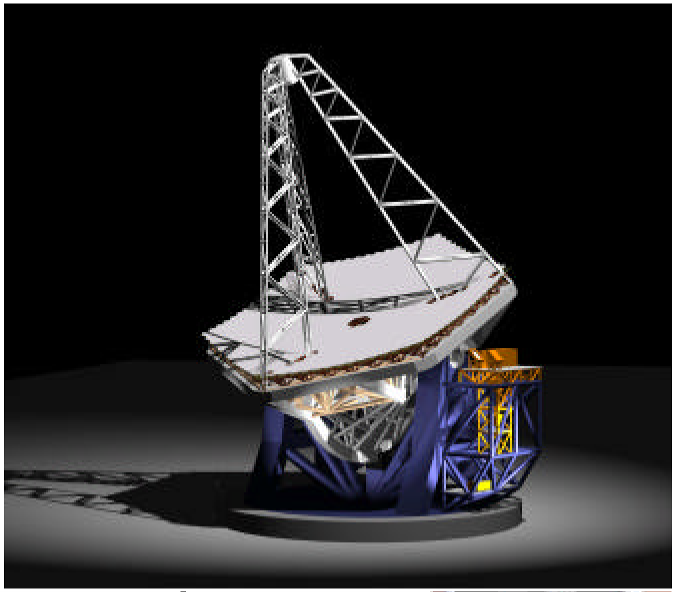
LAMA

Large telescope projects

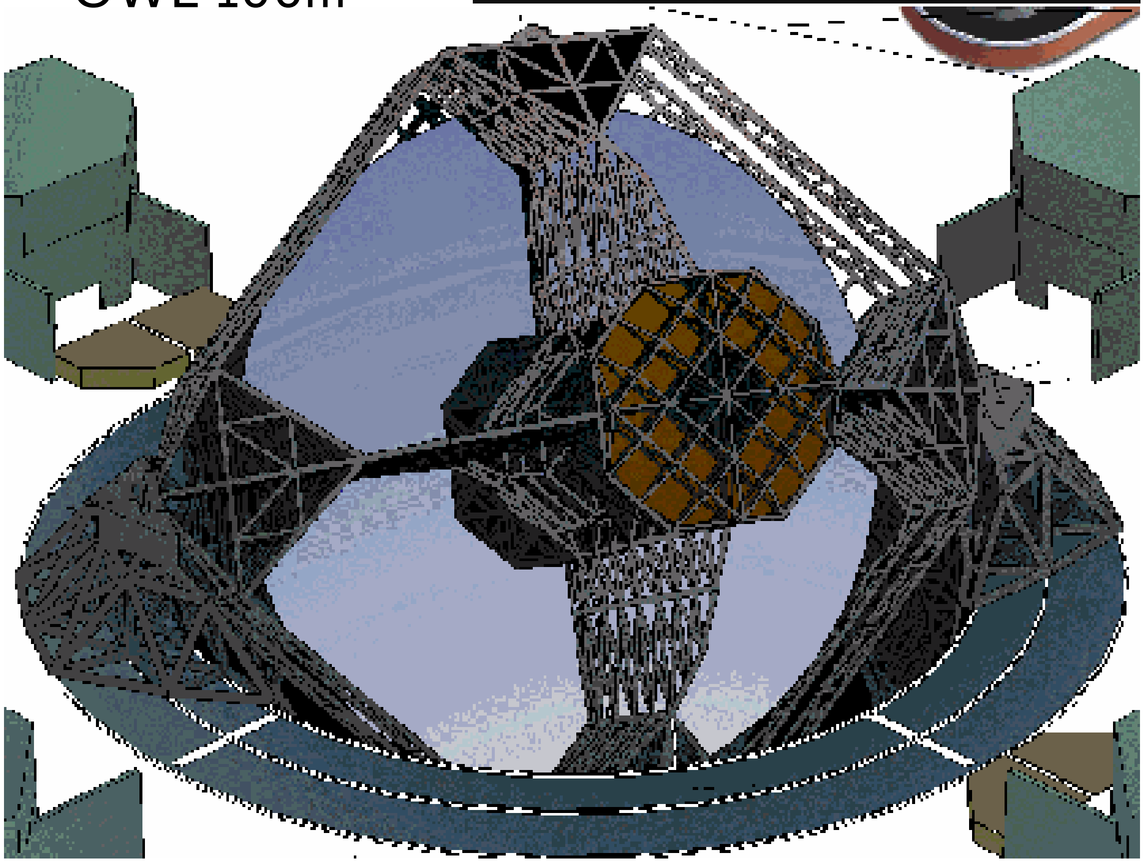


CELT 30m

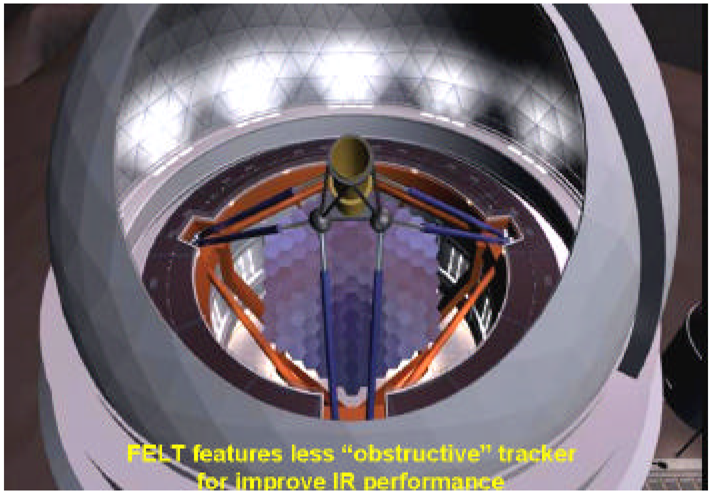
EURO50 50m



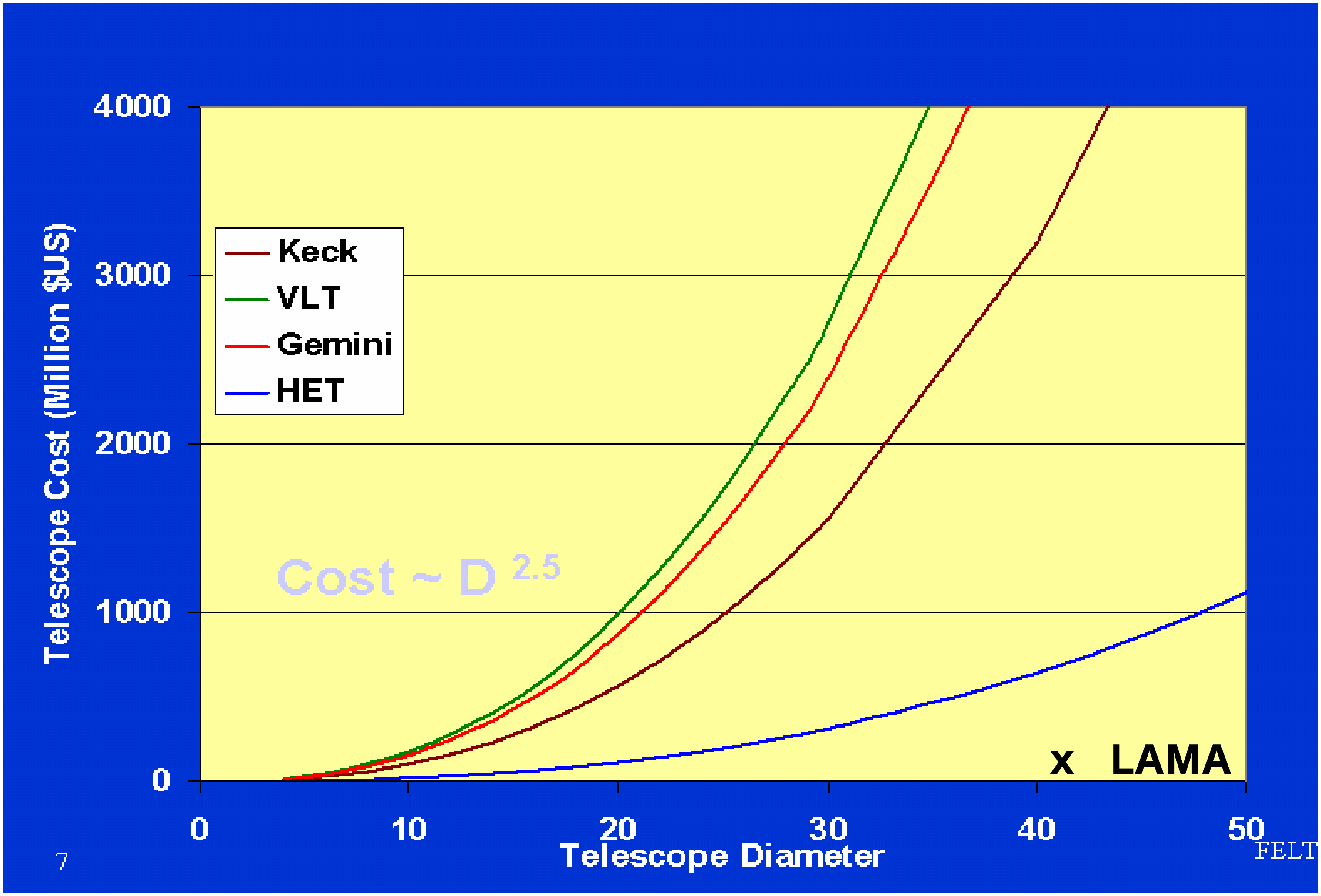
OWL 100m



FELT 30m



Cost scaling of conventional telescopes

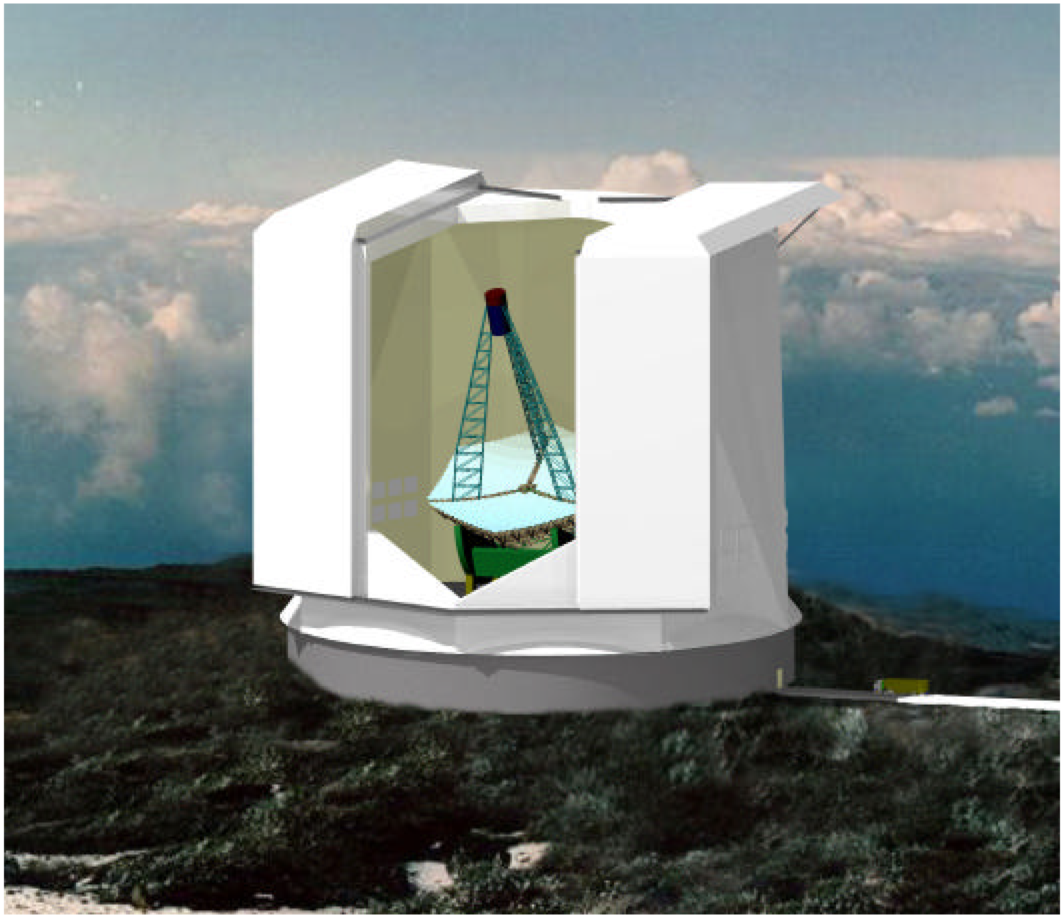


graph courtesy FELT project

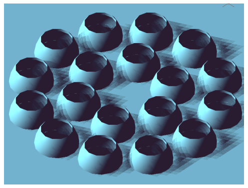
LAMA

Advantages of an array

- Demonstrated technology
- Versatility
- Redundancy
- Cost
  - monolithic ~ $A^{1.3}$
  - array ~ A
  - smaller enclosure
  - economy of scale



EURO50

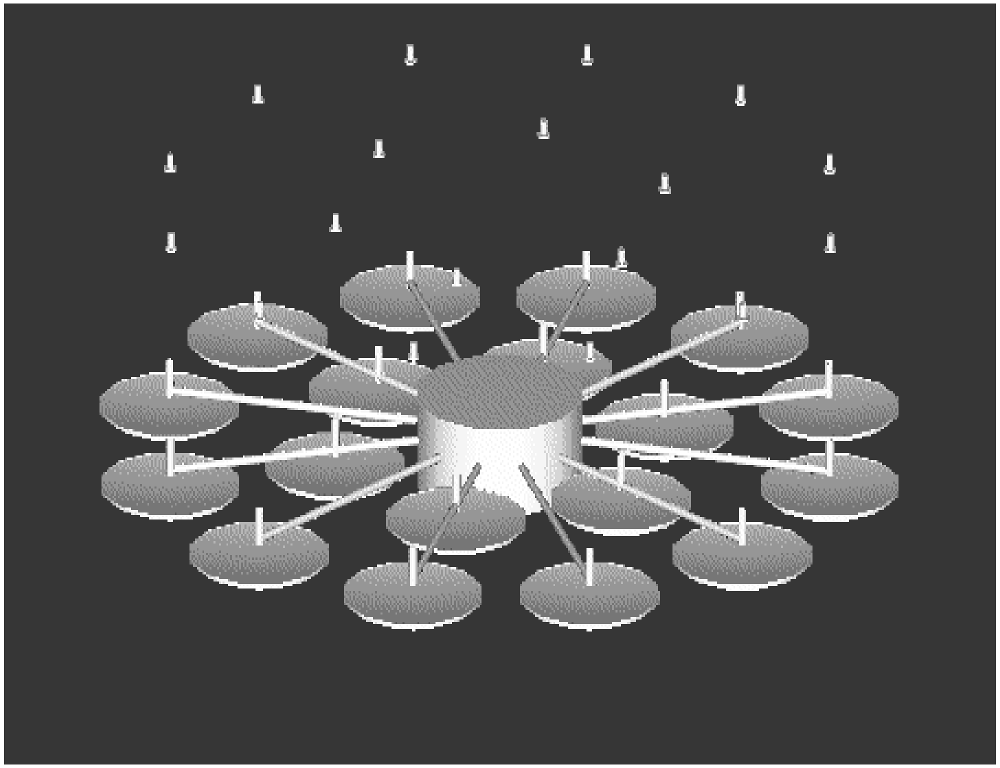


LAMA

LAMA

Lama concept

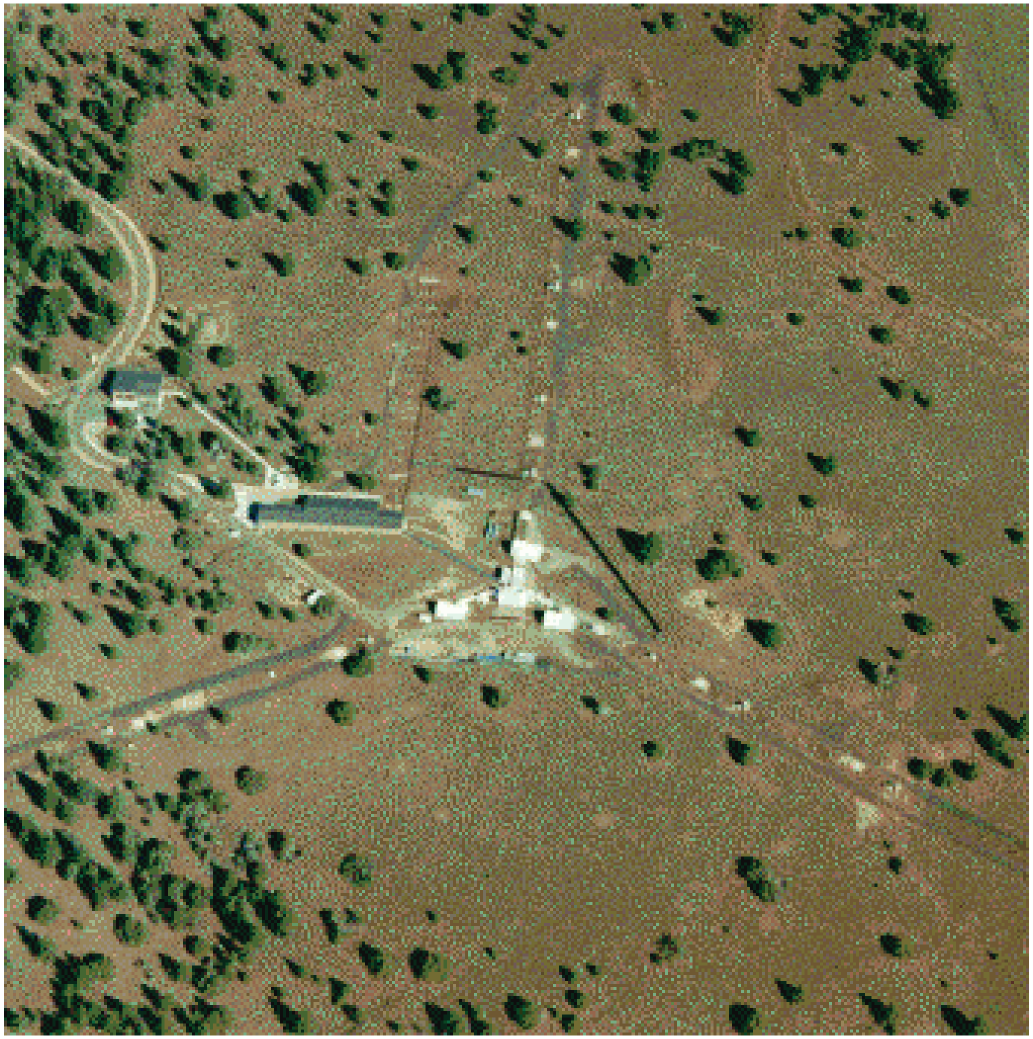
- Array of fixed mirrors
- Central beam combiner
- Near-zenith pointing and tracking
- Adaptive optics on each telescope
- Incoherent and coherent (interferometric) modes
- Simultaneous VRIZJHK imaging camera
- Modular approach



LAMA

Optical Interferometry

NPOI

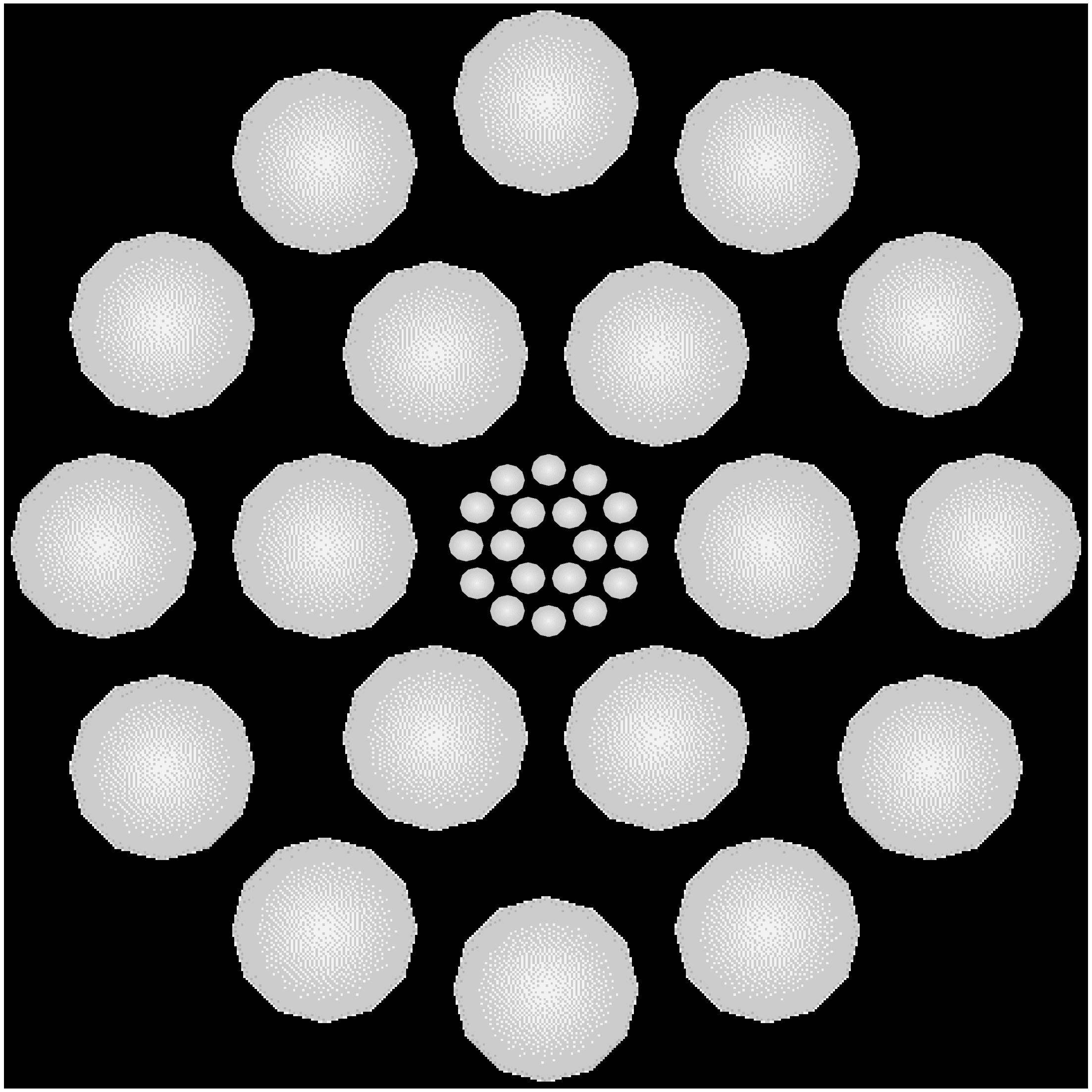


- Demonstrated technology:
  - optical imagery
  - phase closure
  - pathlength control
  - adaptive optics
- Active development
  - NPOI
  - PTI
  - CHARA
  - KECK
  - VLTI

LAMA

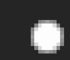
Fizeau interferometer

- Interferometric imaging over an extended field of view
- Geometry of beam combiner must exactly match that of mirror array



LAMA

LAMA PSF



Incoherent

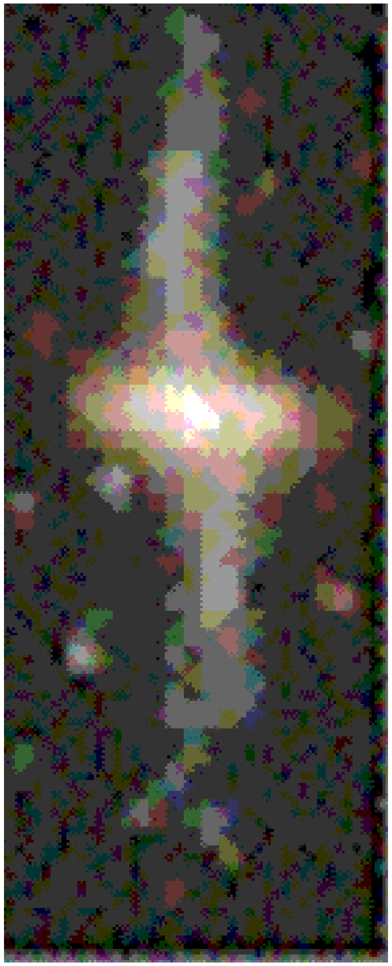
40 mas FWHM at 2 um

Coherent

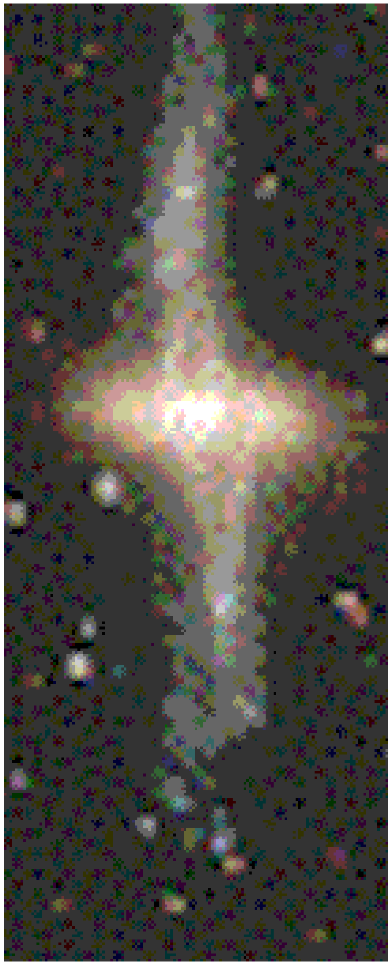
6 mas FWHM at 2 um

LAMA Imaging

HST 2.4m



NGST 8m



LAMA 60m

LAMA

Photo Credit:NASA

Interferometer sensitivity

- Fraction of power in central image equals the filling factor of the array

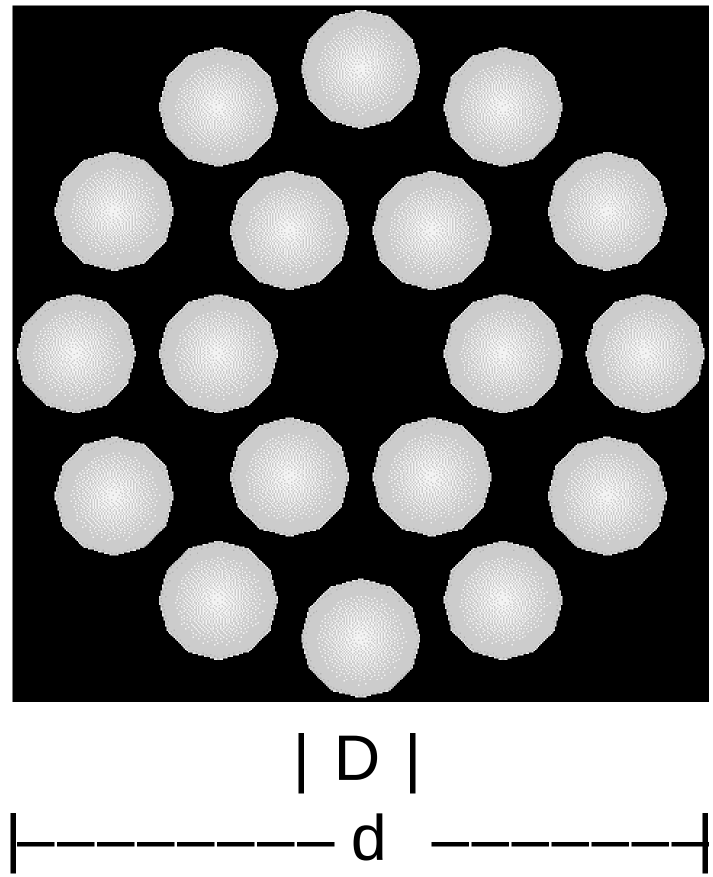
  $$f = ND^2/d^2$$

- Incoherent beam combination

  $$S_I \sim ND^4$$

- Coherent beam combination

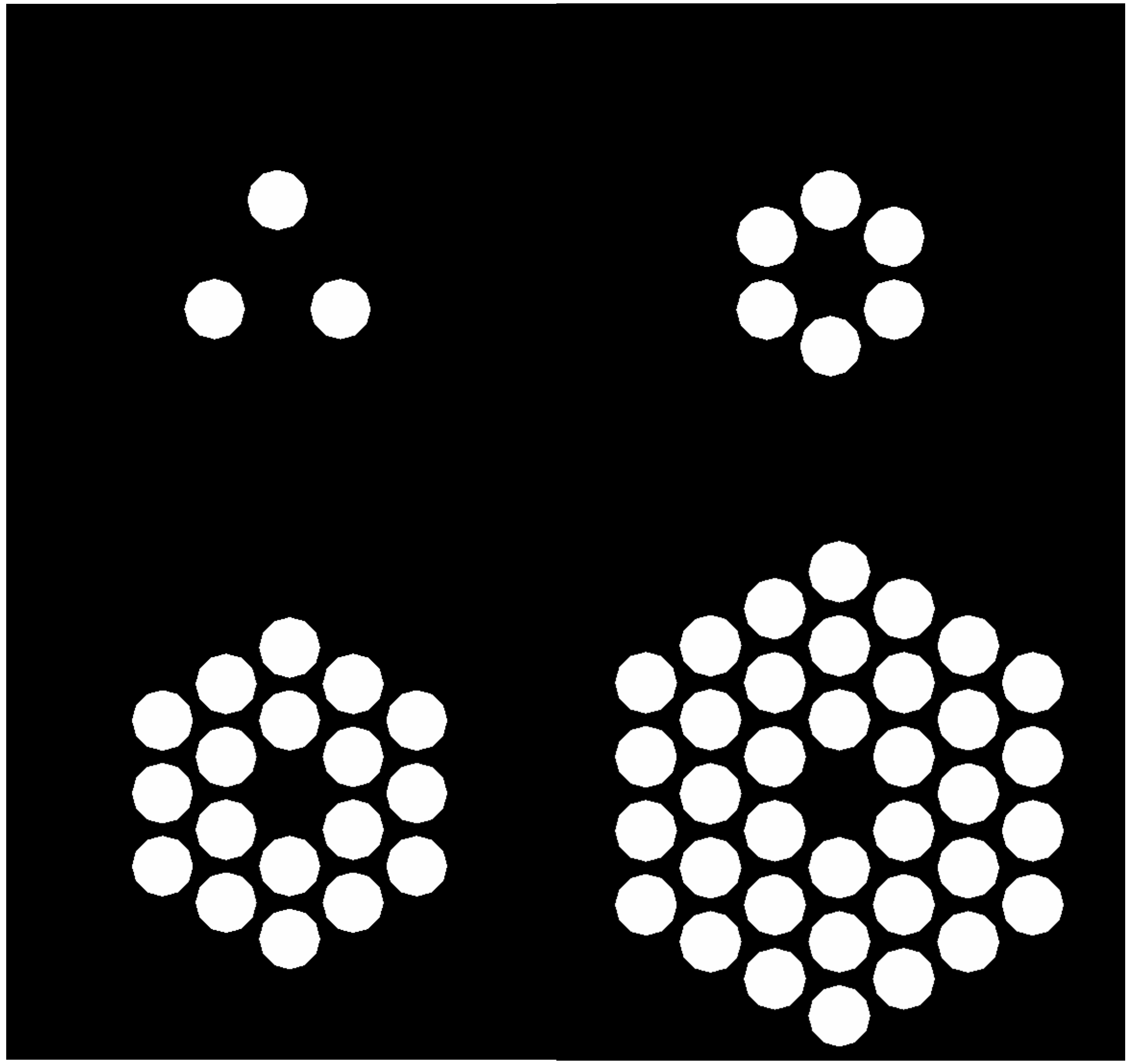
  $$S_C \sim f^2 N D^2 d^2 \sim f N^2 D^4$$



Modular Approach

Equivalent Diameter

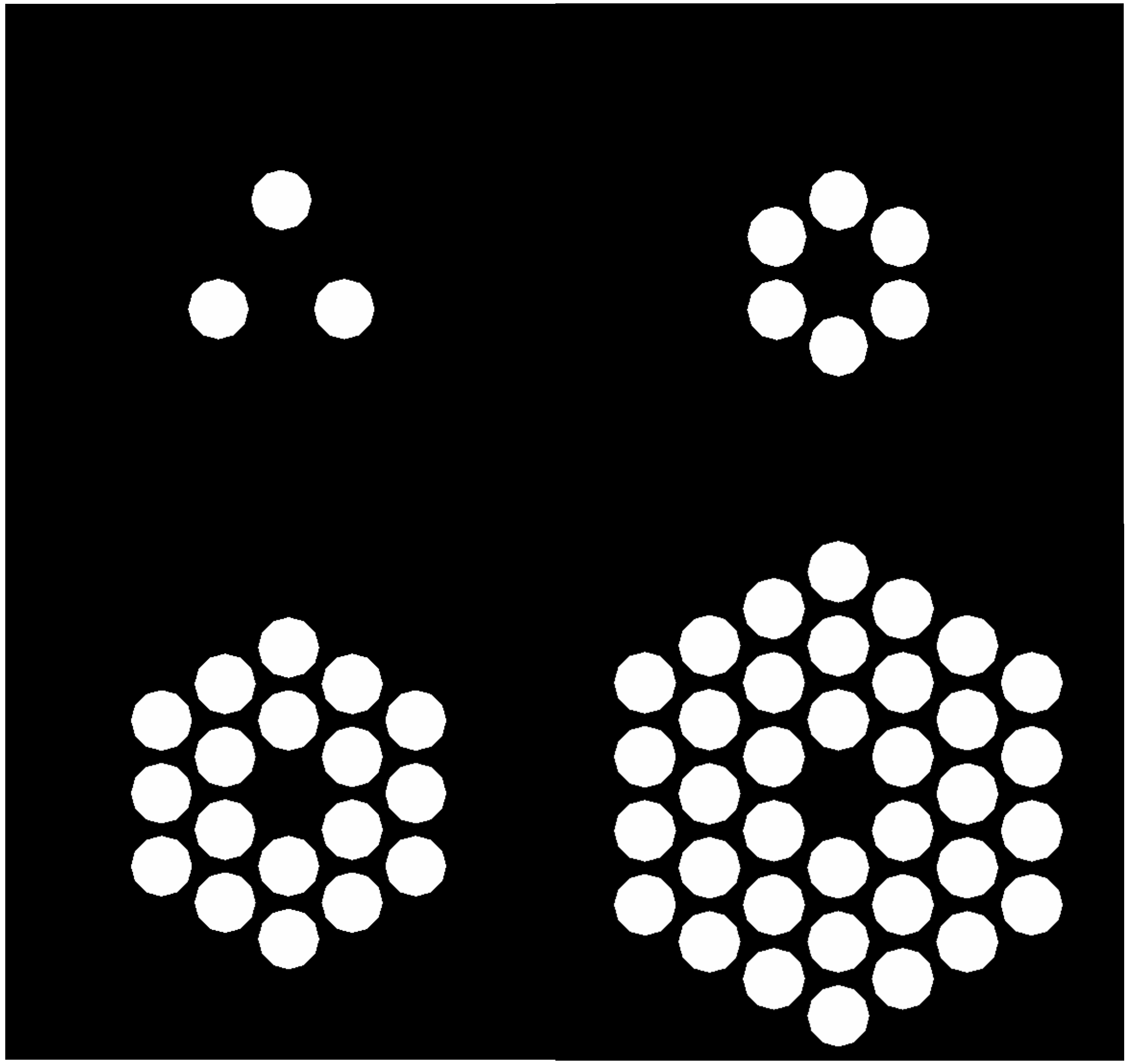
D_A	D_θ
17m	31m
24m	35m
42m	60m
60m	85m



LAMA

Sensitivity compared to a 10m telescope

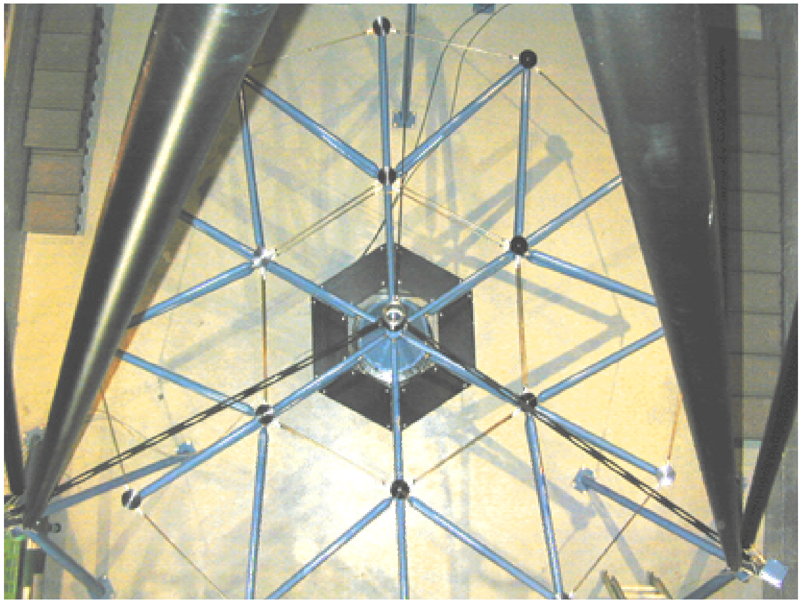
S_l	S_c
3	4.5
6	18
18	162
36	648

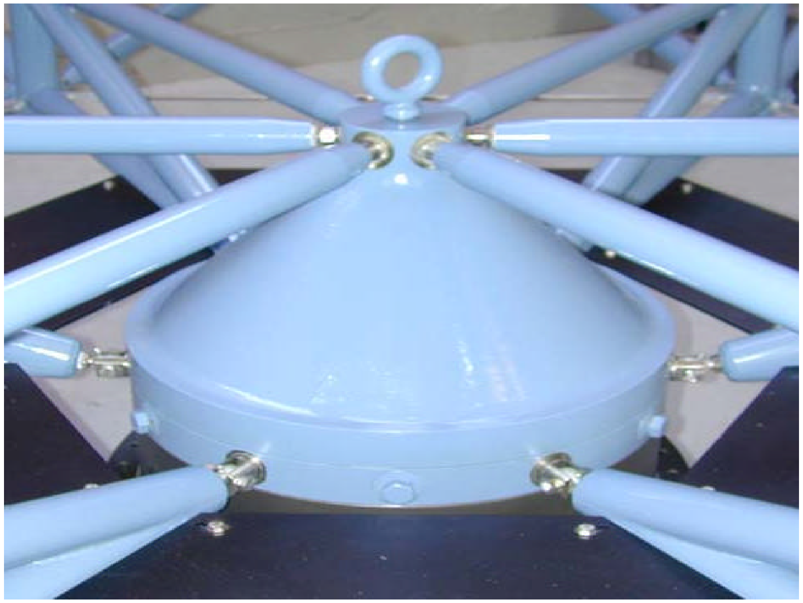


LAMA

LAMA technologies

- Adaptive optics
- Optical interferometry
- Tracking optics
- Liquid mirrors



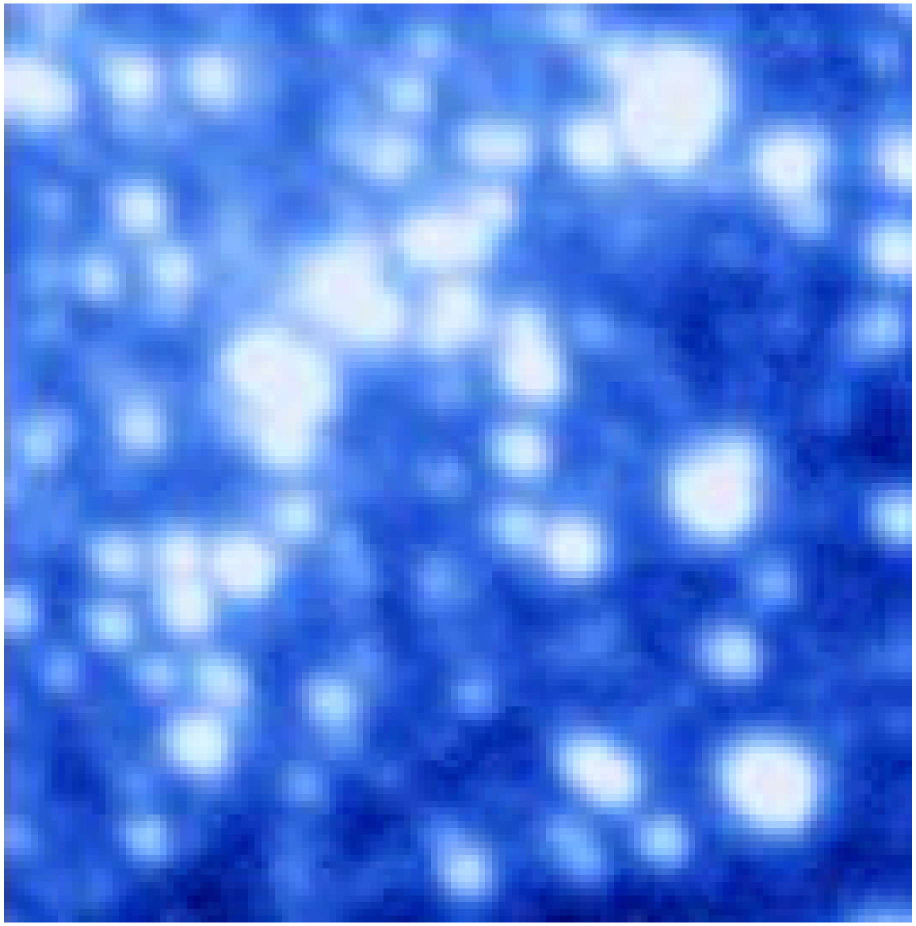


LAMA

Adaptive optics

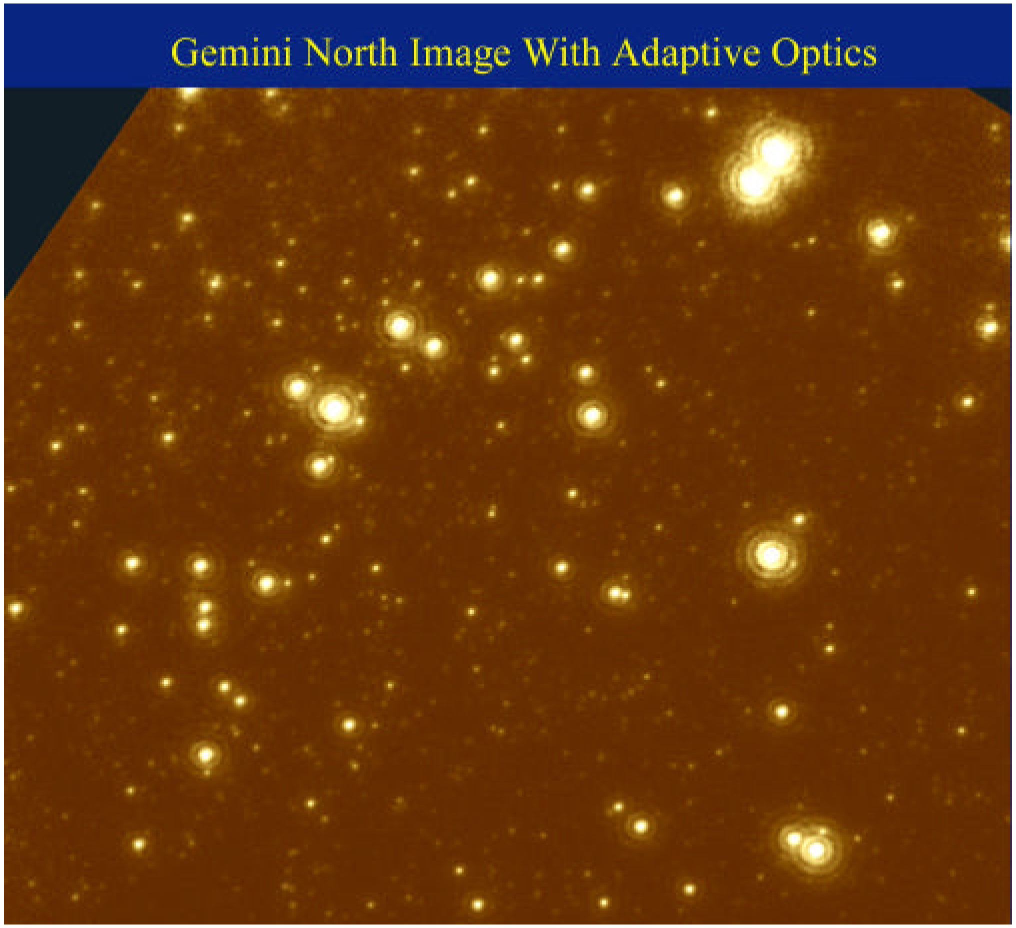
- Demonstrated performance

FWHM = 0.8 arcsec

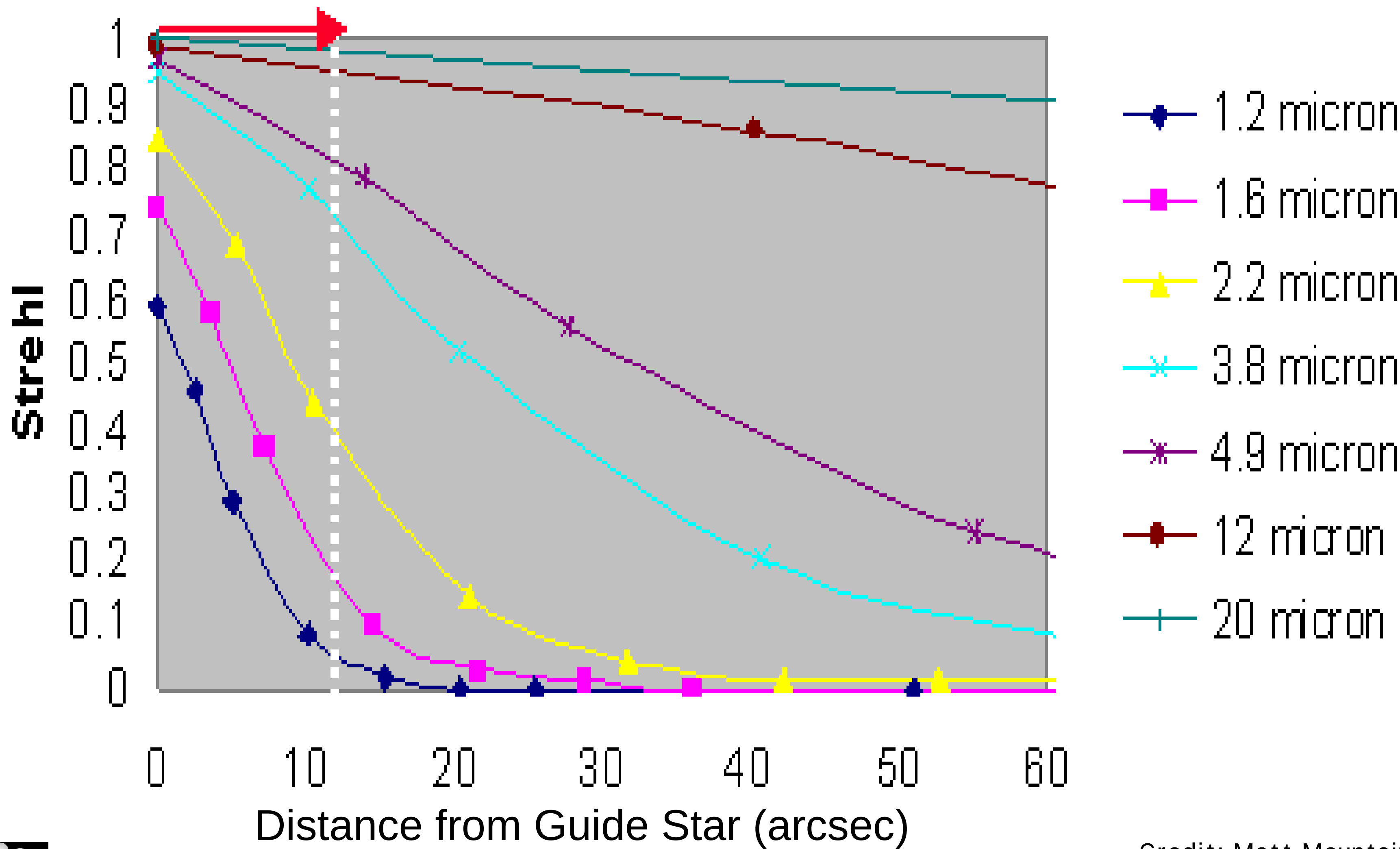


FWHM = 0.08 arcsec

Credit: Gemini Project



Adaptive optics performance

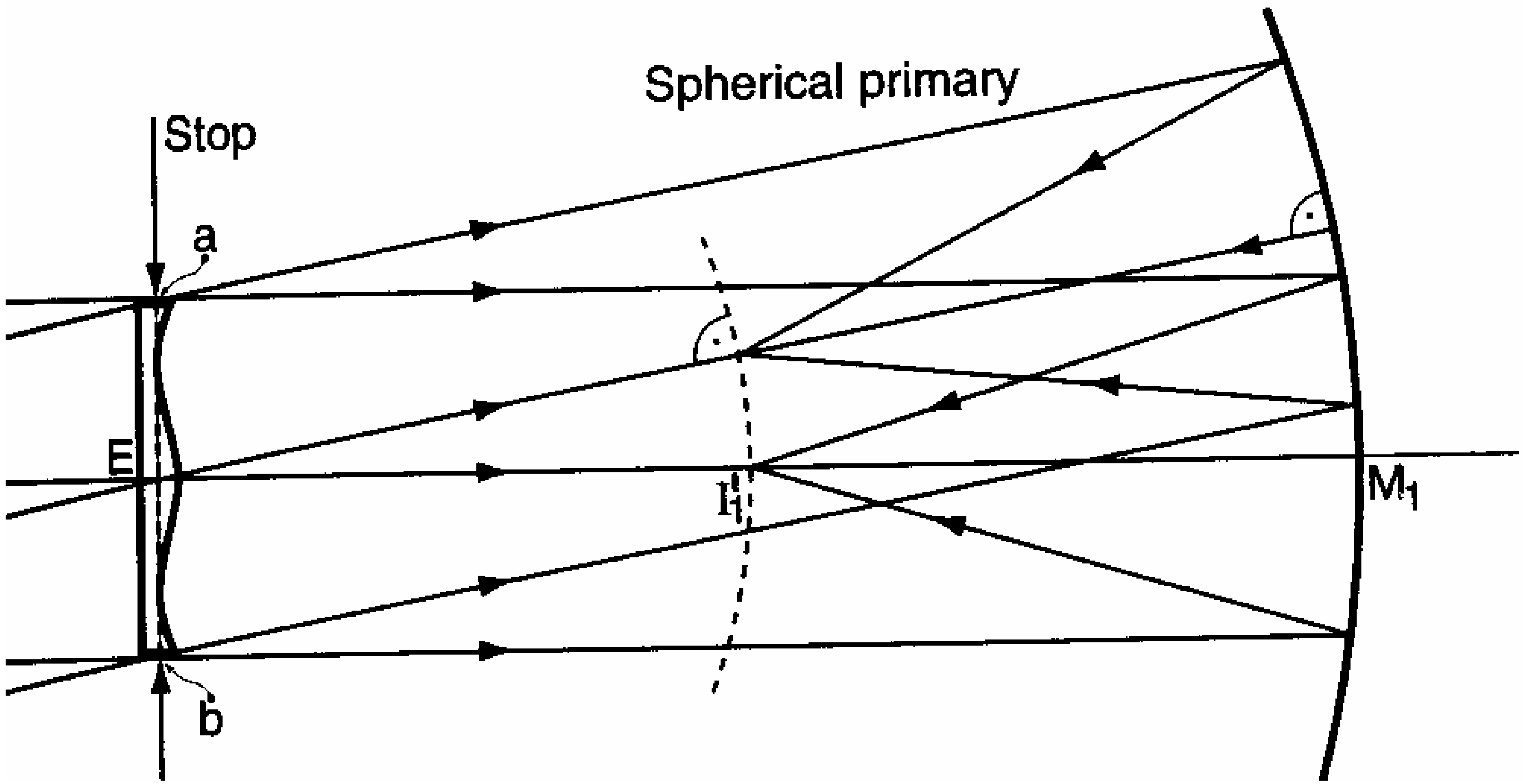


Credit: Matt Mountain

LAMA

Schmidt-Telescope Principle

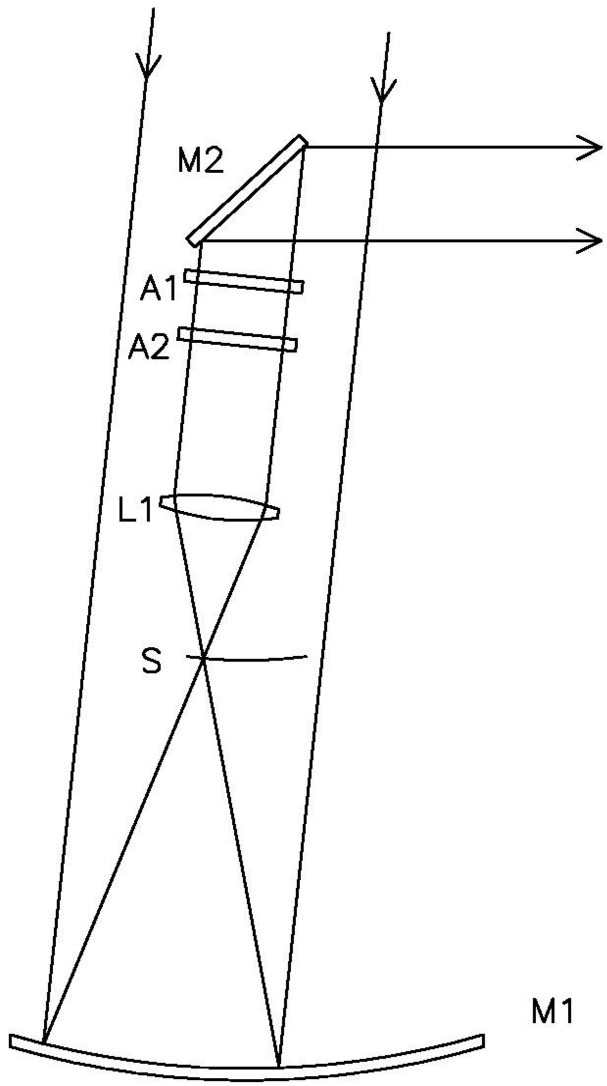
- A sphere has no axis



LAMA

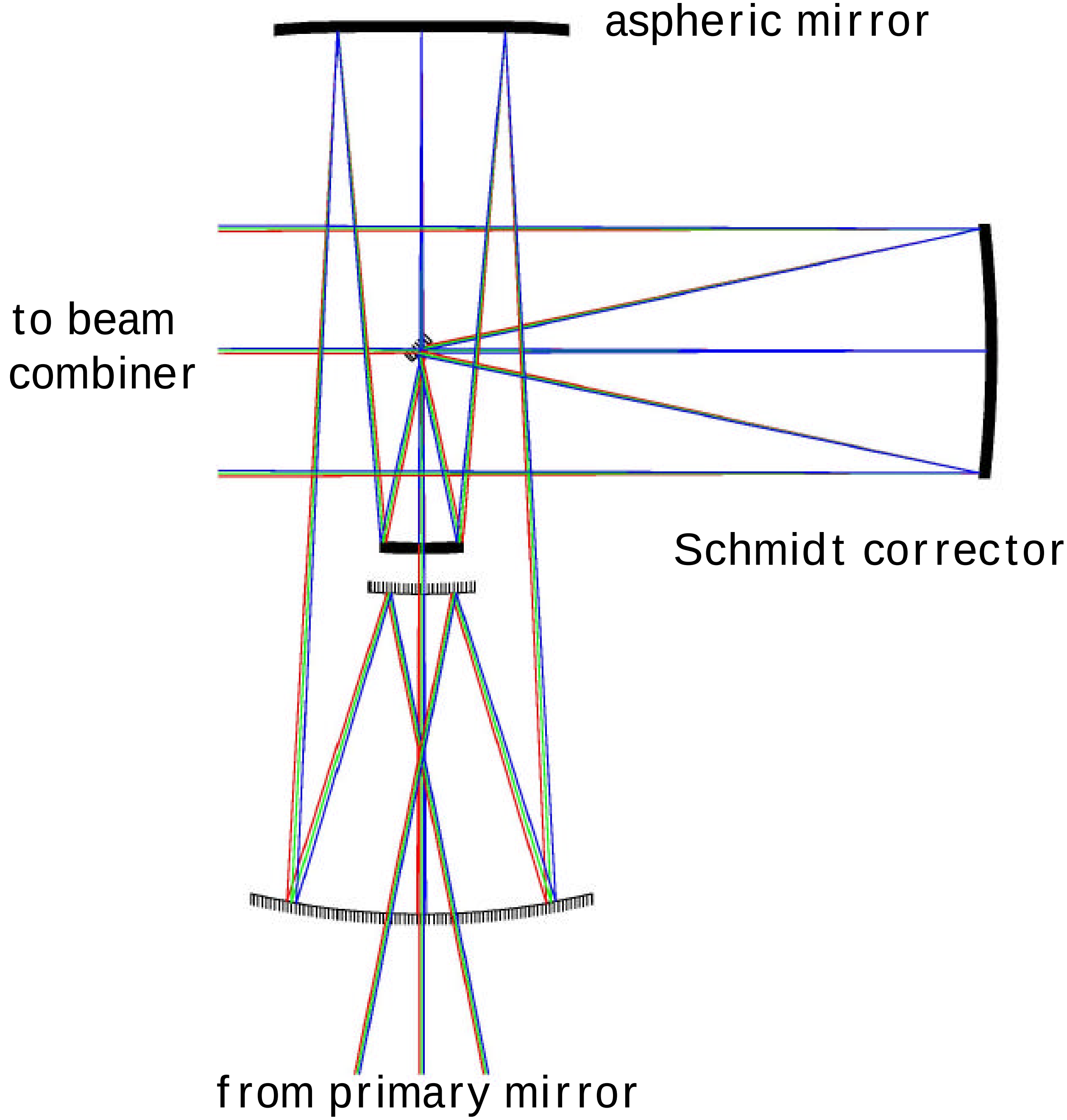
Parabolic primary mirror

- Add aspheric corrector A2, located conjugate to primary mirror M1
- A2 effectively converts the primary mirror to a spherical mirror
- A2 must move transversely, relative to the tracking system, in order to remain conjugate to M1. This does not introduce any distortion or focal plane tilt because A2 has no optical power
- With A2, the system performs like the spherical case, but with a zenith-angle limited by vignetting effects



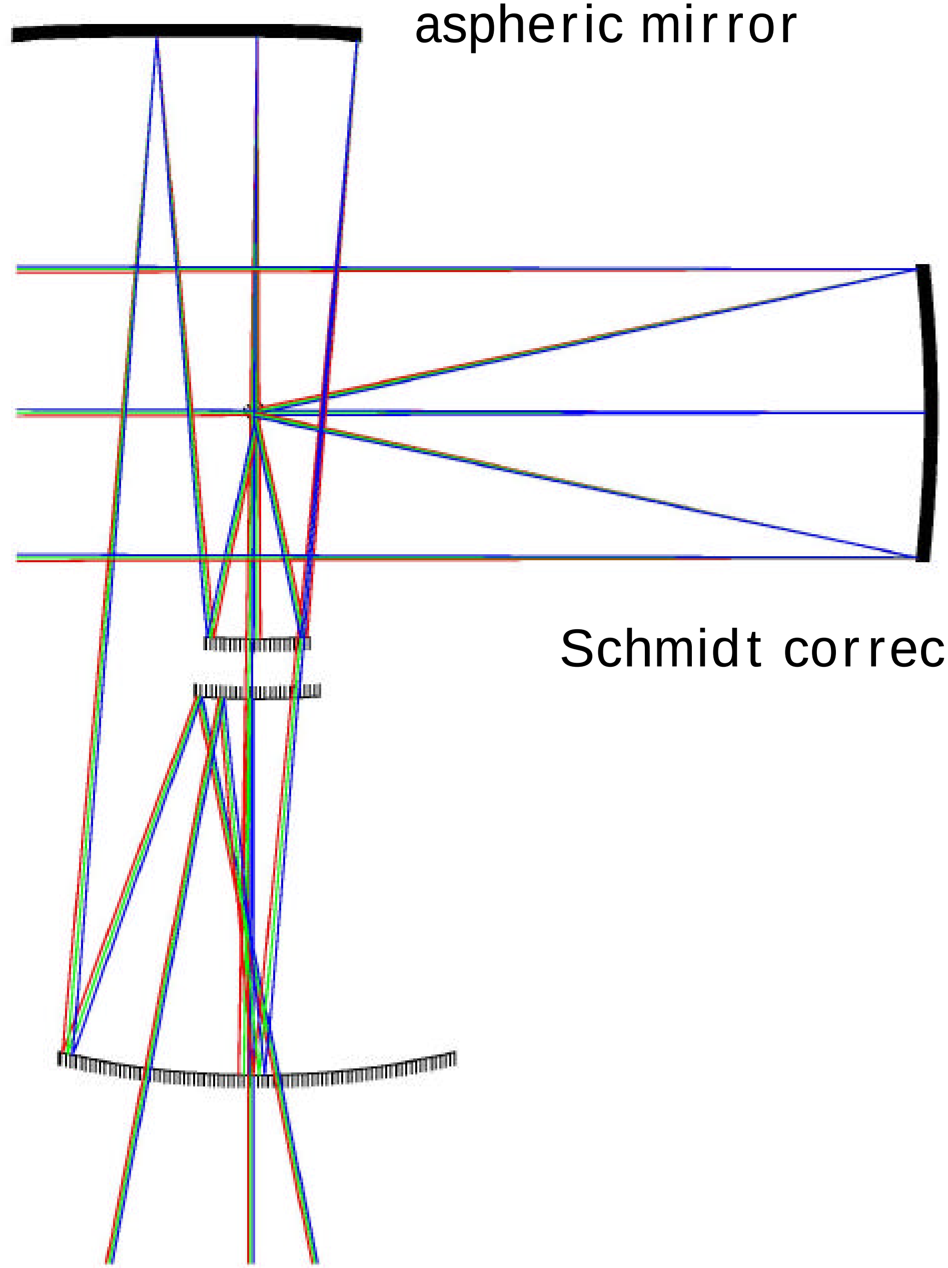
LAMA

LAMA tracking optics



LAMA

LAMA tracking optics



LAMA

Performance of LAMA tracking system

- Points and tracks over an 8-degree diameter area of sky
- Tracking for up to 30 min per field
- All-reflecting design – wide wavelength range
- Feeds light to a fixed focus
- Sub-arcsec natural images
- High Strehl ratio using AO

Zenith angle (deg)	0	1	2	3	4
Field angle (arcmin)	Strehl Ratio				
+0.5	0.89	0.91	0.86	0.60	0.33
0	0.95	0.94	0.90	0.80	0.80
-0.5	0.89	0.91	0.85	0.68	0.33

LAMA

Liquid-mirror issues

- Feasibility
- Performance
- Safety
- Cost

LAMA

Liquid mirror telescopes

A century of progress…

Robert Wood, 1909

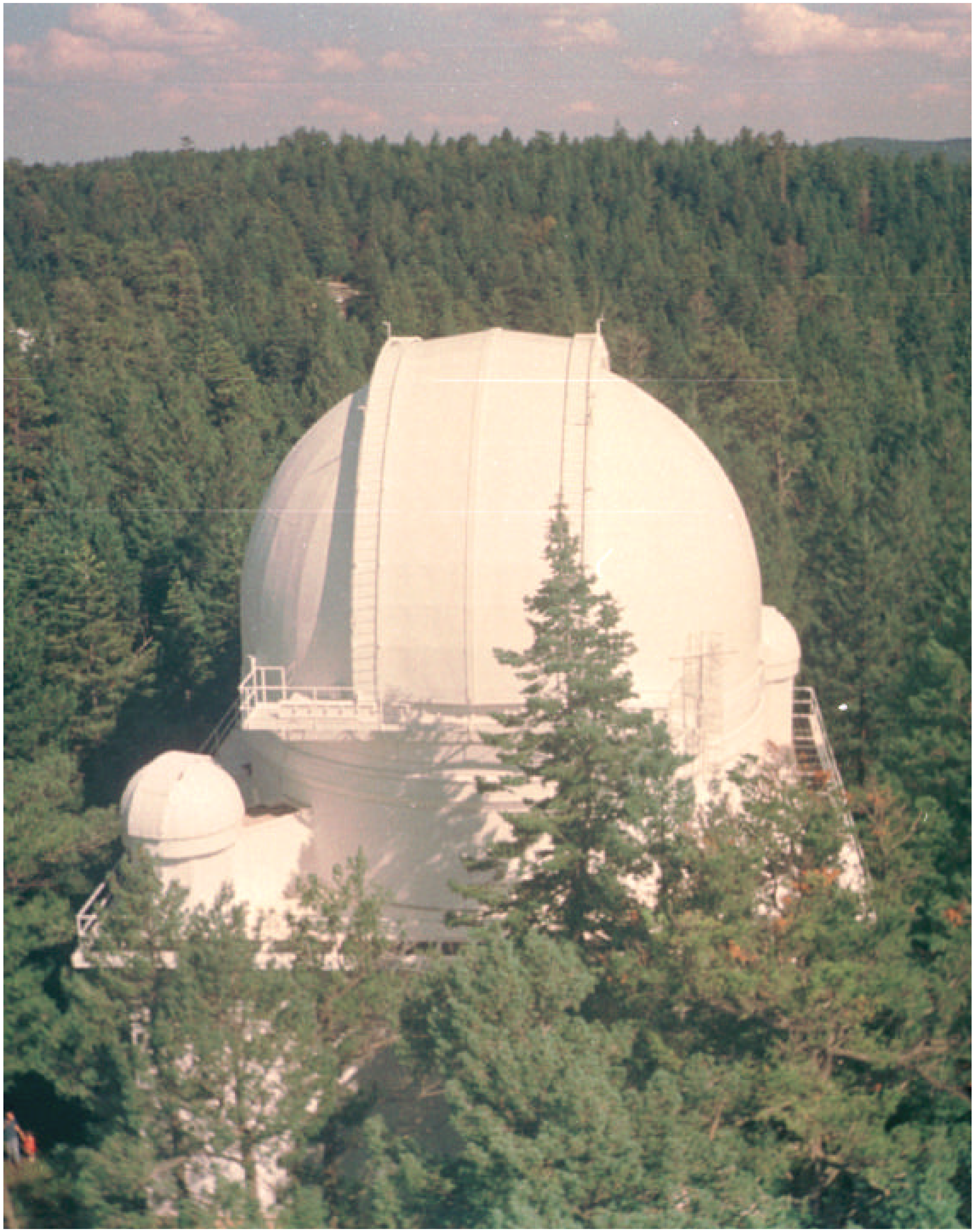
UCLA Lidar, 1995

NASA Orbital Debris Observatory

- New Mexico Sacramento Mtns
- 2772 m altitude
- 50 km North of Sunspot (home of National Solar Observatory, ARC 3 m and Sloan DSS)
- 75% nights clear, 30% photometric
- Seeing 1-2” FWHM

LAMA

Credit: Mark Mulrooney



NASA Orbital Debris Observatory (NODO)

- Near Cloudcroft, New Mexico, USA
- First-light 1995
- 3m f/1.5 primary
- 4-element PF corrector
- NASA Intensified video camera
- UBC 1k x 1k thinned CCD camera

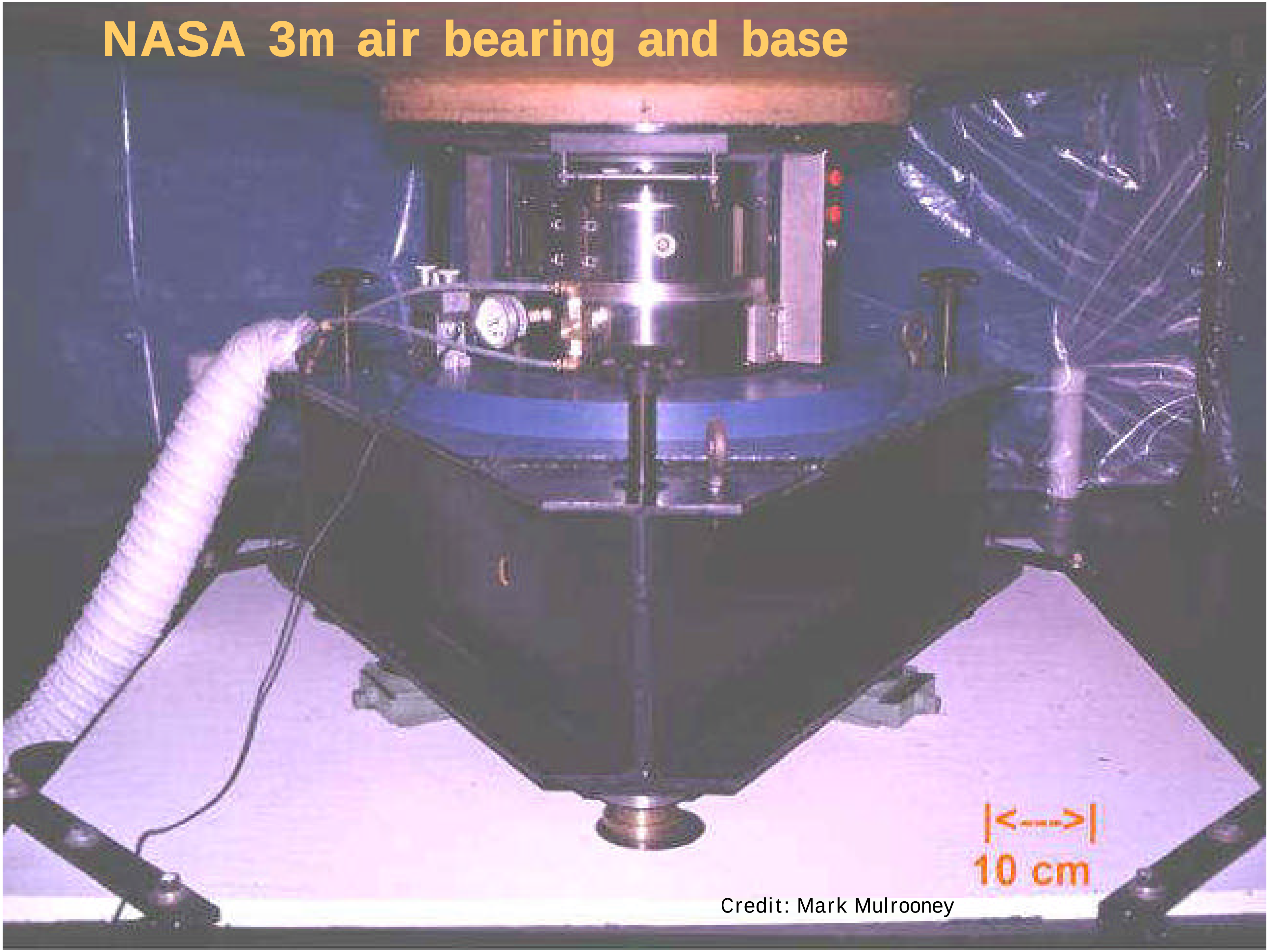
LAMA

Credit: Chip Simons Photography

NODO 3m mirror

Credit: Mark Mulrooney

NASA 3m air bearing and base



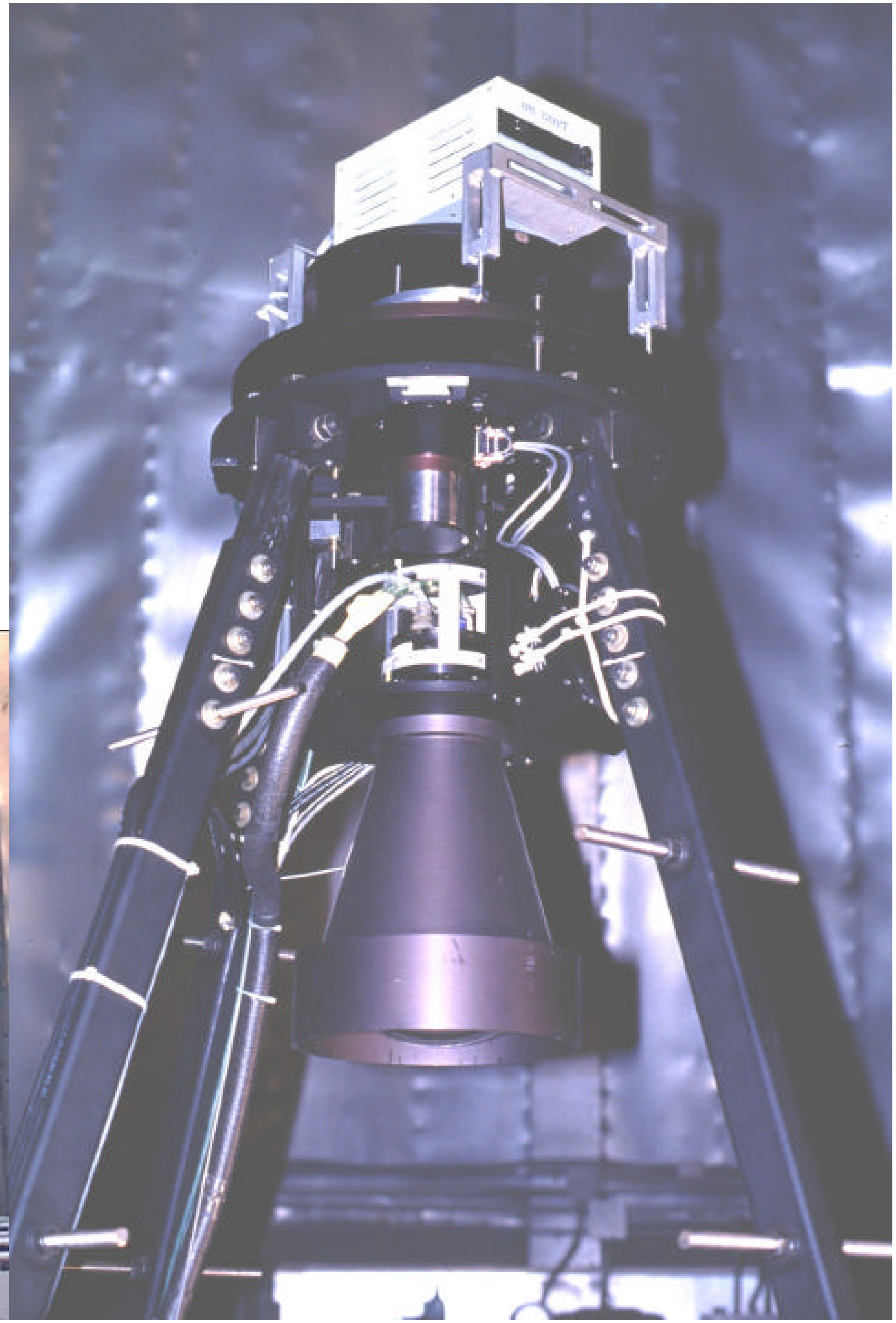
Credit: Mark Mulrooney

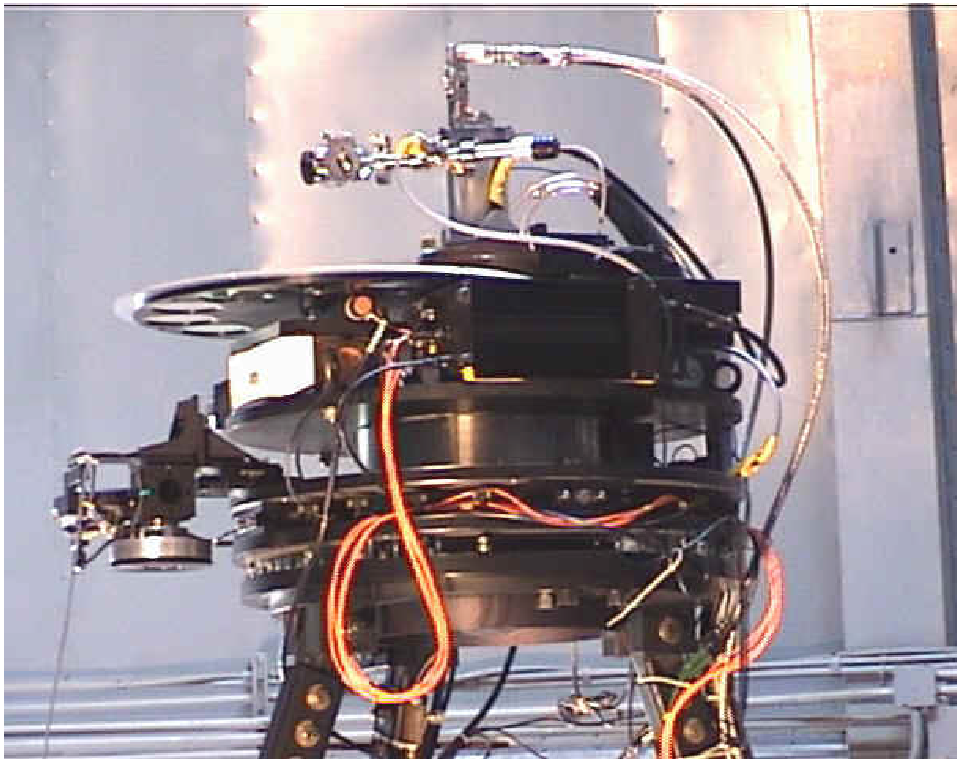
NASA 3m prime focus

Original system

New system with 2Kx2K CCD

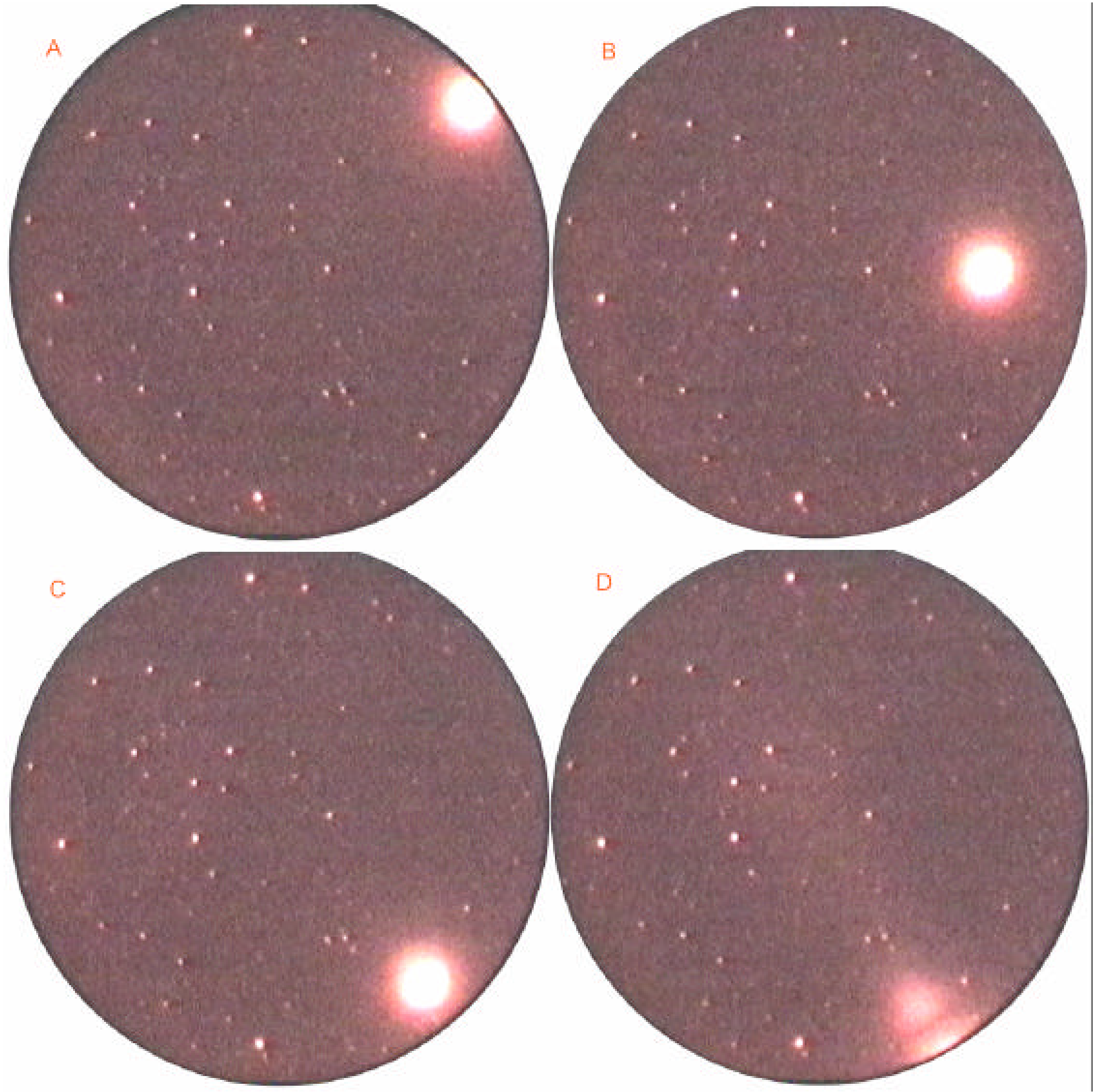
Credit: Mark Mulrooney





Primary NODO mission – space debris

- Detect and characterize the 1-10cm dia debris population in low Earth orbit
- Intensified digital video CCD camera
- Has detected several thousand objects

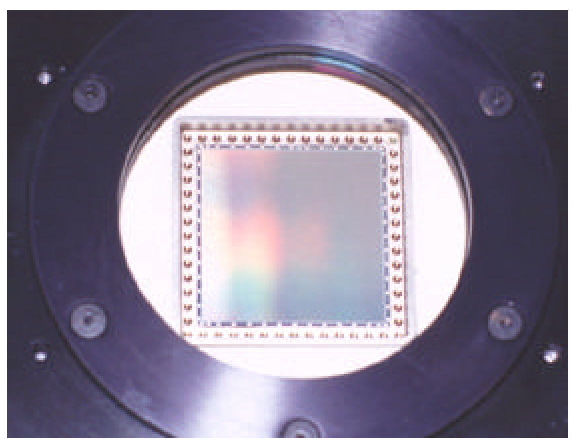


Credit: Mark Mulrooney

LAMA

Time-Delay Integration

- Image moves continuously across CCD due to Earth's rotation
- Charge being generated by photons is shifted electronically along the CCD columns at the same rate
- Data are read continuously all night long, at approximately 13 lines per second
- Integration time is the time taken for an image to cross the CCD (78 sec for the 1Kx1K)



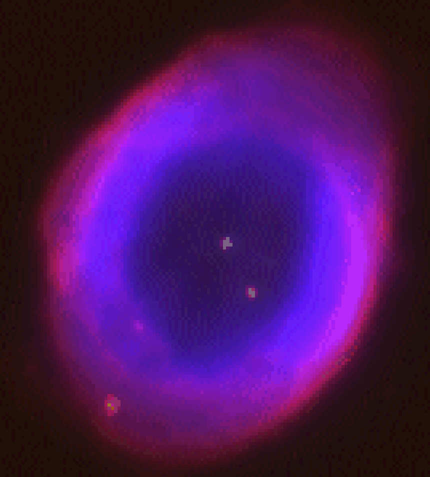
LAMA

LMT imaging with NODO

1-2 arcsec
seeing

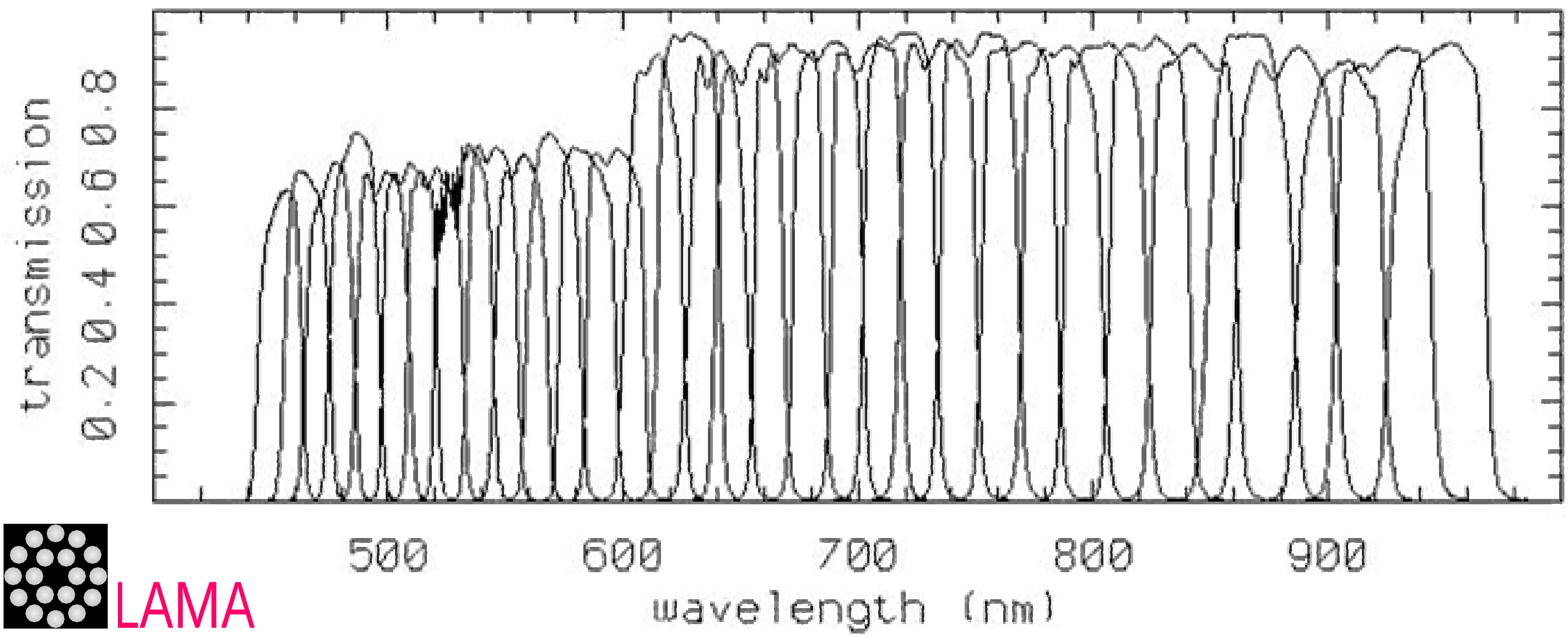
120
photometric
nights/year

22 magnitude
in 78 sec

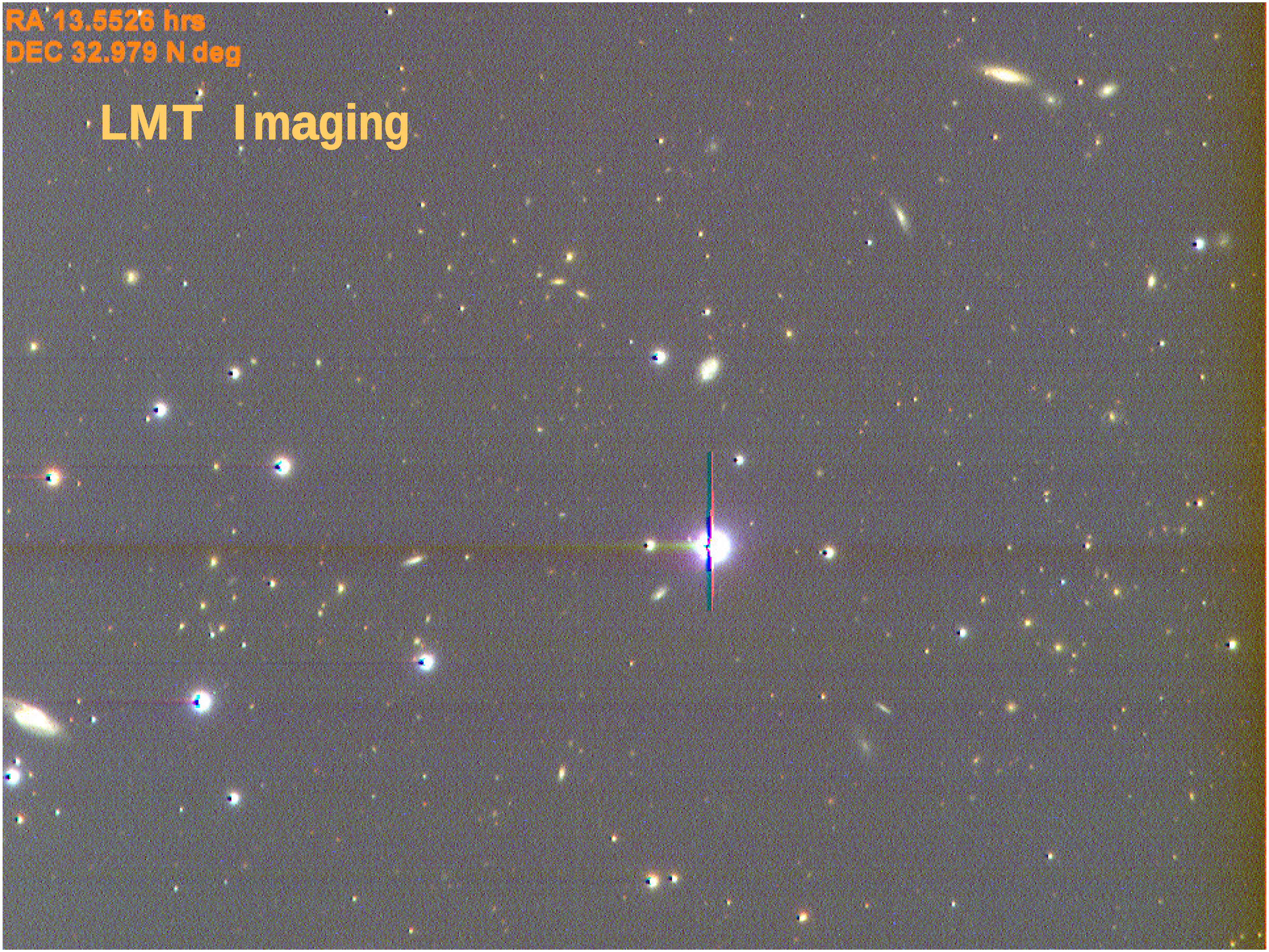


NODO Survey

- Driftscan survey using 1K x 1K CCD
- BVRI + 35 medium band filters
- 12-18 hrs ra at +33 deg dec
- 20-22 magnitude limit
- ~3 million objects



LAMA


RA 13.5526 hrs
DEC 32.979 N deg
LMT Imaging

L
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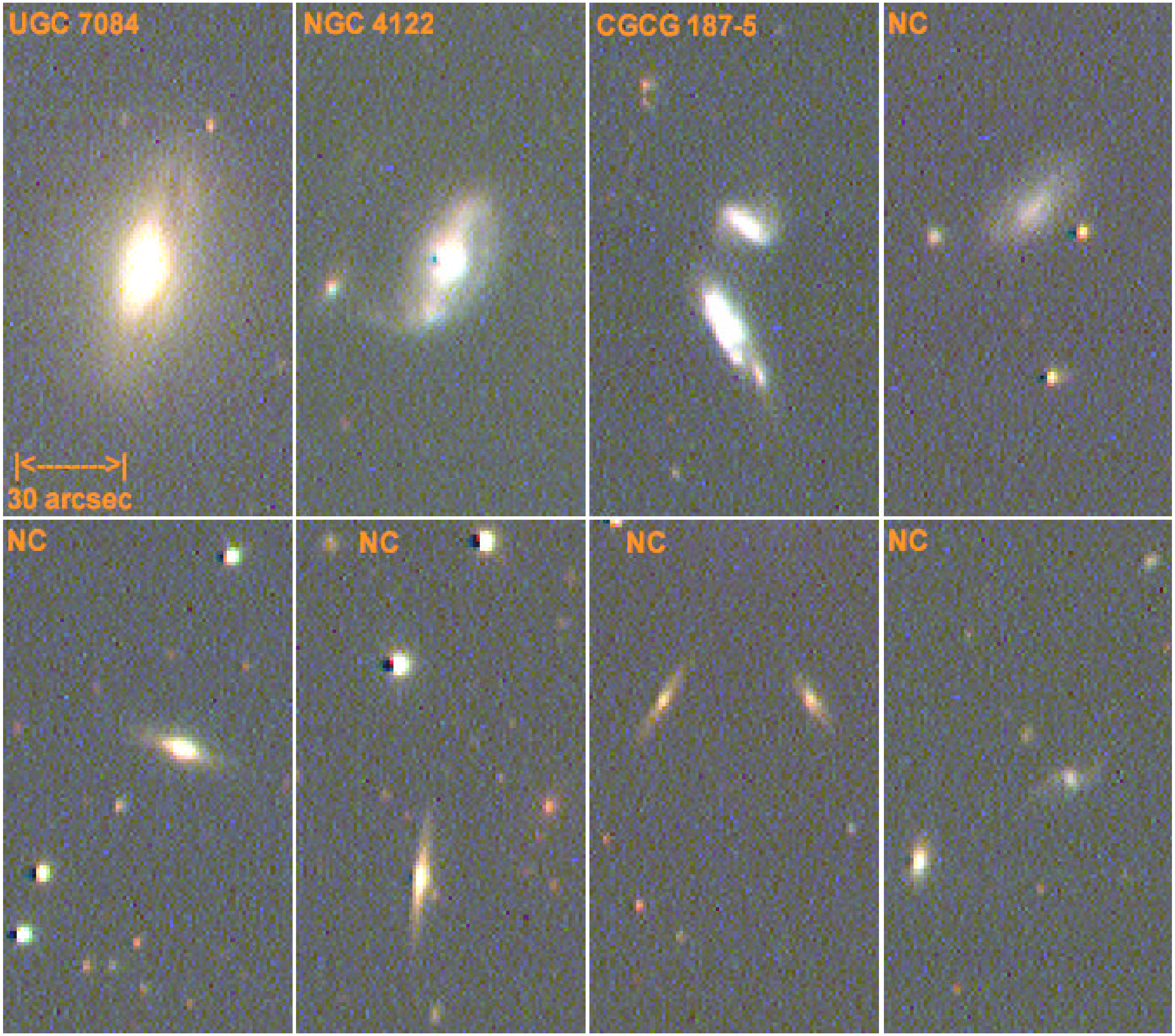
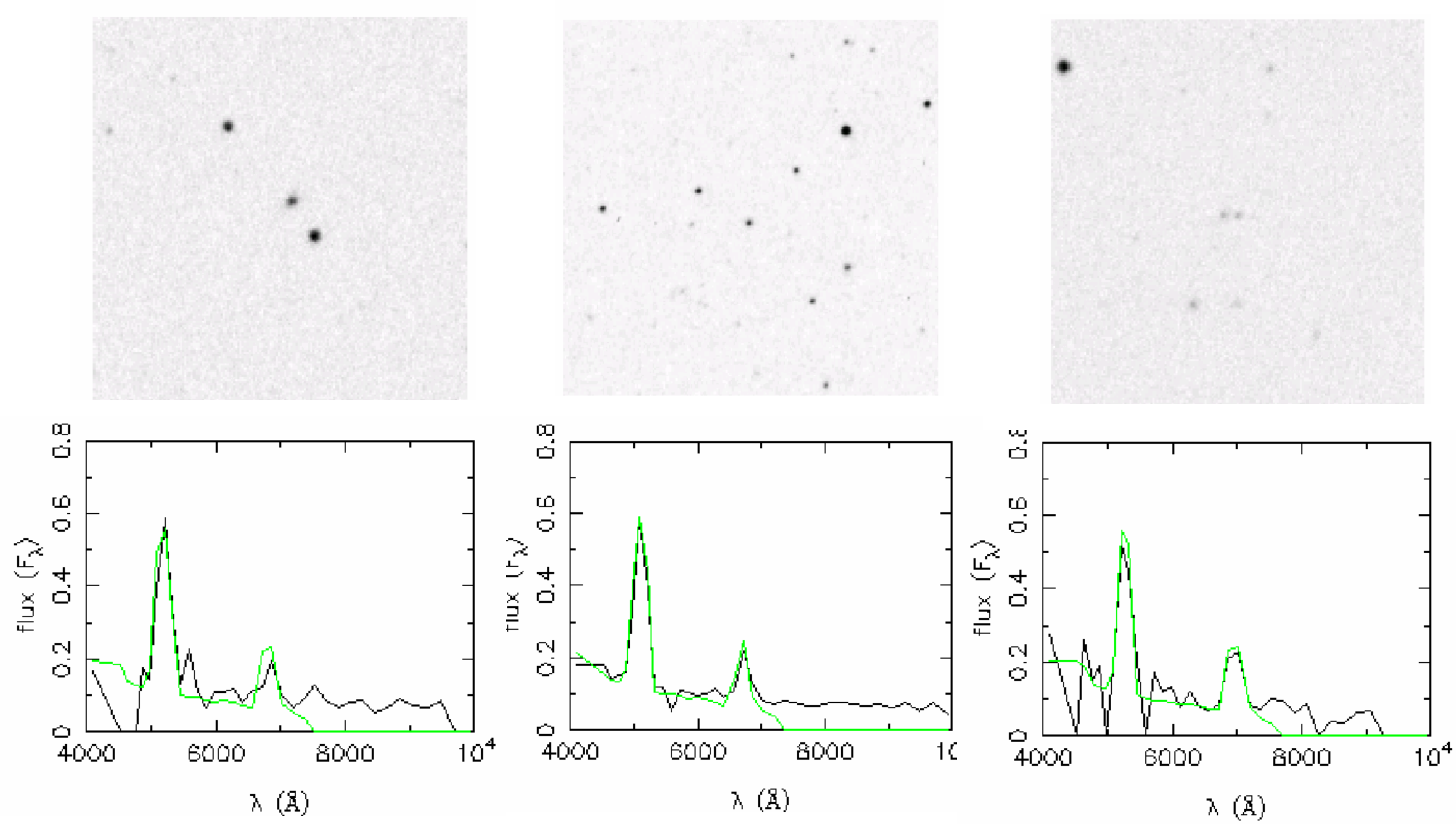


LAMA

NODO survey: emission-line galaxies

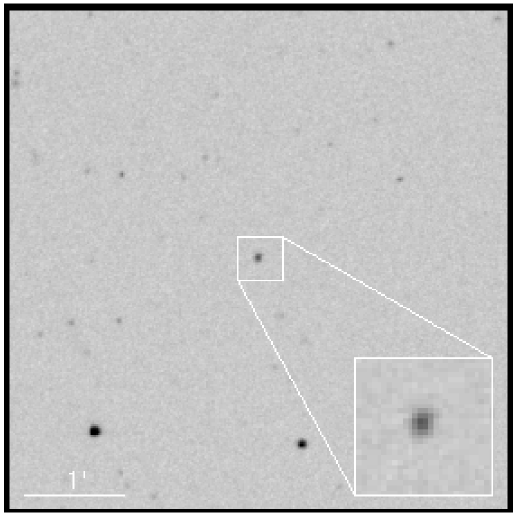


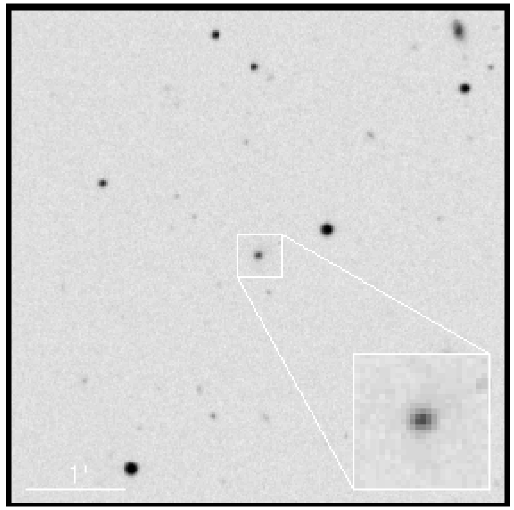
LMT: z = 0.037	LMT: z = 0.017	LMT: z = 0.057
NED: z = 0.038	NED: z = 0.015	NED: z = 0.052

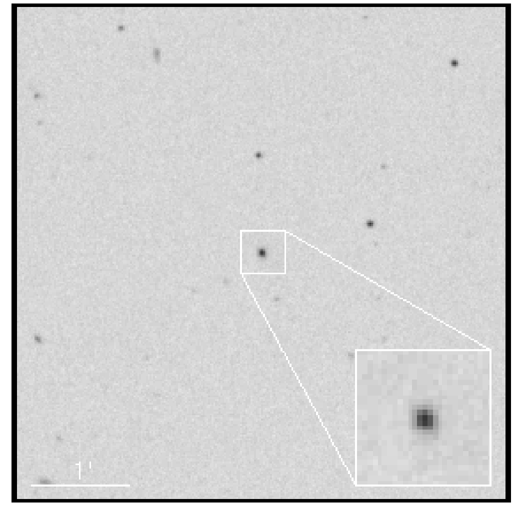
LAMA

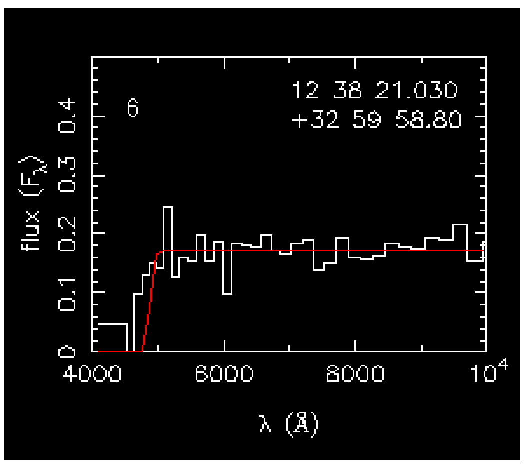
Credit: Remi Cabanac

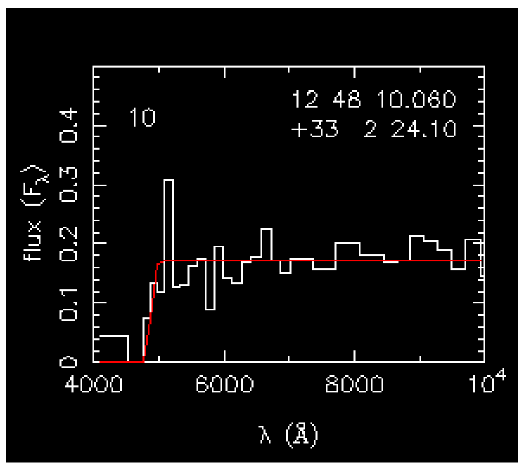
NODO survey: early-type galaxies, z~0.2

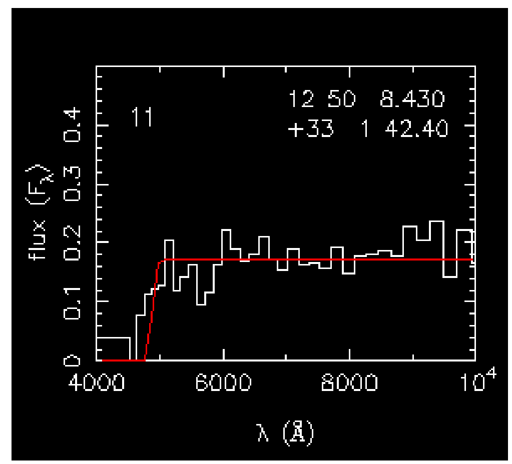












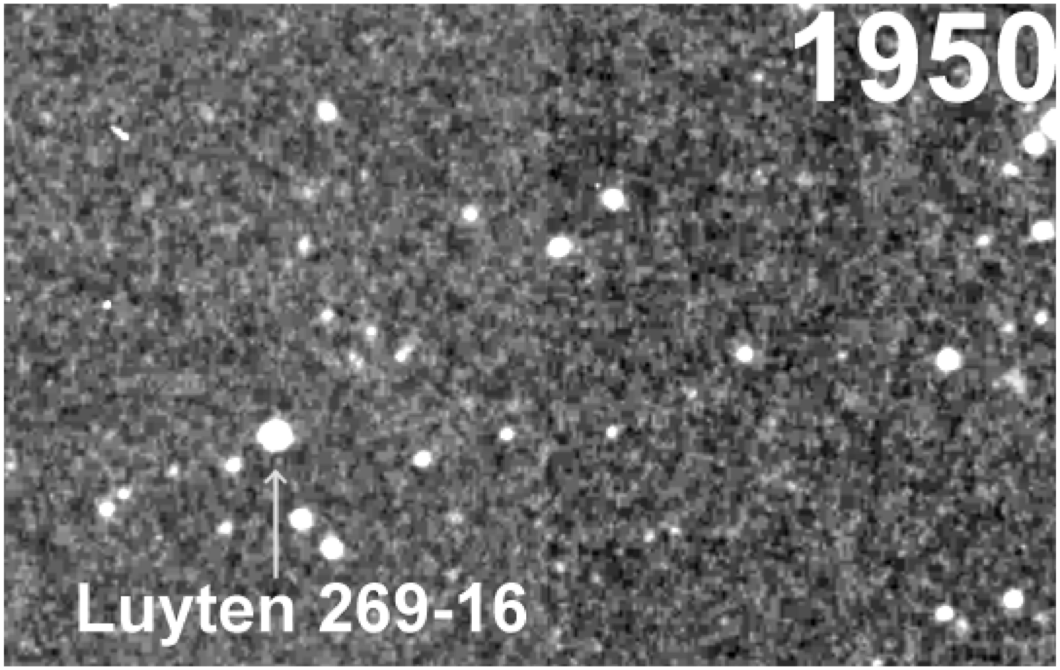
LAMA

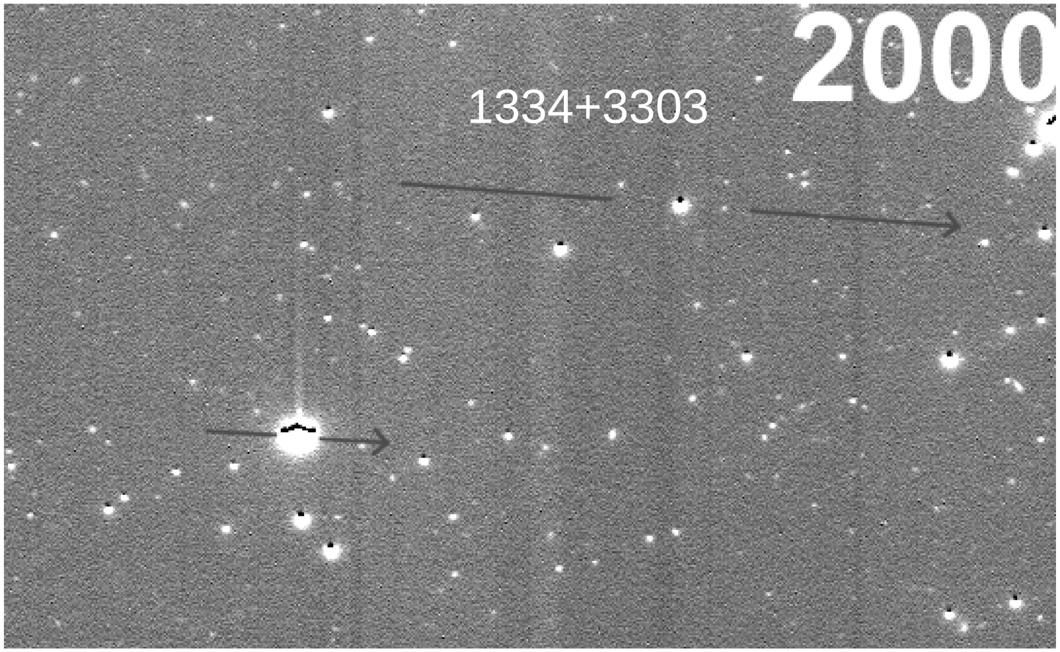
Credit: Remi Cabanac

LMT proper motion survey

- Study local halo-disk populations and search for old halo white dwarfs (dark matter candidate)
- NODO R band blinked against Gen 1 POSS
- 50-year baseline
- 20 sq degrees to 20 mag
- Pm limit ~ 40 mas/yr
- 1104 high-proper-motion stars found (from only 1 night of LMT data)
- BVRI and Multiband data
- 2MASS identifications for 804 stars

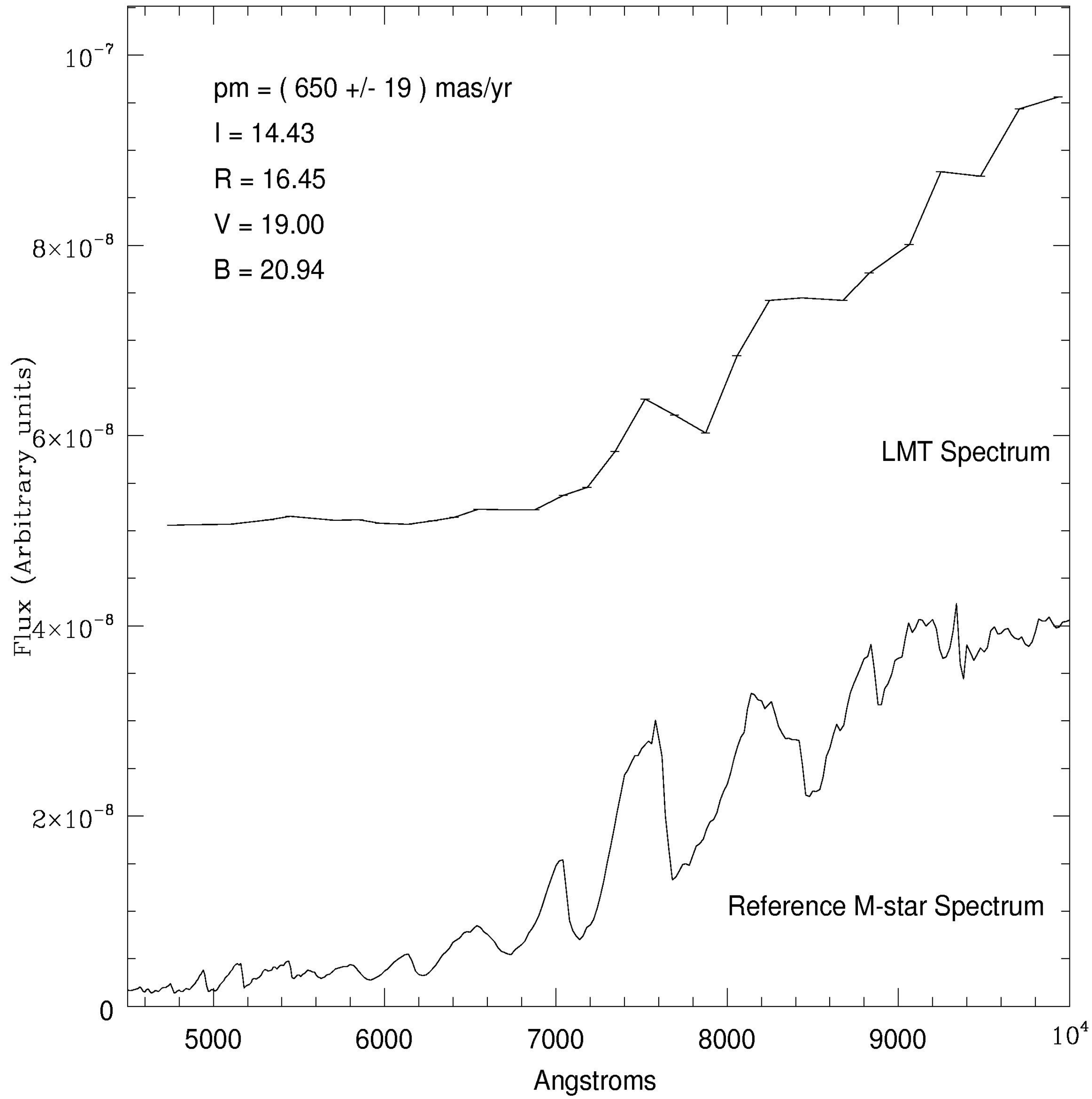
LAMA





1334+3303 photometry and spectral energy distribution

Spectral type
~ M8



LAMA

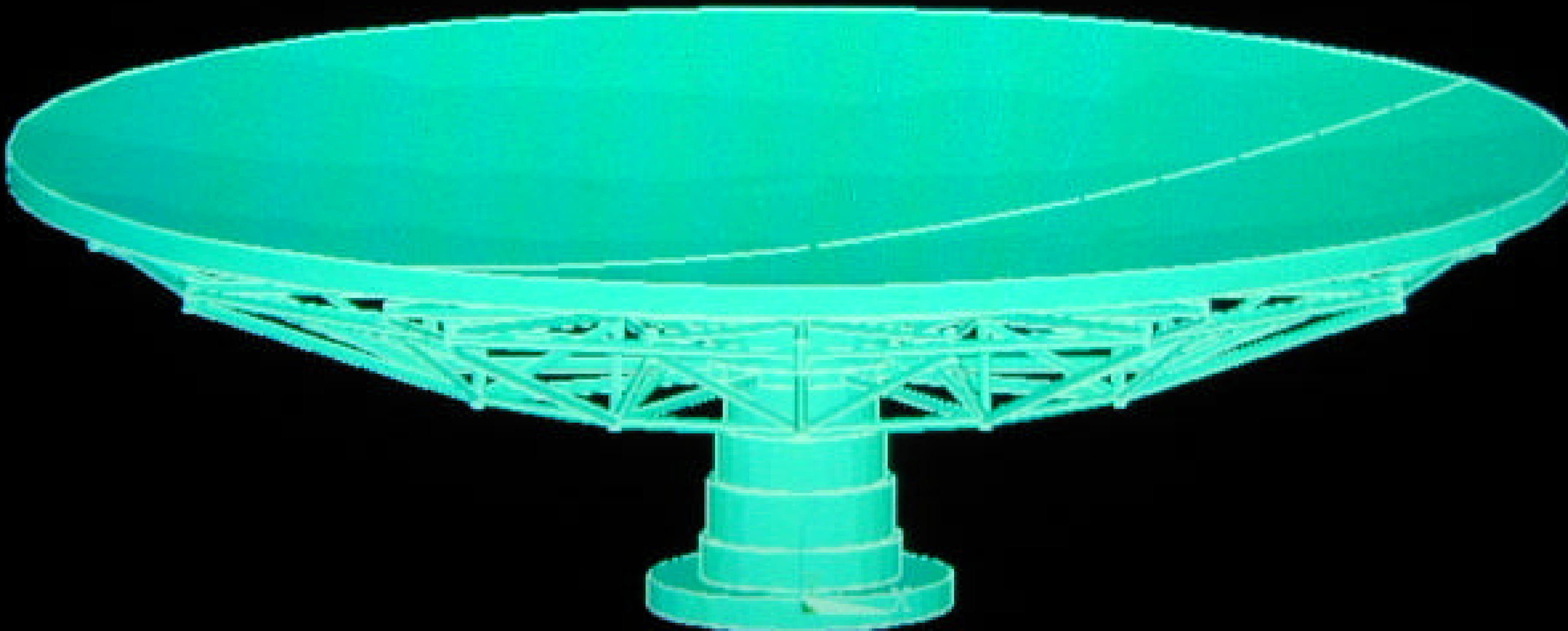
Large Zenith Telescope

- SW British Columbia (Canada)
- 400 m altitude
- 6-m LMT

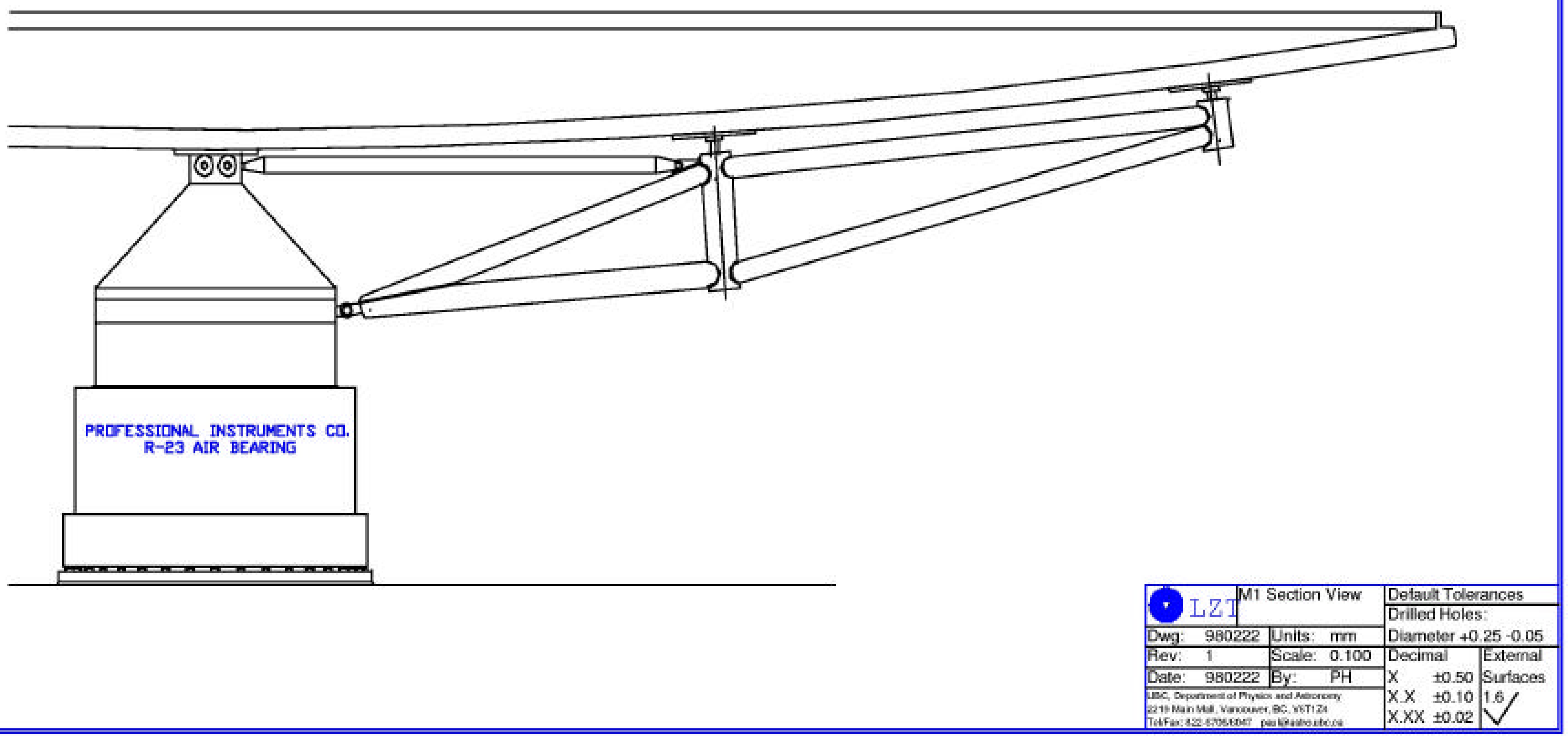
www.astro.ubc.ca/lmt/lzt

LAMA

LZT primary mirror concept

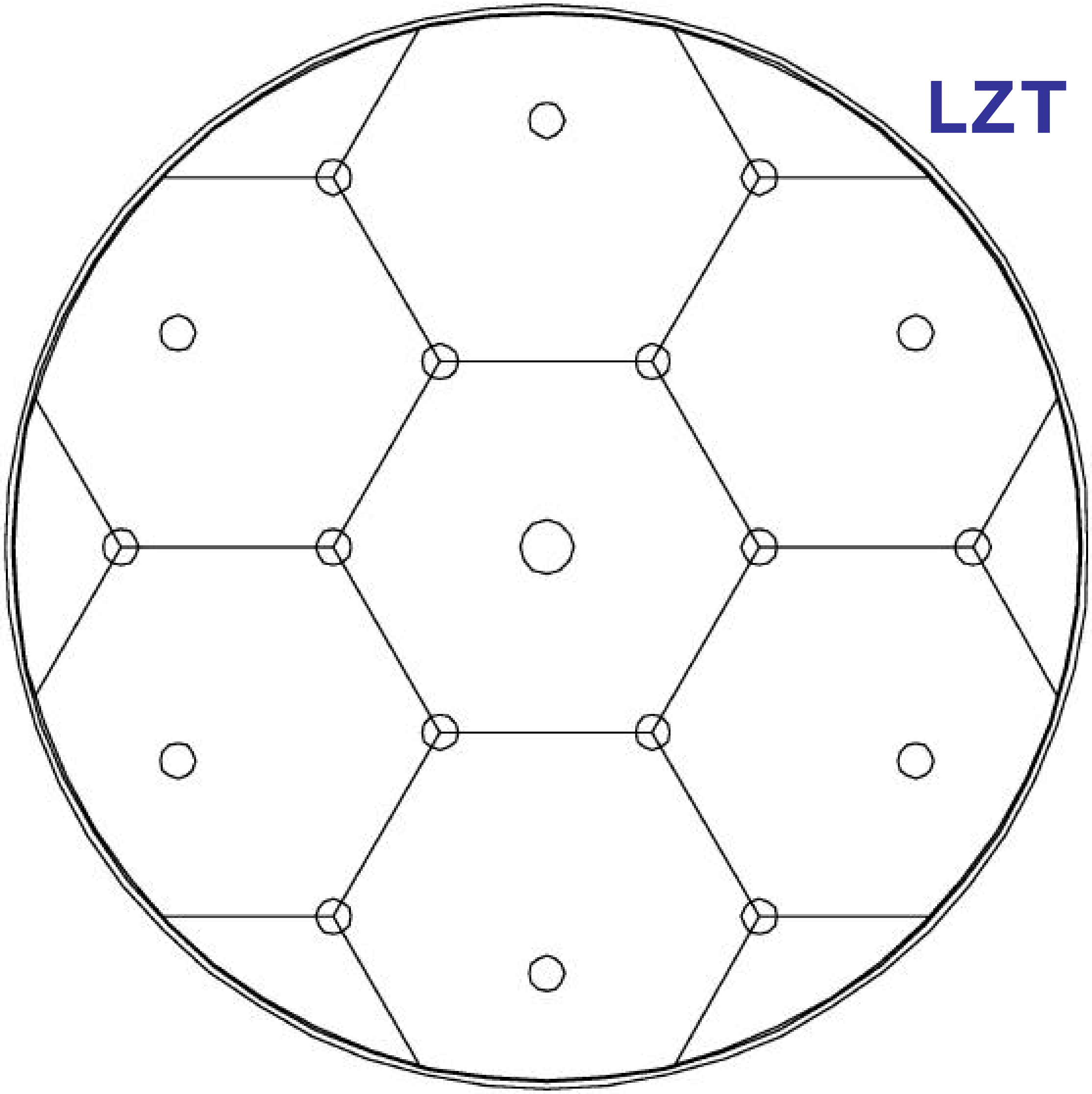


LZT mirror design



LAMA

LZT mirror design



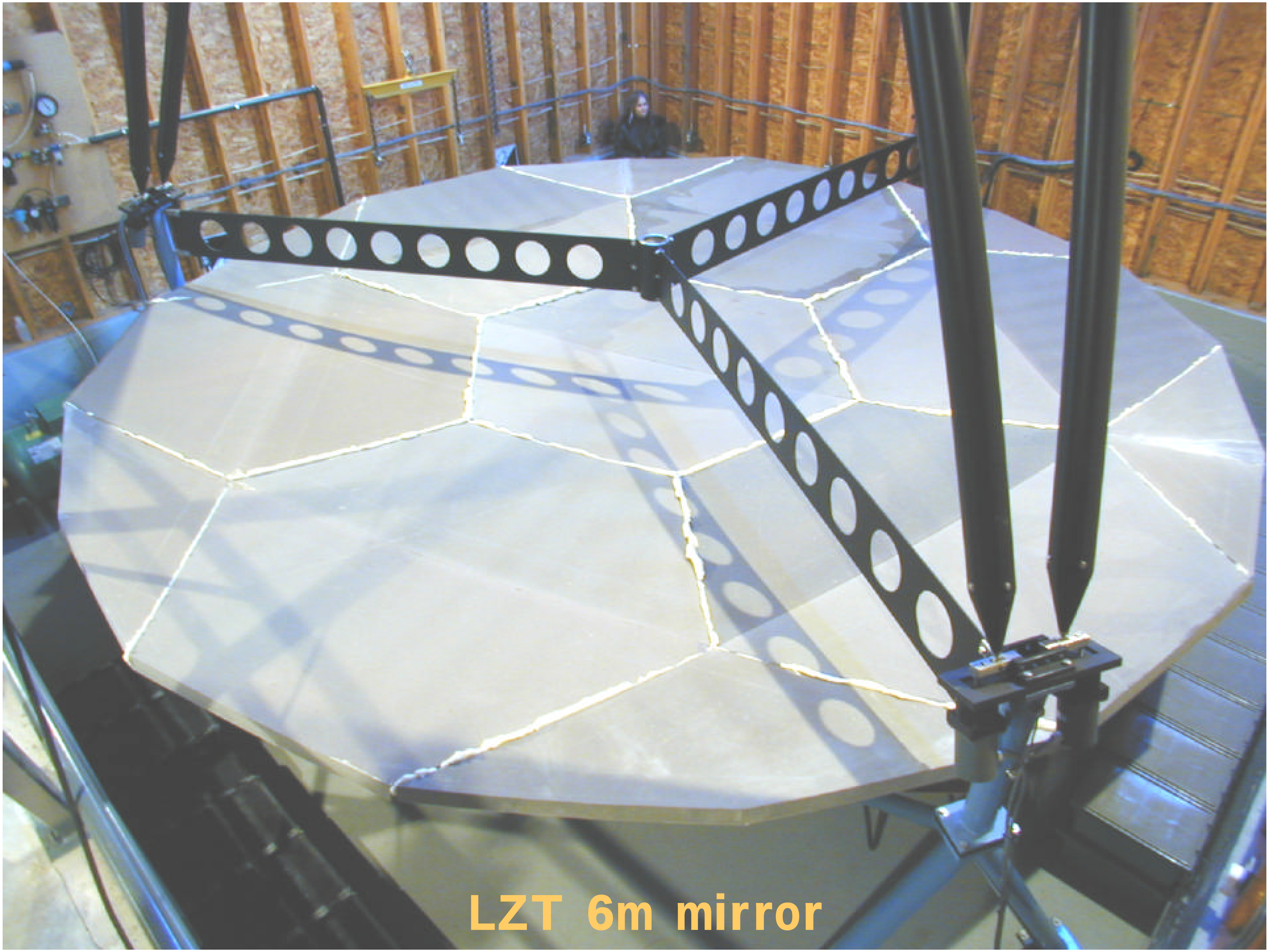
LZT	M1 Hexagon Plan	Default Tolerances	
		Drilled Holes:	
Dwg: 970128	Units: mm	Diameter +0.25 -0.05	
Rev: 1	Scale: 0.040	Decimal	External
Date: 970128	By: PH	X ±0.50	Surfaces
UBC, Department of Physics and Astronomy 2219 Main Mall, Vancouver, BC, V6T1Z4 Tel/Fax: 822-8706/6047 paul@astro.ubc.ca		X.X ±0.10 X.XX ±0.02	1.6 ✓

LAMA

6m Primary Mirror Truss

LAMA

Large Zenith Telescope


LZT 6m mirror

LZT air bearing

- Designed specifically for large LMTs
- 2-year development
- Up to 10m capacity

LAMA

LZT Air System

LAMA

LZT telescope structure

LAMA

LZT enclosure

LAMA

Liquid-Mirror Performance

- Strehl Ratio

  S = central intensity/ideal central intensity

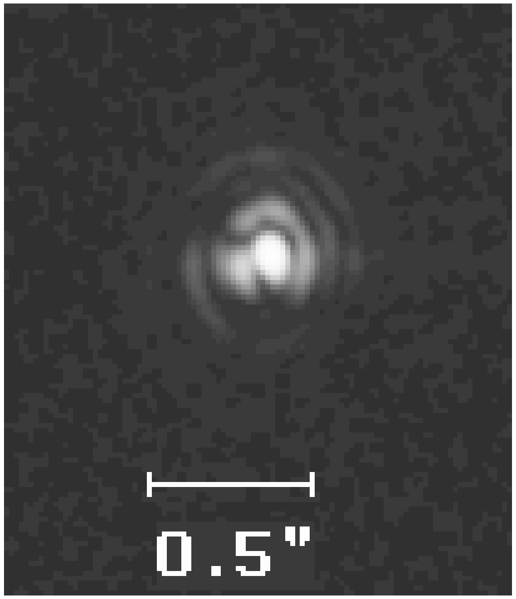
- S = 0.81 measured in lab tests of 2.5m LM

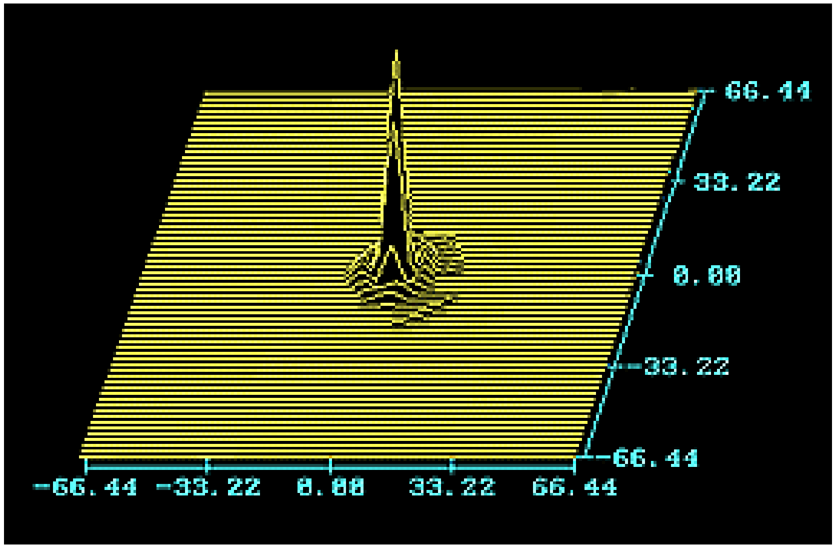
- S ~ 0.5-0.7 estimated for NODO 3m telescope

- $S \sim \exp(-k^2\sigma^2/2)$

  $k = 2\pi/\lambda$

  σ = RMS OPD error

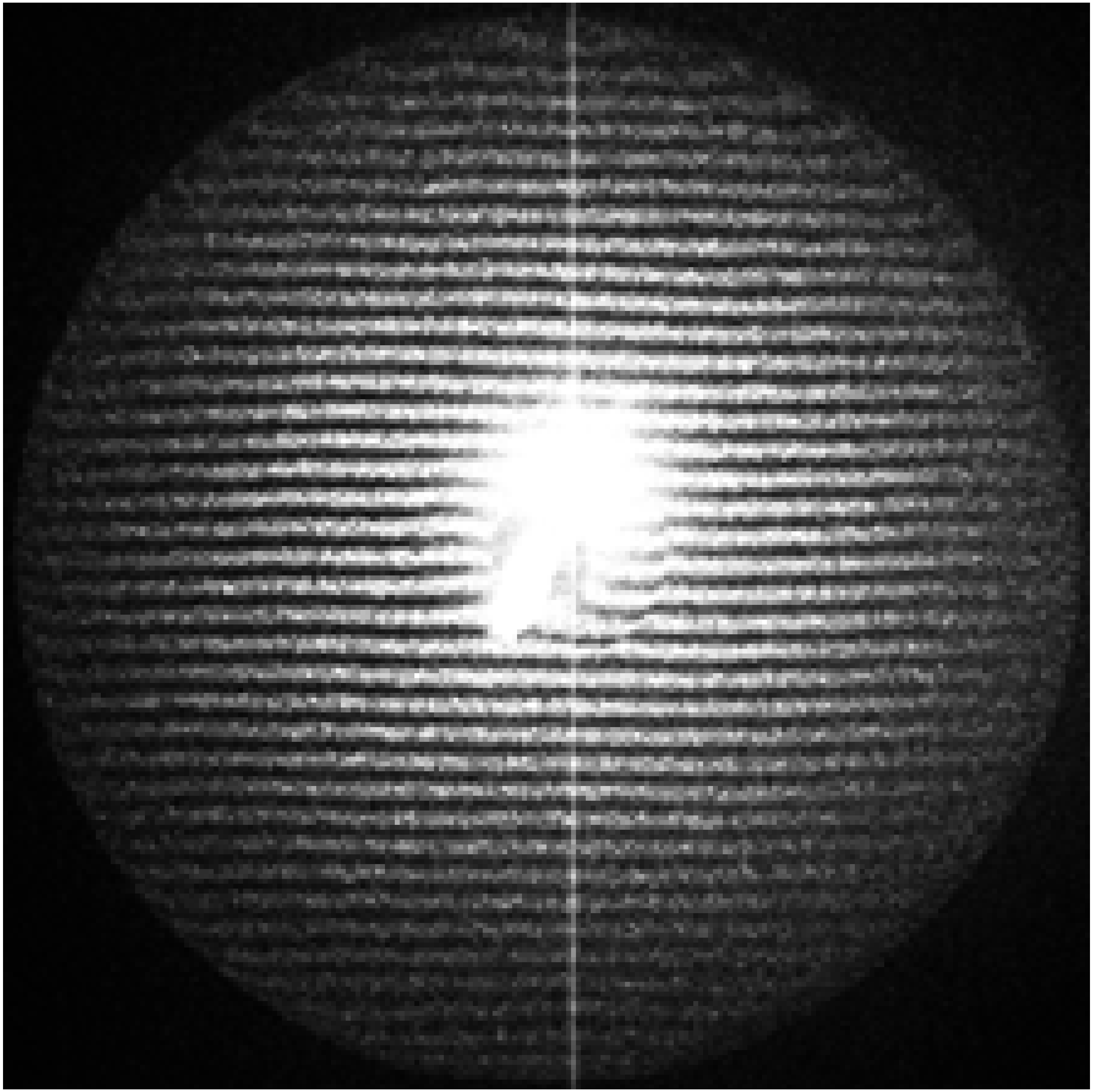




LAMA

Credit: Ermanno Borra

Liquid-Mirror Optical Testing

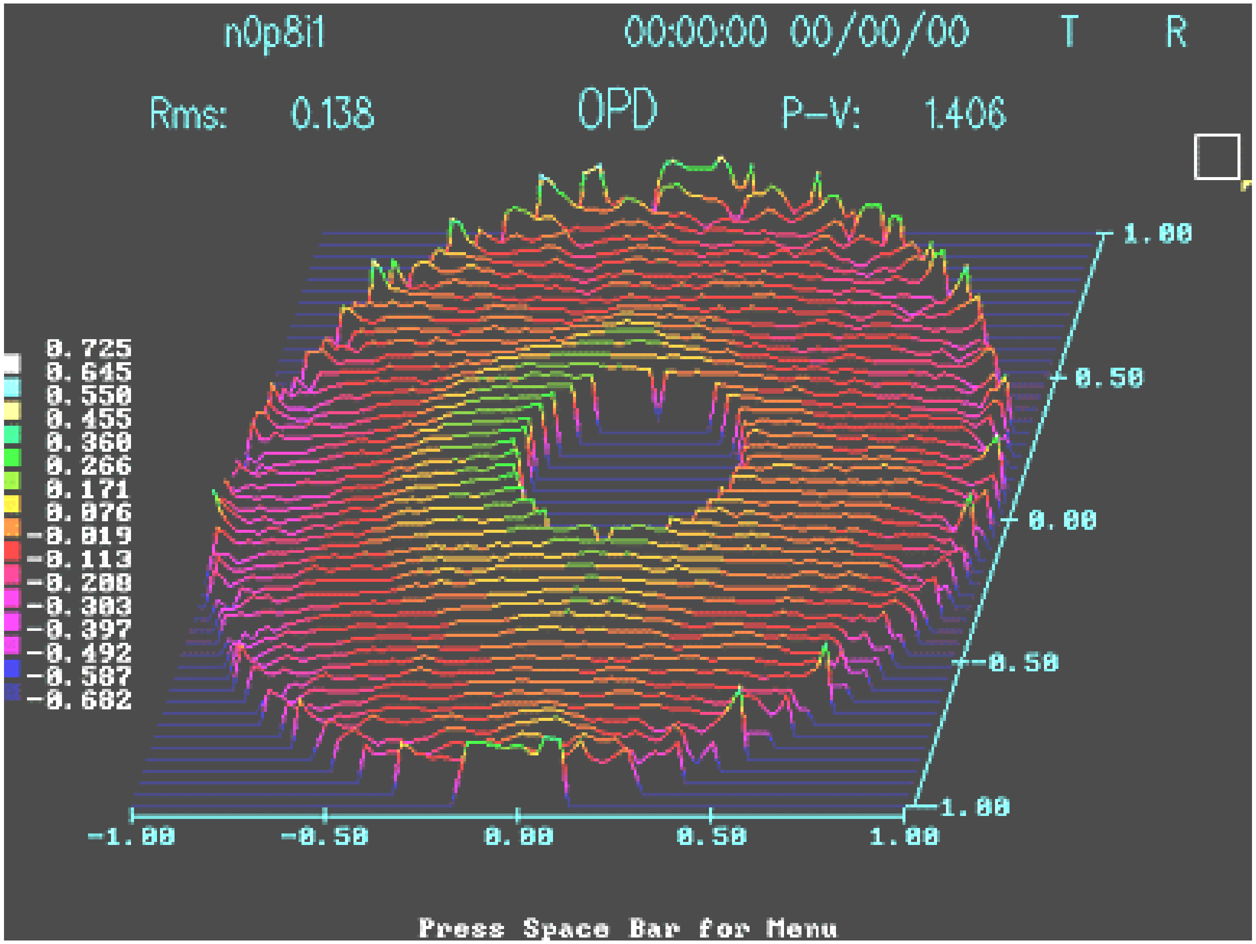


Credit: Ermanno Borra

LAMA

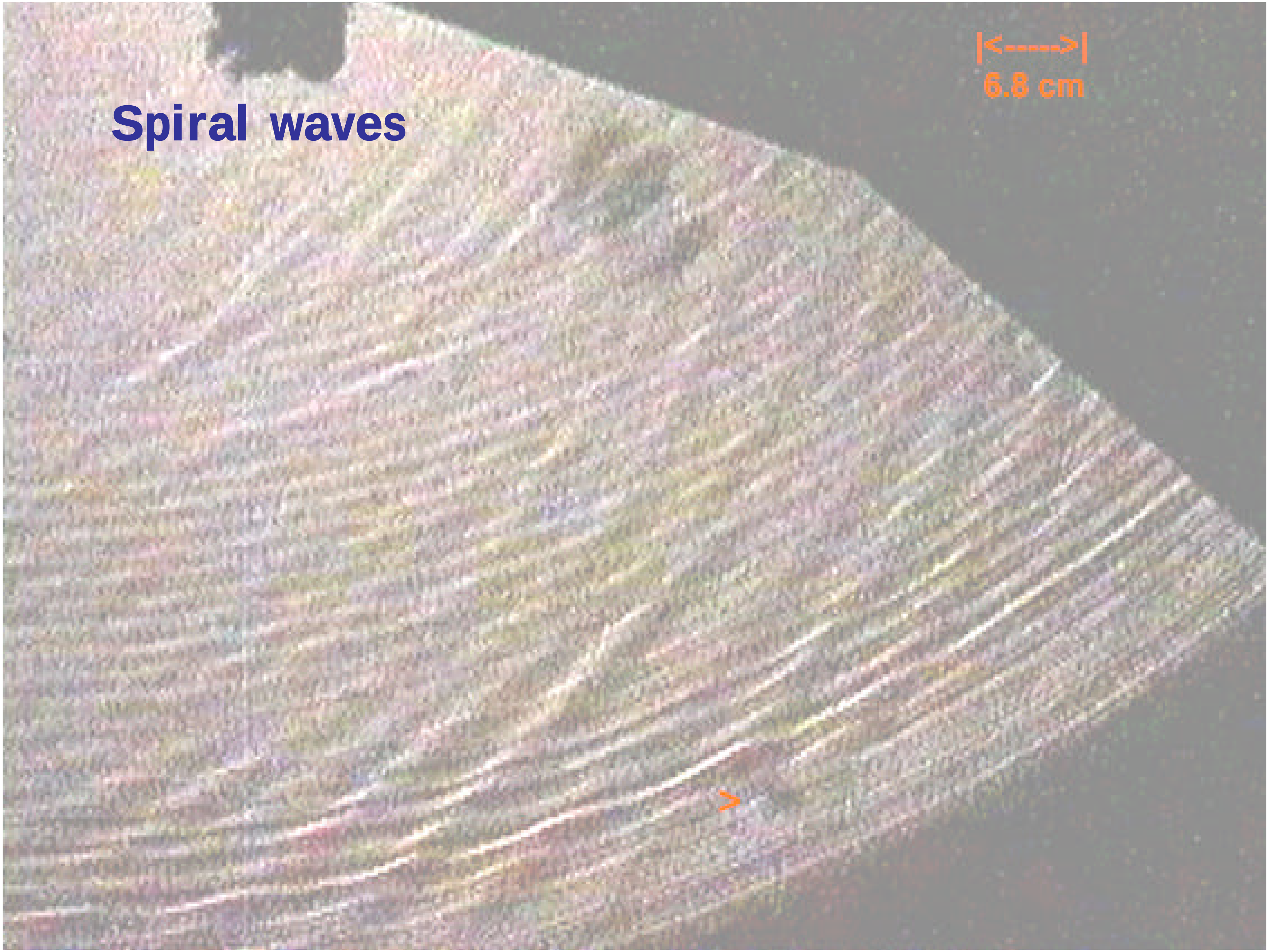
Liquid-Mirror Surface Quality

- 85 nm RMS error
- S = 0.93 at λ = 2 um



Credit: Ermanno Borra

LAMA


Spiral waves
|<------>|
6.8 cm
>

Characterizing Wavefront Structure

- Phase distortion

$$j \equiv \Delta f = \frac{4p}{l}\Delta z$$

- Phase covariance function

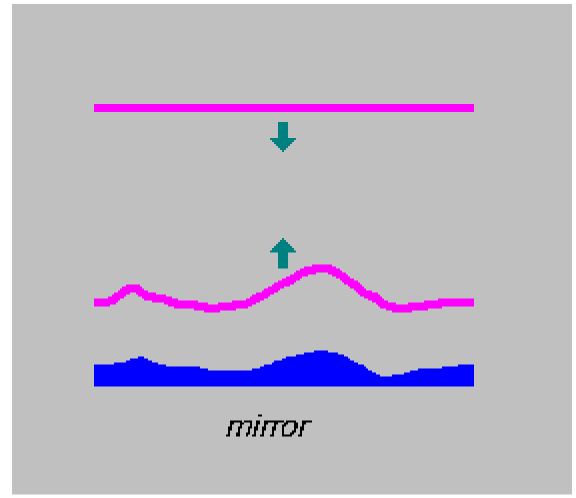
$$B_j(\mathbf{r}) = \langle j(\mathbf{r}')j(\mathbf{r}'+\mathbf{r})\rangle$$

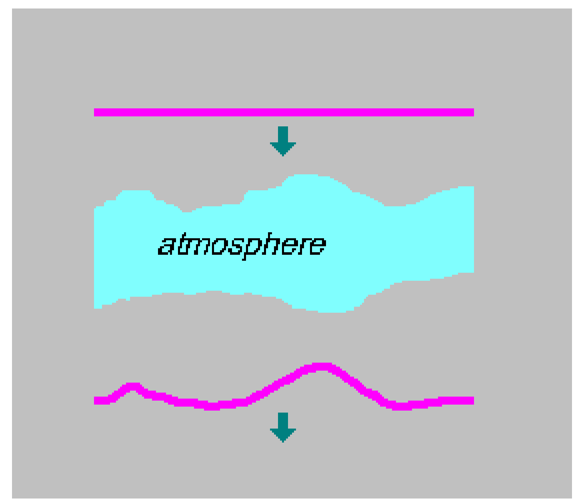
- Phase structure function

$$D_j(\mathbf{r}) = \left\langle \left[j(\mathbf{r}') - j(\mathbf{r}'+\mathbf{r}) \right]^2 \right\rangle$$
$$= 2\left[B(0) - B(\mathbf{r}) \right]$$

- Phase variance

$$s_j^2 \equiv B_j(0) = \langle j(\mathbf{r}')j(\mathbf{r}')\rangle$$





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NODO image analysis

- Measure point spread function (PSF) from star images
- Fourier transform of PSF gives the modulation transfer function (MTF)
- Log of MTF gives the phase structure function

$$D_j(\mathbf{r}) = \left\langle \left[j(\mathbf{r}') - j(\mathbf{r}' + \mathbf{r}) \right]^2 \right\rangle$$

- Subtract atmospheric and diffraction contributions
- This gives the autocorrelation function of mirror surface errors

Characterizing image quality

- Point Spread Function (PSF)

$$r(q) \equiv I(q)/I(0)$$

- Modulation Transfer Function (MTF)

$$t(r) = 2p\int_0^\infty r(q)J_0(2pqr/l)q\,dq$$

- MTF related to structure function

$$t(r) = \exp\left\{-\frac{1}{2}\mathrm{D}(r)\right\}$$

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Atmospheric structure function

- Kolmogorov turbulence

$$D(r) = 6.88\left(r / r_0\right)^{5/3}$$

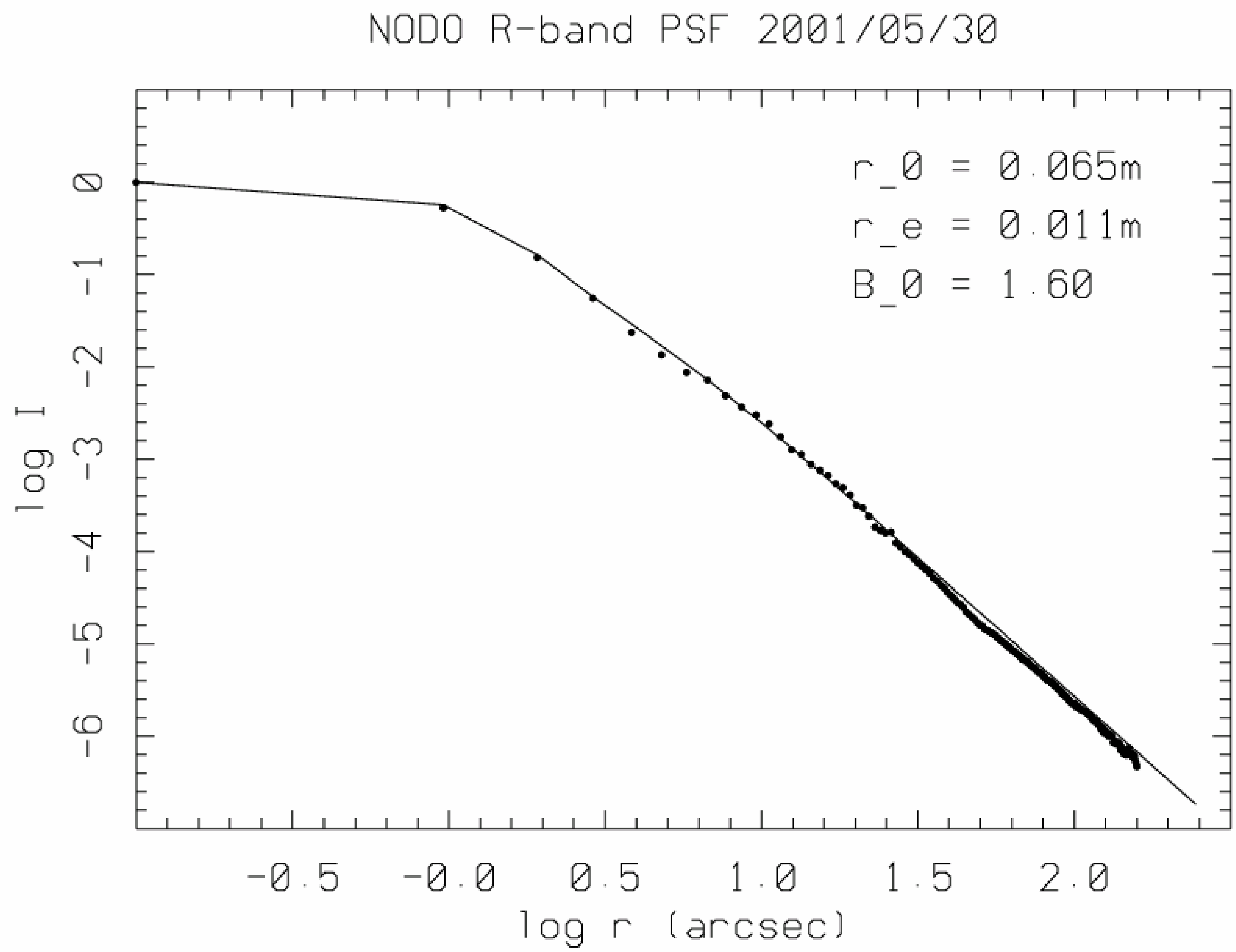
$$r_0 \propto l^{6/5}$$

- Width of PSF core

$$FWHM \equiv 2q_{1/2} \approx l / r_0$$

- Typically, $r_0 \approx 0.1\,\mathrm{m}$ at $l = 0.5\,\mathrm{um}$

NODO PSF



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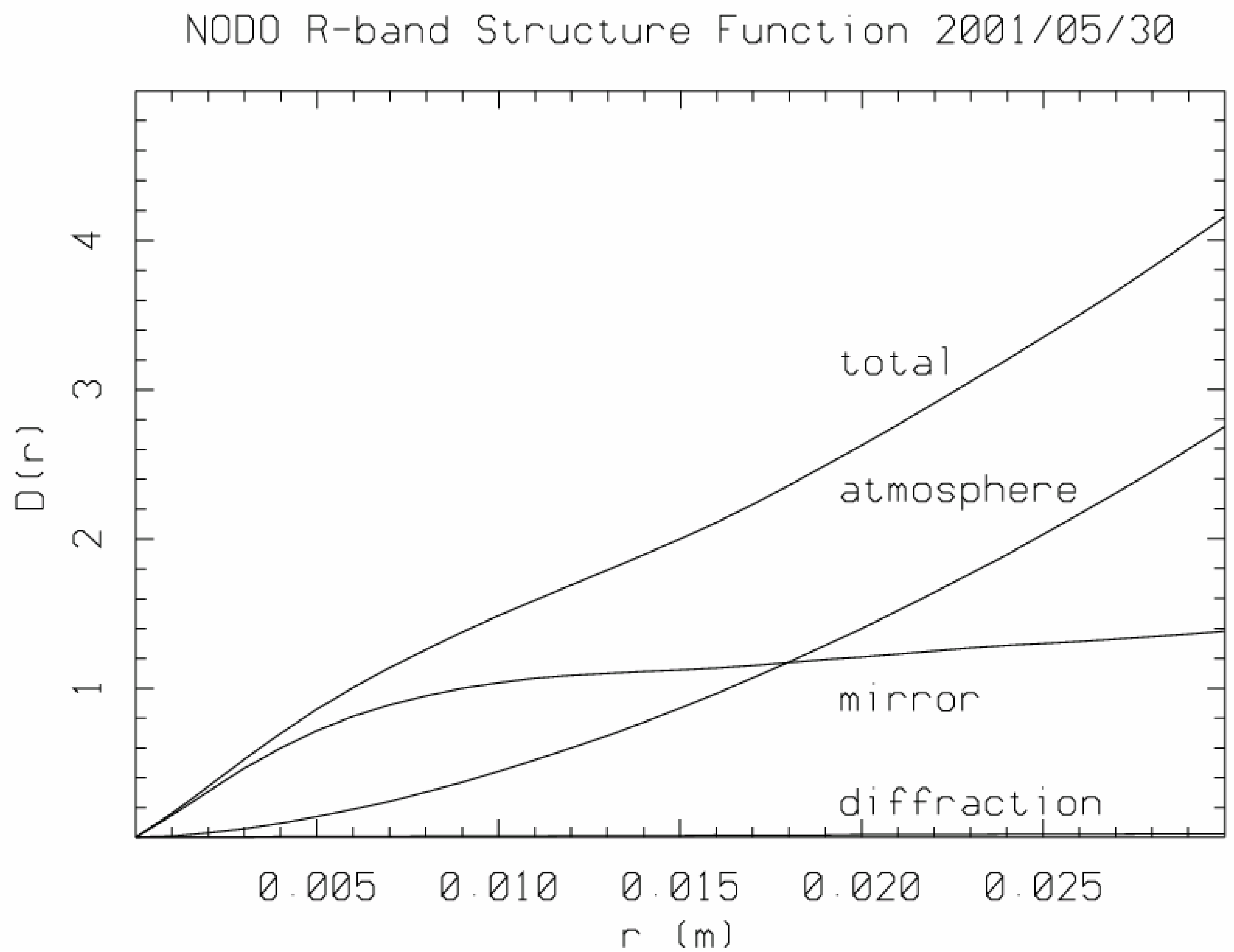
NODO Structure Function



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NODO mirror surface analysis

- RMS wave amplitude:
  46 nm (5 kt wind)
  73 nm (15 kt wind)
- Characteristic scale:
  1.1 cm
- Mercury thickness:
  1.6 mm

Strehl ratio (no atmosphere)

Wavelength (um)	Strehl ratio 5 kts	15 kts
0.50	0.313	0.185
0.65	0.670	0.368
0.85	0.791	0.559
1.00	0.845	0.657
1.25	0.897	0.764
1.60	0.936	0.848
2.00	0.959	0.900

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Primary mirror costs

Approximate costs of possible technologies

Technology	Unit cost ($K\$ /m^2$)	Cost for 1400 m^2
Gemini meniscus mirror	400	560 M$
Segmented mirrors	100	140 M$
Liquid mirrors	5	7 M$

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Summary

- A multi-aperture telescope makes sense
- The technology exists now
- Pointing and tracking are possible with fixed primary mirrors
- Liquid mirrors are a viable alternative to glass mirrors, at about 5% of the cost.

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