“Classical” Interferometric Arrays

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The VLT Interferometer
Optical / Infrared Interferometry

Today

- Access to milliarcsecond-scale phenomena
- Perform interferometric spectroscopy
- Lots of results in stellar astrophysics
- Sensitivity sufficient for a few bright AGN

- Small number of telescopes \( \Rightarrow \) parametric model fits to visibilities, no images
- Sensitivity insufficient for larger samples
- Resolution insufficient for details / more distant objects
Desirable Capabilities of a Next-Generation Interferometer

- Address wide range of scientific topics ⇒ flexibility
- Observe faint objects ⇒ high sensitivity and dynamic range
- Complex objects / limited prior knowledge ⇒ imaging capability
- Access “famous” archetypical and rare objects ⇒ good sky coverage
- Observe time-variable phenomena ⇒ good snap-shot capability
What’s Next?
What’s Next?
Think BIG!
The ELSA Concept – a Strawman Interferometric Facility

- Number of telescopes: 27
- Telescope diameter: 8 m
- Maximum baseline: 10 km
- Wavelength range: 500 nm … 20 µm (?)
- Beam transport: Single-mode fiber bundles
- Beam combination: Michelson
- Sky coverage at 600 nm: ≥ 10%
- Cost: ≈ 400 M€
ELSA Astrometry

- Astrometric error due to Kolmogorov atmosphere scales with $B^{-2/3}$
- ELSA could reach 1 µas over 15" arc
  - Sufficient to detect terrestrial planets around nearby stars
- Even better precision expected due to outer scale of atmospheric turbulence
- Precision requirements less stringent than for Keck / VLTI
ELSA Resolution: 10 \( \mu \)as at 500 nm, 40 \( \mu \)as at 2 \( \mu \)m

- 15,000 km at 10 pc
  - 8 pixels across Jupiter-size object
  - 80 pixels across Solar-type star
- 0.1 AU at 10 kpc
  - GR effects on stars very close to the Galactic Center
- 200 AU (1 light-day) at 20 Mpc
  - Images of AGN Broad-line regions
  - Expansion and light echoes of supernovae
Linear Resolution of ELSA in the Local Universe
Linear Resolution of ELSA at $\lambda = 500$ nm

The graph shows the linear resolution $[10^{17}$ cm] as a function of redshift $z$. The resolution increases with redshift up to a peak and then decreases. The x-axis represents redshift ($z$) ranging from 0 to 6, and the y-axis represents linear resolution in $10^{17}$ cm, ranging from 0 to 3.0.
ELSA Science Case (Galactic)

- Weather on brown dwarfs
- Stellar surface images (spots, flares, convection, differential rotation, oscillations, …)
- Images of interacting and accreting binaries
- Gaps and inner edge of YSO disks, jet formation
- Cores of globular clusters
- AGB stars: dust formation, winds
- Movies of novae
- Gravitational micro-lenses
- General relativity near Galactic Center
ELSA Science Case (Extragalactic)

- Stellar populations in external galaxies
  - Crowding important even on ELT scale
- Expansion and light echoes of supernovae
- Imaging of Active Galactic Nuclei
  - Dynamics of broad line regions
  - Jet formation
  - Black hole masses from stellar orbits
- Resolving gamma-ray afterglows
  - Asymmetries, relativistic beaming
AGN Science with ELSA

- Black-hole mass from stellar and gas dynamics
- Reverberation *mapping* (watch line response to continuum variations in movies) ⇒ physics of BLR, geometric distances
- Optical emission from milliarcsecond jets ⇒ jet collimation, shocks, particle acceleration, …
- Details of clumpy (?) obscuring torus ⇒ dust properties, unification schemes
- “Mirror(s)” in HBLR objects ⇒ AGN physics, unification schemes
ELSA Critical Technologies

- Telescopes
- Array co-phasing
- Beam transport
- Beam combination
- Delay compensation
ELSA Co-Phasing Concept

- Phase individual telescopes with multiple (?) LGS adaptive optics
- Off-axis fringe tracking on “bright” star
- Large aperture $\Rightarrow$ good fringe tracking sensitivity $\Rightarrow$ near-complete sky coverage
- Requirement: fringe tracking at $K \approx 19$
  - One of the drivers for large array elements
- Fringe-tracking chain of neighboring telescopes for bright (resolved) stars
- Fringe tracking between all telescopes for faint (unresolved) stars
Limiting Sensitivity for Fringe Tracking in the R Band
Sky Coverage at NGP for Different Maximum Off-Axis Angles

![Graph showing the relationship between telescope diameter and sky coverage for different off-axis angles (15°, 30°, 60°).]
Array Layout Optimized for Baseline Bootstrapping
A Y-Shaped Configuration
(15 Telescopes)
ELSA Telescopes

- Need to produce twenty-seven 8m telescopes for \( \approx 200 \text{ M€} \)
- Moveable for array reconfiguration if possible
- Small field-of-view
- No scientific instruments (acquisition and fiber-feeds only)
- Take advantage of ELT development
  - Mass production of mirror segments
  - Standardized structural elements
Projected Cost of Telescopes

- Typical scaling of telescope cost with diameter is $\mathcal{E} \propto D^{2.7}$
- Scaling applies at any given time (for similar maturity of technology), not to future projection
- Example: scaling holds for Keck (10m) versus CHARA (1m) telescopes
- Apply scaling to ELT (e.g., European E-ELT concept): 42m for 700 M€ $\Rightarrow$ 8m for 8 M€
- Proof-of-concept for ELT?
Moving Big Telescopes around …
... is Perfectly Doable!
ELSA Beam Transport

- Fibers are much cheaper than beam tunnels
  - Diffraction + field \( \Rightarrow D_{\text{opt}} = k \times \sqrt{\lambda L} + m \theta L \)
- Need advances in fiber technology
  - No significant light loss over 10 km
  - Low dispersion, polarization preserving
  - Fibers for infrared wavelength range
- Need metrology to monitor fiber lengths
- Fiber bundles can handle field-of-view larger than Airy disk
ELSA Delay Compensation

- Switch between fiber segments for bulk delay compensation
  - Add appropriate fibers from set of (1m, 2m, 4m, …)
  - Dispersion is a potential show-stopper
  - Need low-loss fiber-fiber couplers

- Fiber stretching for fine adjustment (sidereal rate plus atmosphere)
  - Fall-back is short classical delay line
ELSA Beam Combination

- Very diluted ($B / D \approx 1,000$) for longest baselines \implies pupil plane combination preferred
  - Field-of-view radius is $R = \lambda / \Delta\lambda$ resolution elements
- Larger field-of-view desired for more compact configurations
  - Homothetic mapping (exact or densified replica of entrance pupil) to be explored
ELSA Site

- Need flat $\approx 10$ km plateau
- Good seeing $(r_0, \tau_0, \theta_0)$ important criterion
- Southern hemisphere preferred
- Requirements different from ELT criteria
- ALMA site probably (marginally) ok
Exceptional Astronomical Seeing at Dome C in Antarctica (?)
Potential Advantages of Dome C

- Larger $r_0 \Rightarrow$ simpler adaptive optics
- Longer $\tau_0 \Rightarrow$ better sensitivity
- Larger $\theta_0 \Rightarrow$ better sky coverage
- Lower temperature $\Rightarrow$ lower IR background
- Or same performance with smaller telescopes
  - 2m at Dome C $\Leftrightarrow$ 8m at traditional sites?
VLTI, ALMA, ELTs, and ELSA

- ELSA has 50 times better resolution than any other facility ⇒ completely new science
- ELSA draws on VLTI / ALMA / ELT heritage
  - VLTI: Interferometric techniques, beam combination, …
  - ALMA: Moveable telescopes, site (?)
  - ELTs: Cheap telescopes through mass production of optics and standardized structural elements
- ELSA could be feasible and affordable in 2015
Conclusions (1): What we Know Already

- There is a large parameter space of first-class science beyond the ELT resolution limit
- Baseline length of $\approx 10$ km required
- Large telescopes or superb site (Antarctica?) needed to get sensitivity and good sky coverage
- A powerful facility could become feasible and affordable in a decade
Conclusions (2): What we Don’t Know Yet

- Can fibers be used for beam transport and delay compensation?
- Which site offers the best trade-off between quality and cost?
- Is the science case powerful enough to make it happen?
Key Technology Needs for Roadmap

- Beam transport with optical fibers
  - Dispersion is a potential show stopper
  - Cost driver ⇒ top priority on my list
- Beam combination concepts and integrated optics beam combiners
- Telescopes
  - Main issue is cost ⇒ link to ELT projects
- Site
  - Evaluate Antarctica
  - Look for good “traditional” sites