Can laser beacons be used as guide stars?

Erez Ribak
Department of Physics
Technion – Israel Institute of Technology
Haifa, Israel

Ringberg meeting
October 2007
LIDARs as LGSs

- The first laser guide stars were developed by experts in probing the atmosphere.
- The main probe tool is the LIDAR, and was developed during decades of research.
- Thus the standard beacons for adaptive optics all have a laser (tuned to the right wave length) and a detector to locate the beam.
- When telescopes grow, and outgrow this technology, other solutions might be required.
- Typical complaints:
  - Beam return too weak
  - Spot elongation
  - Detectors and their optics are complex
Some solutions

- Beam gating to exclude low scattering
- Special detectors to reduce spot elongation effects
  - Rotated CCDs
  - Cylindrical lenses
  - Double measure cross beams
  - Software
- Special optics
  - PIGS
  - Spot follow-up in hardware (fast refocus)

Suggestion:

move the complex optics from the receiver to the transmitter
What we want

- Many beacons (for MCAO)
- No spot elongation
- High efficiency
  - Minimal gating
  - Proper pulse shape, polarisation, frequency
- No Rayleigh backscatter below beacons
- Minimal interference with dome/telescope
Previously

- Effort at transmitter
  - Considerable work on laser conditioning
  - New lasers tested

- Effort at transmitting optics (mainly on paper)
  - Laser fringes on sky
  - Radio fringes on sky (well, not your usual optics…)
  - Use full aperture to project, and sky return as screen
Why does the focus last for 10 km?

- Answer: leftover from LIDAR time (true, also easier to send up)
- Why not borrow from microscopy?
- When the focus is too long, depth resolution is lost
- Shortening the focal spot has been the main theme for decades now
- But not all solutions are transferable, especially those blocking light
- Concentrate on three subjects:
  - Apodisation for focus reduction
  - Side-illuminating microscopy
  - Femtosecond pulse tailoring
Probing the pixels

- We needed to map the inter-pixel responsivity of a new IR detector under production
- The white-light PSF was as wide as the pixels
- We added phase rings inside the aperture
- The diameter and width of the rings was optimised to reduce the central lobe and push out the side lobes
Apodisation

- First ever in hardware

ZnSe *phase* mask

Theory: 75% width  
Experiment: 80% width
Axial optimisation

- Start with the diffraction integral in the Fresnel approximation

\[
\Psi(z) = \frac{2\pi \exp(i k z)}{i k z} \int_0^\infty \exp[i \Phi(r)] \exp \left[ -i \pi \left( \frac{1}{f} - \frac{1}{z} \right) r^2 \right] r \, dr
\]

- Define \( \delta \mu = \mu - \mu_0 = R^2 / 2\lambda z - R^2 / 2\lambda f \), perform Fourier transform

\[
\Psi(\delta \mu) = \sum_{j=1}^{N} \exp(i \phi_j) \exp \left[ -i \pi \left( \alpha_j^2 + \alpha_{j-1}^2 \right) \delta \mu \right] \left( \alpha_j^2 + \alpha_{j-1}^2 \right) \text{sinc} \left( \alpha_j^2 + \alpha_{j-1}^2 \right) \delta m
\]

- \( \{\alpha\} \) are the annuli boundaries and \( \varphi \) the phases (not just \( \pi/2 \))

- Shift \( \alpha, \varphi \) to get shortest spot by optimisation

Sales and Morris, Optics Communications 156, 227-30, 1998
Focus depth

*Phase mask for confocal microscopy*

Simulation: Martínez-Corral, Caballero, Stelzer, Swoger, *Optics Express* 10, 98-103, 2002
LGS options

1. Remove bottom Rayleigh scatter
   Destructive interference up to beacon height
2. Create short spot
   Destructive interference above/below beacon centre
3. Create many spots
   Destructive interference within beacon
4. Combination of items above
Application of Toraldo filters

- Relevant both for Na and Raleigh beacons
- Efficient
  - Examples were for white light, with few percent loss
  - For laser light, even higher efficiency
  - Using phase masks, no light is lost
- Low sensitivity to turbulence
  - Interfering beams share path to sky
- Reduces need for height gating
- Improves resolution along beam
  - Require a different correlation mask for each Hartmann focus
- For multiple beams: no Venetian blind from Rayleigh scatter
**Spot striping**

- The effect can occur naturally when the Na layer is non-uniform
- Requires more CCD pixels for each spot
- Requires pre-calculated filter to match zebra stripes
- Careful: filter averages over turbulence
- Matched filter can be in hardware:

![Diagram](image)

- Erez Ribak
Long beacons

- This opens a new option:
  - Distant laser projection
  - Each zebra stripe is imaged through a different atmospheric path
  - Independent movement of each stripe
- Provides more tomographic information
- Low sensitivity to low-atmosphere scatter
- Also valid for Rayleigh beacon
- Similar to side-illumination microscopy
Zebra beacons

- Geometry
  - project the striped beacons from afar
  - Use the stripes for better sky coverage
  - Design to avoid overlap (Venetian blind)

- Possible limitations
  - Na inhomogeneity
  - Na height variability
  - Global tilt error (but see Ragazzoni 1998, Serezhkin and Yakovlev 2000)

Hartmann pattern from three striped beacons
Simulation

- Tested in Matlab:
  - 36 m telescope
  - 45 m Na patch (for MCAO)
  - 3 beacons, 500 m away
  - 10 km sodium layer
Simulation (2)

- Aperture divided into 50 cm lenslets
- Each lenslet images the 45 m pattern
Simulation (3)

- Showing Hartmann-Shack detail
- Notice rotation of pattern to avoid overlap between lenslets
- For matched filter or Fourier analysis, this overlap is permitted
- For pure centroiding, beams need to be tighter (closer projectors)
A similar effect can be produced by a pulsed laser
In oblique illumination, the pulses follow each other in space and time
With a synchronised shutter, the pulses seem to freeze
This is a stroboscopic measurement
For Rayleigh beacons:
  - CW laser
  - Rotating polarization
  - Polarising beam splitter after the lenslets
Moves some of the burden back to the telescope
  - Shutter (Na) / + analyser (Rayleigh)
  - Large camera (common to all MCAO designs)
  - Software
Pulse length

- Start with a horizontal beam, with $P = 3\text{m}$ cycle
- Shutter speed: $t = \frac{P}{c} = \frac{3\text{m}}{300,000,000\text{m/s}} = 10\text{ns}$
- Many pulses during wave front sensor integration time
**True pulse length**

- Slanted beam, $P = 500\text{m}$ cycle
- Observed obliquely, this is equivalent to $P = 3\text{m}$
- $t = \frac{P}{c} = \frac{500\text{m}}{300,000,000\text{m/s}} = 1.7\mu\text{s}$
- Other rates and duty cycles are possible
- Fast wave front camera can serve as shutter

---

Erez Ribak, Ringberg 2007
Shorter pulses

- Technology used with femtosecond lasers and *two-photon microscopy*
- Oron, Tal, Silberberg, *Optics Express* **13**, 1468-76, 2005
- Useful for non-linear laser guide star
  - Pulse is only visible when energy is high

![Diagram of pulse train and blazed grating]

- Pulse train or beam scan from laser
- Blazed grating
- Projection optics
- Pulses focus from top to bottom
- Pulse train to sky
Tilted pulses

- The blazed grating is *imaged* onto the sky
- The images are also tilted
- The pulse looks narrower at oblique observation
- Changes duty cycle of observed pulses
  - (Inverse PIGS?)

---

e-rez Ribak, Ringberg 2007
Summary

- Microscopy is relevant to astronomy
  - Toraldo apodisation
    - reduce Rayleigh scatter
    - shorten beacon length
    - modulate beacon intensity
  - Side-illumination
    - create, on purpose, elongated beacon
    - train of pulses serves as multiple beacons
    - improve tomographic coverage
  - Pulse-narrowing
    - each pulse in train looks more compact

Spot elongation may be good for you!