Terrestrial combination of multiple sodium guidestar laser beams for increased on-sky brightness
AO4ELT5, 2017-06-29

Robert Johnson, Miles Buckman, Jack Drummond, Mark Eickhoff, Robert Fugate, Shawn Hackett, Lee Kann, Odell Reynolds, Jeff Richey, Keith Wyman
Acknowledgements

- Domenico Bonaccini Calia, European Southern Observatory
- Toptica Photonics, Germany
- Ronald Holzlöhner, European Southern Observatory
- Simon Rochester, Rochester Scientific
Outline

- Background & motivation
- Combining two lasers on the telescope
- Sky data
- Discussion & Conclusions
- Example of recent science with asteroids
• Want to pump between:
  F=2, m=±2
  F=3, m=±3
• Higher cross section
• Enhanced backscatter
  ⇒ Circular polarization
  (Kibblewhite, 12009, AMOS)

(Adapted from Ungar, et al., 1989, JOSA B)
Factors which influence return flux

- Sodium column abundance and altitude
  - Month of year, hour of day, latitude
- Strength and angle of Earth’s magnetic field
  - Elevation, azimuth, latitude, longitude
- Laser parameters
  - Power, polarization, re-pumping (D2b), bandwidth
  - Continuous-wave or pulsed
  - Size of beacon in the mesosphere
- Atmospheric transmission
5 Generations of Sodium Lasers at Starfire Optical Range

- Gen 1 & 2 prototypes for solid state, sum frequency
- Gen 3 used for laser beacon AO for 8 years
- Gen 3+ proof-of-concept for D2b re-pump, 2× increase
- Gen 4 more reliable, shown to be inefficient
- Gen 5 very reliable, good performance 25% of year

Return flux based on sodium column density of 4.2×10^{13} atoms/m^{2} (minimum for Oct–Dec)

Modeled return flux using LGSBloch (Ronald Holzlöhner and Simon Rochester)
Modeling Return Flux

Sodium column density \((10^{13} \text{ atoms/m}^2)\)

Return flux \((10^6 \text{ photons/m}^2/\text{s})\)

**SOR latitude → 35 degrees**

Minimum Oct–Dec → \(4.2 \times 10^{13} \text{ atoms/m}^2\)

(Adapted from J. Plane, 2010, Atmos. Chem. Phys)

Required flux (outside the circle exceeds the required flux)

45° elevation
60° elevation

Modeled return flux with 2 Toptica lasers
(Ronald Holzlöhner and Simon Rochester)
Two Toptica Laser Heads Mounted on 3.5-m Telescope

Photos by RQ Fugate
Optical Setup

Output is two superimposed beams
One left-hand circular and one right-hand circular

Beam expanders

Spectrum analyzer
Photodiode
Monitor for alignment

Output is two superimposed beams
One left-hand circular and one right-hand circular
Measure of Laser Frequency Separation and Bandwidth

- Beat frequency \(\Rightarrow\) separation in MHz
- FWHM of beat = 6.8 MHz \(\Rightarrow\)
- FWHM single laser = 4.8 MHz

**Graph**

- Signal (dBmW) on the y-axis
- Frequency (MHz) on the x-axis
- Peak at approximately 50 MHz
- FWHM of the beat is 6.8 MHz
- FWHM of the single laser is 4.8 MHz
On-sky Data

Photo by RQ Fugate
Rayleigh Scattering and Beacon

Photos by RQ Fugate
Scan to Calibrate Wave-meters

Laser T1

Peak = 1036.8 ± 9.8
\(\lambda_0 = 589.158996 \pm 0.000006\)
FWHM = 0.001164 ± 0.000025

Laser T2

Peak = 1073.0 ± 4.8
\(\lambda_0 = 589.159026 \pm 0.000003\)
FWHM = 0.001272 ± 0.000015
Single Toptica Laser 2017-06-14
Wavelength Scan, 19 W, 10% Repump
Circular, with repump
Circular, without repump
Linear, with repump
Linear, without repump
Two Toptica Lasers 2016-06-17
Power Scan at 100 MHz Offset

Increase T1&T2 power together

Hold T1 power constant
Increase T2 power

Hold T2 power constant
Increase T1 power
Two Toptica Lasers, Offset Scans

Change the wavelength of each laser and measure return flux
Two Toptica Lasers 2016-06-17
Offset Scan, 10% Repump, Redshift T1

Offset both lasers
Offset only one laser

60 MHz

Return flux (photons/s/cm²) vs. Offset (MHz)
Two Toptica Lasers 2016-06-17
Offset Scan, 10% Repump, Redshift T2

Return flux (photons/s/cm²)

60 MHz
Offset both lasers
Offset only one laser

Offset (MHz)
Offset Scan, 39.1 W, 10% Repump, Redshift T2

Return flux (photons/s/cm$^2$)

Offset (MHz)

94 MHz
Two Toptica Lasers 2017-06-16
Offset Scan, 39.1 W, 10% Repump, Redshift T2

- Peak possibly due to increased sodium density
- 5.8–6.6 UT Measured beat frequency each time
- 6.6–6.9 UT Did not measure beat frequency each time
- 60 MHz
- 94 MHz

Return flux (photons/s/cm²) vs. Offset (MHz)
Competitive Downpumping

(Adapted from Ungar, et al., 1989, JOSA B)
Conclusions

- Increased return flux by $1.6 \times$ versus a single Toptica laser
- Complicated interaction between two polarizations
  - Results of wavelength offset scans varies from night to night
  - Peak flux usually ~ 200 MHz offset
  - Features at 60 MHz and 94 MHz offset (credit to R. Holzlöhner)
  - Likely due to competitive down-pumping
  - Would like to collaborate with others to model this behavior
- Perhaps slewing the beacon could further improve return flux
  - Plan to conduct scans while slewing this fall
- Plan also to measure bandwidth of individual lasers
  - Using a ~100 kHz bandwidth low-power laser from Toptica
Asteroid (22) Kalliope & Moon Linus

- Observations made over 4 months: 2016-11-07 to 2017-02-10
- Sodium LGS 40 W with re-pumping (4 W into D₂b)
- Kalliope $V = 10.9$
- Kalliope–Linus $\Delta J = 2.7$ to 3.5
- Separation = 0.2 arc-sec to 0.8 arc-sec

Images by J. Drummond
Two Toptica Lasers 2016-06-17
Offset Scan, No Repump

![Graph showing offset scan results with different waveplates.]
Two Toptica Lasers 2016-06-22
Offset Scan, No Repump
Two Toptica Lasers 2016-06-22
Offset Scan, 10% Repump
Two Toptica Lasers 2016-07-12
Offset Scans
Two Toptica Lasers 2016-07-13
Power Scan, Offset 200 MHz, Redshift T2
Two Toptica Lasers 2016-07-13
Offset Scans, Az = 0, El = 70
Two Toptica Lasers 2016-07-14
Offset Scans, Az = 0, El = 70
Two Toptica Lasers 2016-07-14
Offset Scans, Az = 180, El = 70
Half are opposite handedness circular

4.0-6.1 UT
8.2-9.0 UT