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Dueling lasers! A comparative analysis of two different sodium laser technologies on sky

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ABSTRACT

Sodium guide star technologies for Adaptive Optics (AO) have been around for over 20 years. During this time, the technologies for the lasers used to excite the mesospheric sodium have been in constant development, with the goals being not only to excite as much sodium as possible, but to do so efficiently, while producing a round guide star, and while offering a reliable facility. The first lasers in use were dye lasers with a liquid gain medium, while these lasers were able to produce sodium guide stars, the liquid dye used was toxic and flammable. The second generation of guide star lasers used sum-frequency-mixed solid-state lasers. These lasers provided excellent return but were notoriously difficult to calibrate and maintain, requiring a full-time laser engineer on staff. The current third generation of sodium guide star lasers use Raman fiber amplification to generate a laser that is very efficient at exciting sodium with a good spot profile and offer a high degree of reliability. The Gemini South observatory for the last few years has been in the process of obtaining one of these third-generation lasers, a Toptica Sodium Star 20/2 while maintaining its second-generation Lockheed Martin Coherent Technologies (LMCT) 50W CW Mode-locked laser. In October of 2017 successful on-sky commissioning of the Toptica laser was executed while the LMCT laser was still active and in operations. During the course of the commissioning run both lasers were used on sky in close in time in possible. We present a comparative study of the performance of each laser.

Keywords: AO, LGS

1. INTRODUCTION

Adaptive Optics (AO) is a technique used in astronomy to compensate for the induced aberrations in incoming wave fronts by the earth atmosphere. The compensation is done by an adaptive element normally a deformable mirror in real time and enable diffraction limited images on large ground based telescopes that would otherwise be impossible. In order for AO systems to work a bright source is needed to be able to measure the atmospheric turbulence in real time. The bright source used in the first AO systems were bright Natural Guide Stars (NGS). While NGS are easy to use as they require only a high-speed wave front sensor, they are not always in the location of an object of astronomical interest and thus the use of NGS leads to a very small amount of the sky that can be observed with AO. In order to increase the sky coverage the idea arose to create an artificial guide star (Foy & Labeyrie, 1985)^[1]. The first sodium guide star was created on the summit of Mauna Kea Hawaii in 1987 (Thompson and Gardner, 1987)^[2]. Since that time there have been several generations of sodium guide star lasers. With each new generation comes new advancements in photon return and in operational stability. At the Gemini South observatory as part of the Multi-Conjugate Adaptive Optics System GeMS, two different generations of sodium laser technologies have been used.

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For a full review of GeMS design and commissioning see Rigaut et al. (2014)^[3] and Neichel et al. (2014)^[4]. During the upgrade from one generation to the next we had the unique opportunity to use both lasers on sky and compare their performance. Below we give a brief history of guide star laser technologies and then detail our results on sky.

1.1 First-generation guide star lasers (Dye Lasers)

The first generations of lasers used in astronomy were liquid dye lasers. The first laser used by Thompson and Gardner^[3] was a dye laser that had been used in LIDAR measurements. This was a pulsed laser and its design has been continued to be used at different LIDAR observatories. Much more powerful dye lasers were later built in the 1990s, with the 1.1kW Lawrence Livermore National Laboratory (LLNL) Atomic Vapor Laser Isotope Separation (AVLSI) dye laser producing the brightest ever sodium guide star (Avicola et al., 1994)^[5]. Leading to a facility sodium guide star laser at the Lick observatory (Friedman, et al. 1995)^[6] and also leading to the facility guide star laser at the Keck observatory (Friedman, et al., 1997)^[7].

At the same time as the development of the pulsed dye lasers, Continuous-Wave (CW) dye lasers were also being developed. The most well known in the PARSEC CW dye laser used at the European Southern Observatory (ESO) (Rabien, 2003)^[8], which produced the first sodium LGS in Chile (Banaccini 2006)^[9]. Dye lasers while used as facilities at multiple sites had issues as the dyes used are often flammable and carcinogenic.

1.2 Second-generation guide star lasers (Solid State)

Solid state laser technology began to take off in the 1980s and 1990s and offered an alternative to dye lasers. There distinct technologies were developed. Macro-Micro-Pulsed Sum-Frequency Lasers, Continuous-Wave Sum-Frequency Lasers, and Continuous-Wave Mode-Locked Lasers. The last generation Macro-Micro-Pulsed Sum-Frequency laser developed by The University of Chicago based on the designs of a Massachusetts Institute of Technology/Lincoln Lab (MIT/LL) lasers (Jeys, 1991)^[10] and was used on the Palomar 5-meter Hale Telescope (Dekany, et al 2005)^[11]. The second type of solid state lasers were developed for use at the Starfire Optical Range(SOR), with the final 50 W version being used on sky in 2005 (Denman et al., 2005)^[12]. The SOR also developed a 20W laser and had the opportunity to use both the 50W and 20W laser on sky with one locked on the sodium D2a line and the other on the D2b, this experiment showed that pumping both sodium lines resulted in a higher sodium return (Drummond, 2007)^[13]. Lastly the CW Mode-Locked lasers were developed at the Gemini, Keck, and Subaru Observatories with a 14W laser for Gemini North (d'Orgeville et al., 2005)^[14], a 20W laser for Keck I (Lee et al., 2008)^[15], a 50W laser for Gemini South (d'Orgeville et al., 2012)^[16], and a 5W laser for Subaru (Hayano et al., 2010)^[17].

While large observatories were able to purchase and install these second-generation lasers, their price remained high, and more importantly their stability was low. Observatories had to invest significant amounts of effort to maintain the laser systems at the specified output power.

1.3 Third-generation guide star lasers (Fiber lasers)

The current generation of lasers in use are Fiber lasers. This technology is far simpler to maintain compared to the first-generation dye lasers and the second-generation solid-state lasers. That being said it was not until recently that the fiber technology had reached the maturity necessary for the manufacture of these laser. The most used version of these lasers are Raman Fiber Lasers developed by ESO in collaboration with industrial partners. The commercial version of this laser known as the Toptica Sodium star (Enderlein, 2014)^[18]. This laser has been commissioned at the ESO VLT, the Keck Observatory and the SOR. It has also now been commissioned for the Gemini South telescope and is planned to be deployed at the Gemini North telescope.

For a full and comprehensive review of the history of lasers in astronomy see d'Orgeville and Fetzer 2016^[19].

2. OBSERVATION SETUP

2.1 Two lasers

The Gemini South Observatory in 2017 upgraded their second-generation solid-state laser produced by LMCT to a third generation Raman Fiber laser by Toptica photonics. Both of the lasers are located on the telescopes gravity invariant azimuth platform, from there they are sent via a series of free space Beam Transfer Optics (BTO), up along the telescope trusses to the top end ring where a series of polarizing beam splitters divide the beam from one beam into five beams that then propagate across the spider veins and eventually to the laser launch telescope (LLT) that is located behind the

telescopes secondary mirror. The LLT projects the laser on sky in a five-die shape that is 1x1 arc-minute square with one spot on each corner and one located in the center.

For the laser upgrade it was decided early in the project that the installation of the new laser would not prevent the operation of the old laser. This means that a method had to be developed to inject the new laser into the BTO without preventing the old laser from being propagated into the BTO, the requirement was also that it would not be possible to propagate both lasers into the BTO at the same time.

To meet these requirements a new Beam Injection Module (BIM) was developed in house. The BIM has three fold mirrors a half-wave plate and a beam splitter cube. The three fold mirrors are used to send the new laser beam into the BTO with the third fold mirror being deployable. While it is deployed the new laser can propagate into the BTO and the old laser is blocked, and when it is removed the old laser can propagate into the BTO and the new laser is blocked. The half wave plate and the beam splitter cube allow for the new laser to be propagated at low power ($<1\text{W}$) into the BTO, this capability is not provided by the laser manufacture. For a full review of the BIM see Chirre et. al 2018^[20].

Figure 1. The Gemini south BTO on the left and the new setup with the two lasers on the right. The LSE houses the old second-generation laser, while the new third-generation laser is the EC and the LH. The output box houses the BIM.

3. OBSERVATION SETUP

3.1 Observations

In October of 2017 the Gemini Observatory had its on-sky commissioning run of its new Toptica laser. During 6 nights at the end October the unique opportunity was present to use both laser on sky and do a direct comparison of the two lasers on sky performance with only a few minutes of time between the observations. Observations were taken with both the telescopes acquisition camera and the GMOS-S optical imager (Hook, 2004)^[21]. The observations were done at different telescope elevations and azimuths to fully sample the sky. At each pointing images of the LGS were taken with the acquisition camera, while images with GMOS-S were only taken at Zenith (Elevation = 90 degrees), in addition to the images of the LGS images were also taken of the detuned laser in order to get the sodium backscatter for subtraction in reduction. The output power of the LMCT laser was 44W while the Toptica was 22W.

Figure 2: Images of the LGS spots as seen by GMOS-S, the 44W LMCT laser is on the left while the 22W Topica laser is on the right.

Table 1. Summary of laser observations pointings.

Telescope Azimuth degrees	Telescope Elevation degrees
0	90
0	80
0	70
0	60
0	50
90	80
90	70
90	60
90	50
180	80
180	70
180	60

180	50
270	80
270	70
270	60
270	50

3.2 Photometry

For each pointing the set of five images on the acquisition camera were subtracted for the backscatter and then stacked. V-band aperture photometry was taken and a V-band magnitude calculated, the same was done for the GMOS-S data but in r-band. The acquisition camera V-filter has a throughput of 74.2% at 589nm and the r-band filter in GMOS-S has a throughput of 87.5% at 589nm. The photometry for each spot was done individually. The magnitudes are reported in table 2 for the zenith pointing in both V-band and r-band.

Table 2. Summary of Zenith V-band and r-band magnitudes

Spot	V-Band Toptica	V-Band LMCT	r-band Toptica	r-band LMCT
Top Left	10.12	9.97	9.81	9.57
Top Right	9.79	9.62	9.38	9.17
Center	10.25	10.07	9.90	9.69
Bottom Left	10.06	9.95	9.88	9.67
Bottom Right	9.88	9.63	9.52	9.25

Table 3-4 shows how the magnitude changes with different telescope pointings for both lasers using the Top Right spot as it is the brightest, the other spots show a similar pattern.

Table 3. Summary of V-band magnitude for the Toptica laser top right spot, with azimuth on the vertical axis and elevation on the horizontal axis.

	90	80	70	60	50
00	9.79	9.82	9.90	9.92	10.19
90	9.79	10.21	10.26	10.38	10.60
180	9.79	10.06	10.11	10.18	10.52
270	9.79	9.86	10.10	10.20	10.57

Table 4. Summary of V-band magnitude for the LMCT laser top right spot, with azimuth on the vertical axis and elevation on the horizontal axis.

	90	80	70	60	50
00	9.62	9.58	9.60	9.84	10.12
90	9.62	9.95	10.01	10.10	10.34
180	9.62	9.82	9.90	9.94	10.21
270	9.62	9.66	9.86	9.96	10.31

In all cases the LMCT laser is brighter than the Toptica laser by ~ 0.2 magnitudes, but as the power of the LMCT is double that of the Toptica laser we can say that the Toptica laser is 60% more efficient at exciting sodium than the LMCT.

3.3 Image quality

The image quality of the LGS was also checked at all pointings. Figure 3 summarizes the image quality measurements.

Figure 3: Contour plots of the laser spots from the Zenith images with the telescopes acquisition camera. The FWHM in arc seconds is given along with the ellipticity measurements.

The Toptica laser spot is 15% smaller on sky than the LMCT spot. The noise measurement is proportional to the FWHM, so you get a reduction of the noise measurement. The smaller spot makes the Toptica spots more sensitive to elongation, but this is more than compensated by the smaller spot size.

4. COMPARISON WITH PREDICTED RETURN

4.1 Photometric comparison

Simulations done by Holzlöhner et al (2009)^[22], an internal study done by Rochester Scientific and measurements of sodium return on Cerro Pachón and Cerro Tololo by Neichel et al (2013)^[23], predicted that the output from the Toptica laser should be at least as good as that of a 35W LMCT laser. As our LMCT laser was 44W the prediction from Rochester is consistent with what we see on sky. That being said the Rochester study done using the LGSBloch simulation package was found to overestimate the return of pulsed lasers by a factor of two (Rampy, 2013)^[24]. This would mean that even at double the power the LMCT laser should have had a lower return, which is not what we saw in the on-sky observations. We have two main ideas to explain this discrepancy, the first being the relatively low laser power sent to sky. As we split the laser beam into five and with the low throughput of the BTO (50%), the flux that is propagated to sky is on the order of a few watts, at this power the benefits of the CW Toptica laser over the LMCT CW mode-locked are less. The other explanation is the poor control of polarization in the Gemini BTO. In the photometric data we collected we can see that each spot has a different intensity, this is because the control of the circular polarization is done as a constellation adjustment and not individually for each beam (Araujo, 2016)^[25].

5. CONCLUSIONS

Two generations of sodium guide star lasers were used on sky on the same night. The third-generation Raman fiber Toptica laser was 60% more efficient per watt at exciting sodium than the second-generation solid-state LMCT laser. This is in agreement with modeling that shows that the Toptica laser should be more efficient, however it was not as efficient as expected. The reasons for this are likely due to the Gemini environment and not to the laser technologies themselves. The Toptica laser did produce a smaller spot on sky which will lead to a much better signal to noise measurement in the AO system. The other added benefit of the Toptica laser is that it is much more reliable and much easier to operate than the LMCT laser.

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