Sodium Recoil at Starfire Optical Range

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ABSTRACT

Previous attempts to observe sodium recoil occurred in 2008 at the Starfire Optical Range (SOR), and we were unable to observe sodium recoil due to laser stability issues and narrower laser linewidth than reported previously. In 2018, SOR separated their two new cw lasers at a fixed frequencies and observed on average a 15.7% increase in flux returns at fixed separation values within the accumulated doppler shift for a cw sodium beacon. Additionally, SOR successfully closed their adaptive optic loops on a sodium beacon that was partially mitigating sodium recoil for the first time.

Keywords: Sodium Laser Guidestar, mesosphere, atomic recoil

1. INTRODUCTION

The idea of frequency chirping a sodium laser guidestar is to mitigate the detrimental effects of radiation pressure (also known as sodium recoil).[1] Each time a sodium atom absorbs a photon from a laser, the sodium atom gains speed in the direction opposite of emitted photon based on the conservation of momentum. Based on Newton's Third law, the sodium atom will experience a change of momentum equal to the photon's momentum or $\frac{h}{\lambda}$ (where h is planck's constant and λ is the wavelength of the photon) and dividing the photon's momentum by the mass of a single sodium atom in kilograms will provide the change in speed for the sodium atom. At a wavelength of $589.159nm$, the change in velocity is $2.95cm/s$ in the direction of laser propagation (for backscattered photons). Based on the doppler effect, the change in frequency (assuming that the speed of the sodium atom is much smaller than the speed of light in the mesosphere) is given by

$$\Delta f_{perEmission} = \frac{\Delta V}{\lambda} \tag{1}$$

where ΔV is the change in velocity along the direction of laser propagation. Therefore, in order for the sodium atom to absorb an additional photon, the atom now requires a photon that is red-shifted by $50KHz$ (based on the doppler effect) from the wavelength of the previous photon.

As long as the velocity of the sodium atom in the direction of the laser remains 0, the sodium atom will continue to absorb and spontaneously emit photons compounding the redshift effects.[2] The sodium atom will stop absorbing additional photons until either a collision or spin exhange causes the atom to change its velocity in the direction of the laser or the source of radiation can no longer provide photons at the appropriate wavelength due to the cumulative effects of the doppler shifts.

Because the laser line-width for SOR's' SodiumStars 20/2 (Toptica systems) are $5MHz$, a sodium atom can emit a photon 100 times before the source of photons can begin to no longer keep up with cumulative Doppler shifts. Although the radiative lifetime of the sodium atom is $16.24ns$,[1] the average time a sodium atom will emit a photon depends on the fraction of sodium atoms in the upper state. Under continuous illumination,[2] the fraction of atoms in the upper state, N_{upper}, is defined by

$$N_{upper} = \frac{1}{2}(1 + \frac{I_{sat}}{I})^{-1} \tag{2}$$

where I is the intensity of the laser at the mesosphere and I_{sat} is the saturation intensity for the sodium atoms in the mesosphere. Equation 2 can be derived from the steady state case for the basic rate equation. Note that the saturation intensity depends on laser linewidth and downpumping effects. Kibblewhite[3] argues that the $62.4W/m^2$ is peak return (line center) of the $(2,2)$ to $(3,3)$ sodium transition while $250W/m^2$ is for the photon return integrated across Doppler frequencies at Zenith at SOR for a laser without repump but with circular polarized light. The average time a sodium atom will spontaneously emit a photon, t_{avgSE}, then becomes

$$t_{avgSE} = \frac{\tau_{radiative}}{N_{upper}} \tag{3}$$

where $\tau_{radiative}$ is the radiative lifetime of the ${}^2P$ states of the sodium atom ($16.24ns$). As the laser intensity grows to infinity, the average time a sodium atom will emit a photon in the mesosphere decreases to two times the radiative lifetime or $32.48ns$.[2] When both of SOR's SodiumStars 20/2 are projected on-sky using polarizing beam combination,[4] we expect an intensity of about $53.5W/m^2$ in the mesosphere equating to a photon emitted every $184ns$ at $I_{sat} = 250(W/m^2)$.

Now the number of emissions that a sodium atom can undergo, $N_{emissions}$, will equal

$$N_{emissions} = \frac{t_{MFT}}{t_{avgSE}} \tag{4}$$

where t_{MFT} is the mean free time of a sodium atom in the mesosphere. The mean free time will change according to sodium concentrations (which varies according to altitude), mesosphere temperatures and winds. The mean free time is an important quantity because a collision with another molecule or atom will change the velocity component along the direction of laser propagation. Most likely, the sodium atom will now have a velocity component in the direction of laser propagation and will minimally interact with the laser. Eventually, the sodium atom will collide with another molecule or atom and have a near-zero velocity component in the direction of laser propagation. Depending on the environment in the mesosphere, the average collision time can vary from $27 - 200\mu s^{531}$.[6] Based on photon returns at SOR in 2009, Kibblewhite estimated the mean free time to be $40\mu s$.[3]

Finally, the total doppler shift within the period of the mean free time, $\Delta\lambda_{perMFT}$ can be expressed as

$$\Delta f_{perMFT} = N_{emissions}\Delta f_{perEmission} \tag{5}$$

For a mean free time of $40\mu s$, a saturation intensity of $250W/m^2$, and a mesosphere intensity of $53.5W/m^2$, we have a redshift of $10.9MHz$. Now a Gaussian beam with a full width at half maximum (FWHM which is the line-width of a Gaussian beam) will have a standard deviation of $\sigma \approx FWHM/2.355$ with 99.95% of the laser intensity within $\pm 3.5\sigma$ of the line center. Because 99.95% of the combined SodiumStar's 20/2 laser intensity is less than the doppler shift of $10.9MHz$ (in fact $10.9MHz$ is within 5.11σ of the laser center), only the first 148 out of 217 possible emissions events are occurring for 99.95% of the sodium atoms in the upper atmosphere (the number drops down to 99 emissions for 99% of sodium atoms). As a result, we should expect approximately 69 more photons per sodium atom for 99.95% of sodium atoms (118 per atom for 99% of sodium atoms) under the conditions stated above. Therefore, chirping should at a minimum, increase the photon return by 32% for 99.95% of atoms (54% for 99% of atoms).

Based on the variability of the sodium mesosphere, we can have a doppler shift between $7.3MHz/27\mu s$ to $54.3MHz/200\mu s$ (on the same time scale that corresponds to a rate of $270.4KHz/1\mu s$ to $271.5KHz/1\mu s$) with the number of possible emissions varying from 146 to 1085 for the current laser configuration at SOR. The chirp rate changes based on saturation intensity or to $700KHz/\mu s$ for $I_{sat} = 62.4W/m^2$.

2. EXPERIMENTAL SETUP

In 2015, SOR purchased two SodiumStar 20/2 laser systems, Raman Fiber Amplifiers centered at $1178nm$. The output of the amplifier undergoes Second Harmonic Generation in the laser head unit to generate approximately $22W$ of total output power at the peak of the sodium D_{2a} line. The SodiumStars are capable of $2W$ of integrated optical sideband generation centered at a frequency separation of $1.713GHz$ in each direction from the peak of the sodium D_{2a} line. Additionally, the output of the laser head is linearly polarized with a polarization extinction ratio of $100:1$. Using a quarter-wave plate, the laser output is converted to circularly polarized light before reaching a launch telescope on the side of SOR's $3.5m$ telescope.

In 2016, the two SodiumStar laser systems were side-launched from the side of the telescope. To create a single beacon on-sky, SOR used opposite handedness of circularly polarized light for each laser to combine the two laser outputs immediately preceding the launch telescope.[4] As shown in Figure 1, the output of the first SodiumStar 20/2 is linearly polarized in the horizontal direction (p-polarized) while the output of the second SodiumStar 20/2 is linearly polarized in the vertical direction (s-polarized). The polarizing beam splitter combines the two lasers by reflecting the first SodiumStar 20/2 (p-polarized) and transmitting the second SodiumStar 20/2 (s-polarized). Without the half-wave plates, the tiny fraction ($< 1\%$) of s-polarized light from the first SodiumStar 20/2 and the tiny fraction ($< 1\%$) of p-polarized light from the second SodiumStar 20/2 is sent to the optical diagnostic while the rest is sent to the launch telescope. The half-wave plates control the intensity of light on-sky for each SodiumStar 20/2 by controlling the percentage of light in the p-polarized or s-polarized basis. Meanwhile, the quarter-wave plate is positioned such that both the p-polarized and s-polarized light makes 45° to the fast and slow axes of the wave plate which then converts the linearly polarized light of both lasers to circularly polarized light. The p-polarized light of the first SodiumStar 20/2 becomes right hand circularly polarized while the s-polarized light of the second SodiumStar 20/2 becomes left hand circularly polarized.

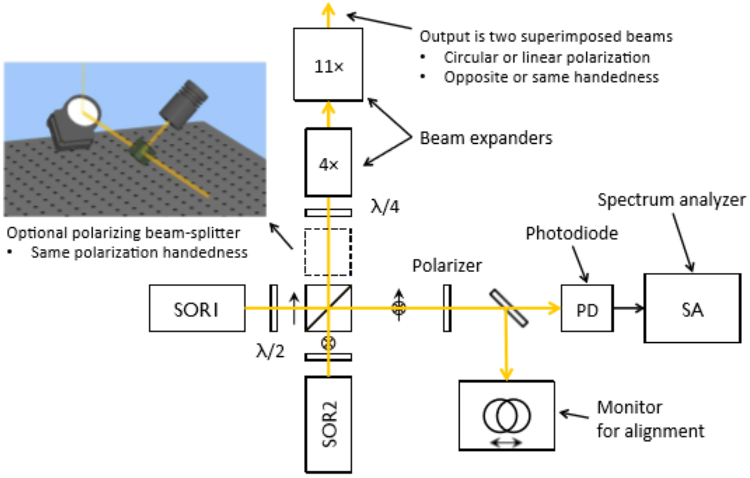

Figure 1. Optical setup for combining the two SodiumStar 20/2 owned at Starfire Optical Range before the launch telescope. The beam combining optics and diagnostics are largely the work of M Eickhoff. The 11 beam expander or launch telescope was designed by J. Spinhirne.

To make both lasers the same polarization, a second beam splitter is added before the quarter-wave plate. The beam splitter is angled at 45° from a plane parallel to the surface of the ground so that the s-polarized and p-polarized light both make a 45° angle with the optical axix of the beam splitter. As a result, both SodiumStar 20/2 lasers have equal components in the s and p basis. When the quarter-wave plate is rotated 45°, then both lasers will have the same handedness of circularly polarized light. Although 50% of the beam is reflected into a beam dump using the second beam splitter, SOR can still detect sufficient photon returns from the sodium beacon.

The unique setup and the frequency stability of the lasers allowed SOR to observe the effects of sodium recoil. During testing at the end of 2018, the laser operator would keep one SodiumStar 20/2 set the fundamental wavelength to $1178.3181nm$ while the second SodiumStar would be set a $100MHz$ (which is not necessarily at $1178.31856nm$ due to uncertainties in the wavemeters of each SodiumStar 20/2) longer in wavelength from the first. We would measure the separation by sending light to a beat note frequency counter. The laser operator would then adjust the wavelength of the second SodiumStar 20/2 such that the frequency separation between the two lasers decrease. At various frequency separations, the 3.5m telescope would look at the sodium beacon produced on-sky. The return photons would either be sent to SOR's Andor camera for photometric evaluation or to the laser guidestar wavefront sensor and i-band camera to test system performance. At each frequency separation that the test director determined was appropriate for collection, the half-wave plates would be set to the optical home position (0°) so that all of the light from both lasers would be sent down the optical diagnostic leg to reduce the noise on the frequency counter. Once the beat note was recorded for 15 seconds, the half-wave plates were adjusted to maximize the amount of light on-sky (45°). The laser operator would then record 15 seconds (52 frames at 200ms exposure on the Andor camera) worth of data for each of the following laser configurations:

1. First SodiumStar 20/2 turned on while the second SodiumStar 20/2 turned off
2. First SodiumStar 20/2 turned off while the second SodiumStar 20/2 turned on
3. Both SodiumStar 20/2 turned on
4. Repeat steps $1-3$ at least 3 times

After the data was collected for a given frequency, the half-wave plates were homed and the beat note frequency was measured for another 15 seconds to determine the shift in frequency separation. While the half-wave plates were homed, the laser operator would change the wavelength of the second SodiumStar 20/2 and repeat the experiment. Due to time constraints, about $4-8$ frequency separations were collected on a given night. On each night, star data was recorded on the Andor camera and sometimes the i-band camera and laser guidestar wavefront sensor to calibrate the sensors.

3. OBSERVATIONS

Since 2016, Starfire Optical Range has recorded the photon returns on the Andor camera over several nights of testing. Under standard operating conditions, SOR uses the setup shown in Figure 1 without the optional polarizing beam splitter. With this setup, the sodium beacon consists of the output of two SodiumStar 20/2 but with opposite handidness. Figure 2 shows typical returns observed under this configuration.[4] When SOR wants to compare the returns of a single beacon to the performance of each SodiumStar 20/2 individually, SOR uses a piezoelectric controlled mount to adjust the mirror uniquely associated with one of the SodiumStar 20/2s

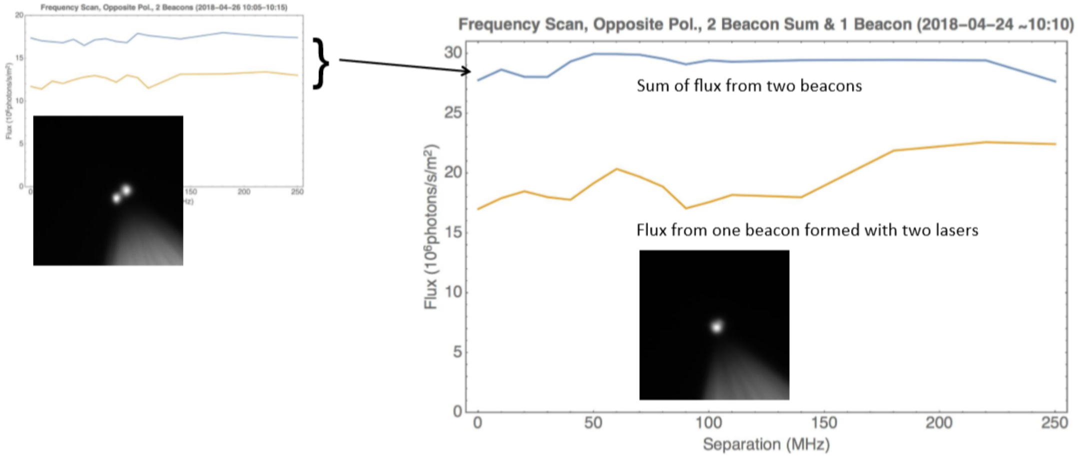

Figure 2. The smaller plot on the left-hand side shows the return flux from two beacons formed from two lasers with circular polarization of opposite handedness. The larger plot on the right-hand side shows the sum of the return flux from two beacons (upper blue curve) compared to the return flux from a single beacon (lower yellow curve) formed from two lasers with circular polarization of opposite handedness.

optical paths in order to spatially separate it from the other SodiumStar 20/2 on-sky. Consequently, two spatially separate, sodium beacons are produced on-sky simultaneously as shown in the small subfigure of figure 2. The photon returns of each beacon are summed together and compared to the photon returns from a single beacon formed by the combination of both SodiumStar 20/2s. We have repeated the two beacon versus a single beacon for multiple frequency separations, and we believe the difference in returns from a single beacon versus two spatially separate beacons is a result of competitive down-pumping.

Based on conversations with Dr. Dominico Bonaccini Calia of the European Southern Observatory and Dr. Frank Lison of Toptica Photonics, we began using SOR's two laser setup in late 2018 to determine if we could observe sodium recoil over SOR. We followed the steps outlined in the experimental setup adding in the optional polarized beam splitter so that both lasers had the same polarization. We first tested linear polarization on-sky, and the results for linear polarization are shown in figure 3. The blue data points are the sum of photon returns from each individual laser producing their own beacon on sky. The orange data points are the photon returns due to a single beacon formed by combining the two laser beams. The photon returns are plotted against the frequency separation between the two SodiumStar 20/2s. The error bars represent 95% confidence levels. Due to the noise limitation of the beat note frequency counter, we were not able to observe any photon returns below $4MHz$ separation. We see that sodium flux returns for the single beacon formed by combining both SodiumStar 20/2s is less than the sum of two separate sodium beacons each formed by a single SodiumStar 20/2. These results are consistent with the data published[4] and from observations based on SOR's standard configuration as shown in figure 2. We believe that we will not see the effects of recoil under linear polarization because we are no longer optically trapping sodium atoms. Although atomic recoil will still occur, we predict that with the loss of circular polarization, the total doppler shift will be *add* which is less than linewidth of the laser.

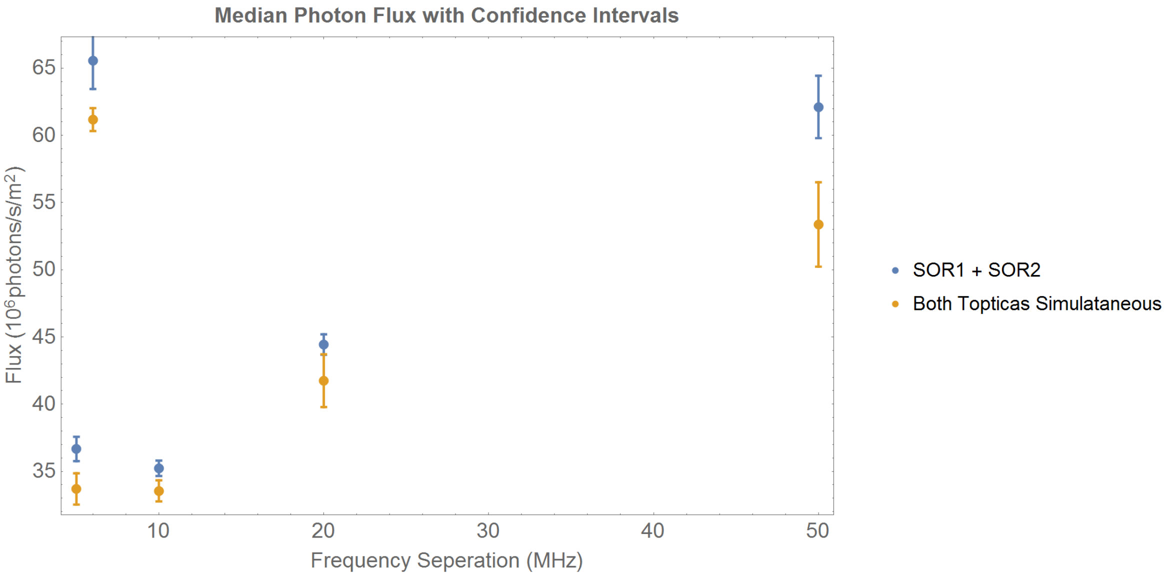

Figure 3. Photon returns as a function of frequency separation between two SodiumStar 20/2 laser systems on November 7. Both lasers are linearly polarized in the same direction. Blue data points are the sum of photon returns from two separate beacons each formed by a unique SodiumStar 20/2. Orange data points are the photon returns from a single beacon formed by the combination of both SodiumStar 20/2 laser systems. All error bars represent 95% confidence intervals.

On a separate night, SOR repeated the steps outlined in the experimental section except both lasers were left hand circular polarization at the launch telescope, and the results for the circular polarization experiment are shown in figure 4. Again, the blue data points represent the sum of photon returns from each laser separately while the orange data points represent the photon returns from a single beacon formed by combining two lasers, and the error bars represent the 95% confidence levels. For the first time at SOR, the single beacon formed by combining two lasers produced enough photon returns that either matched the sum of two beacons formed by a

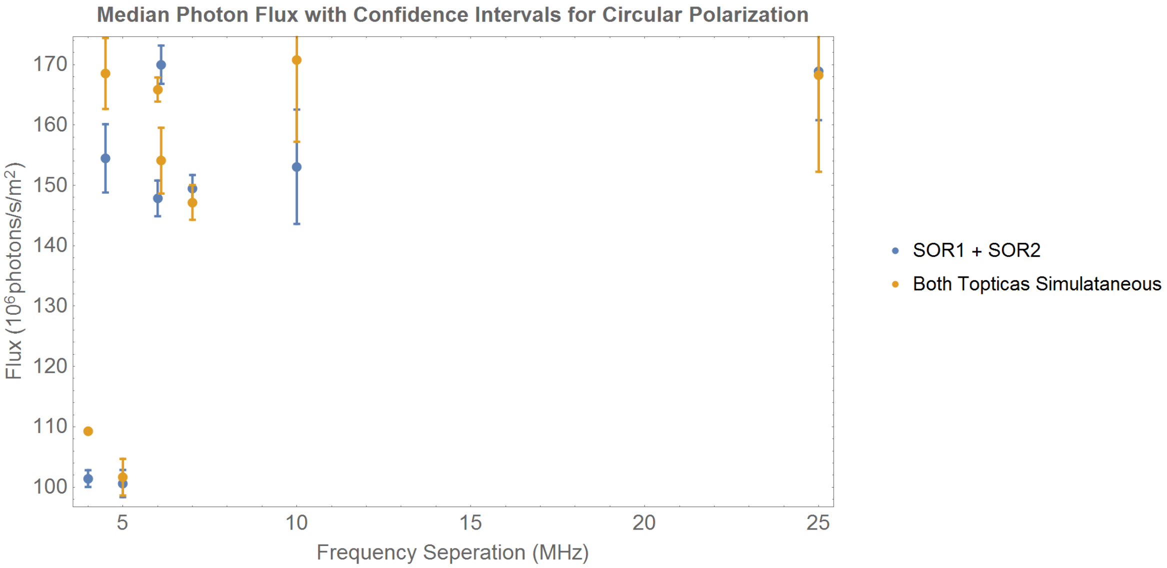

Figure 4. Photon returns as a function of frequency separation between two SodiumStar 20/2 laser systems on November 9. Both lasers are left-hand circularly polarized. Blue data points are the sum of photon returns from two separate beacons each formed by a unique SodiumStar 20/2. Orange data points are the photon returns from a single beacon formed by the combination of both SodiumStar 20/2 laser systems. All error bars represent 95% confidence intervals.

single laser within uncertainty limits or provided greater photon returns. If we normalize the data points to the peak flux return for each night, we see on average 15.7% increase in photon return at low frequency separations. We repeated the circular polarization experiment on another night but with larger frequency separations, and as shown in figure 5, at large frequency separations, the sum of the photon returns of two beacons each formed by a single laser is greater than the photon returns of a single beacon formed by combining two lasers. As noted

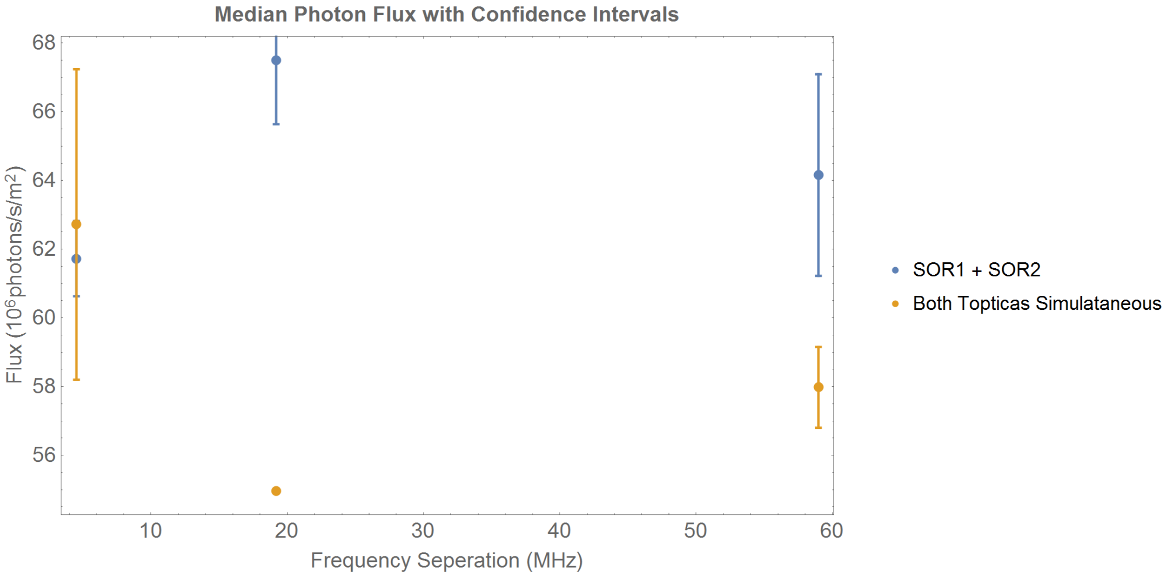

Figure 5. Photon returns as a function of frequency separation between two SodiumStar 20/2 laser systems on December 12. Both lasers are left-hand circularly polarized. Blue data points are the sum of photon returns from two separate beacons each formed by a unique SodiumStar 20/2. Orange data points are the photon returns from a single beacon formed by the combination of both SodiumStar 20/2 laser systems. All error bars represent 95% confidence intervals.

in the background section, we do not expect any doppler shifts greater than $54MHz$ and with an average mean free time of $40-60MHz$ at SOR, we would on average not expect any doppler shifts greater than $10-16MHz$. Figure 5 demonstrates that at higher frequencies than the doppler shift, there is no enhancement due mitigating sodium recoil for 100 additional number of emissions. We believe that the discrepancy between figure 4 and 5 at the separation values of $20-25MHz$ is due to differences in atmospheric conditions on those separate nights. Unfortunately, SOR does not have a sodium lidar at the time of this publication and is unable to verify this claim.

Previous attempts to observe sodium recoil occurred in 2008 at SOR.[5] At that time, SOR was unable to observe sodium recoil due to the laser systems being used at that time. Besides the laser stability issues mentioned, we believe that the FASORs were significantly narrower ($100KHz$ compared to $10MHz$). A year later, Dr. Edward Kibblewhite of the University of Chicago experimented with chirping for pulsed LGS and observed an 80% increase in flux returns at a chirp rate of $600\frac{KHz}{\mu S}$.[3] Since 2009, the authors are unaware of anyone testing for sodium recoil until recently at the European Southern Observatory. SOR separated their lasers at a fixed frequencies to see if they could observe an increase in flux returns at fixed separation values within accumulated doppler shift for a cw sodium beacon. Additionally, SOR successfully closed their adaptive optic loops on a sodium beacon formed by two laser combined with the same polarization at $50MHz$, $10MHz$, and $4MHz$ separation values. Using the I-band camera, we observed an increase in strehl ratio by 73%. In the near future, the European Southern Observatory will attempt to mitigate sodium recoil for both a cw and a pulsed laser in the summer of 2019 by actually chirping their sodium beacons which would see much greater enhancements than for this experiment.

4. CONCLUSION

For the first time at SOR, the single beacon formed by combining two lasers produced photon returns that either matched the sum of two beacons formed by a single laser within uncertainty limits or provided greater photon returns. If we normalize the data points to the peak flux return for each night to account for changes in the mesospheric concentrations, we see on average 15.7% increase in photon return at low frequency separations. We then closed AO loops on a star using the configurations mentioned above and calculated strehl ratios on the i-band camera using the ratio of energy-normalized image PSF to an energy-normalized diffraction-limited PSF as the definition of strehl. We see on average an increase in the fractional change of Strehl.

Future tests at SOR will repeat the experiment made by Hillman back in 2008.[5] In this test, SOR will use both of the SodiumStar 20/2 laser systems as a pump/probe experiment to measure the frequency distribution density of sodium atoms in the mesosphere.

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