In the paper „Frequency control and monitoring of the ALOMAR RMR lidar's pulsed high-power Nd:YAG lasers" the authors give a technical overview on the build-up-time resonator stabilization and real time frequency monitoring of their lidar's Nd:YAG laser. The frequency stabilization of the injection seeder by iodine spectroscopy is described in another paper (line 54), therefore the title might be considered misleading, because the part of frequency control is described in another paper. The main scope of the paper is performance monitoring of the injection seeder build up time resonator stabilization. Of course, injection seeding can be seen as "frequency control", but the resonator control mostly controls, which adjacent longitudinal modes to the injection seeder start to oscillate and how fast they start (build up time). Additionally, the Piezo shifts the whole longitudinal mode spectrum. So dependent on how good the resonator length is stabilized to the injection seeder, the bandwidth of the pulsed laser is reduced to nearly single longitudinal mode operation and low frequency offset to the injection seeder.

For the application the bandwidth and the relative frequency control is crucial, but bandwidth is only discussed in figure 7. For a full analysis of the presented system tuning the piezo of the laser over a full spectral range (1⁄2 µm) would have been interesting.

Furthermore, clarification about the setup is needed, since not all components mentioned in the publication are depicted in the setup.

Therefore, I advise major revisions.

We thank the reviewer for careful examination of our manuscript and for giving additional references. We agree that injection seeding and the associated resonator control of the power laser is *frequency control* as the spectrum of the emitted light depends on these processes. The crucial parameter for Doppler wind determination with our lidar is the frequency deviation of the power laser pulse with respect to the seeder, rather than the bandwidth of the pulse. We agree with the reviewer that low frequency deviation to the seeder and minimized bandwidth are interdependent. In this sense the spectrometer measures the most important parameter for our application. For additional information we add a supplement with some unpublished figures showing a piezo scan over several resonance conditions of the power laser cavity, temporal courses of the laser pulse, and a spectrometer image with multiple modes in one single pulse.

Comments on the individual sections:

Section 2: System setup

■ In figure 1 components are missing (e.g. diffuser/lens/fiber couplers). The components should be described in this section.

We will add components to text and figure.

Section 3: Pulsed Nd:YAG laser frequency control

■ In line 76 the authors write: "When the seed laser radiation is within the bandwidth of a longitudinal mode of the power laser resonator, it is resonantly amplified in the Nd:YAG rod. "

Is the true? When the Q-switch is operated only one round trip of seed laser radiation will be present in the resonator which is specially broadened due to the Q-switch. So the adjacent longitudinal modes will always receive a higher start energy than other longitudinal modes (in classical laser theory they start for 0.5 photons :)). I'll add some measurements in the appendix. As the resonator mode is better matched to the seed laser wavelength and mode, other modes get suppressed more until the gain of the laser is used up (works with homogeneous broadened gain media).

We will be more precise at this point.

■ In Figure 2 the authors depict the build-up-time and the piezo control voltage after switching the laser on. The histogram of the laser build-up-time is shown but nowhere discussed. An evaluation is difficult because the build-up time (minimum) is not only dependent on the resonator length control but also on the gain in the laser itself. And the gain might be dependent on the temperature of the pump diodes. For this a synchronous plot of the output energy could explain the 2 ns increase in minimal build up time at 8:20.

Yes, the minimum BuT depends on several parameters and temperature matters. Both power lasers at ALOMAR run at quite different cooler temperatures, the one showed in figure 2 at 18.5 °C and the other at 24°C, to match the pump diode properties. Slight BuT variations after switching on are a regular behavior of this laser which is with considerable certainty due to the different warm-up process compared to the other laser not showing this behavior. In general, the absolute value of the build-up time is of less importance (they differ by 12 ns between the both lasers). It is important that the control algorithm always finds the currently minimum possible value. The data shown in figure 2 was collected during a regular atmospheric sounding of the lidar and thus no measurement of the output energy was available.

Section 4: Laser pulse spectrometer

■ The authors should motivate their design considerations and add a literature study on the topic. E.g. a fast real time wavemeter for injection seeded lasers using a fabry-perot as pulsed wavemeter was presented in 1993 by Hahn et. al. „Fabry–Perot wavemeter for shot-by-shot analysis of pulsed lasers“ DOI:10.1364/AO.32.001095. or ”A simple real-time wavemeter for pulsed lasers”, Ja-Yong Koo and I Akamatsu DOI 10.1088/0957-0233/2/1/009.

The motivation for our spectrometer design was relatively simple: the development should require minimal effort for the mechanical and optical construction and the device should be robust as it is used at a remote place without permanent access in case of problems. Consequently we purchased the appropriate parts, assembled them, and wrote software to use the parts as a spectrometer. At the end we determined the quality of the spectrometer using our ultra-stable seed laser locked to an iodine absorption line. The result was that the spectrometer can even follow the very small residual frequency variations of the seed laser (∼300 kHz at 532 nm). The corresponding sensitivity is $\sim 5x10^{-10}$ at a measurement rate (pulse repetition rate) of 100 Hz. Hahn et al. reported a precision of <10 MHz when measuring a cw laser with their etalon based wavemeter, temperature stabilized to 5 mK. Koo and Akamatsu reported a resolution of 10^{-7} for their etalon based wavemeter operated at 10 Hz pulse rate. To be fair, it must be said that there are ∼30 years of technical development between their and our devices. We will add the information that existing systems did not meet our requirements and therefore we had to develop our own solution in the manuscript.

■ Why did they choose a camera instead of a line camera? The camera produces more data, which might be redundant and is therefore more demanding on the signal processing.

Using a 2-d camera and processing each pixel illuminated by the interference rings increases the signal-to-noise ratio and allows the operation of the spectrometer during weaker light intensities, compared to using only a cross section of the rings as provided by a line camera. The device is more robust against unexpected changes in lighting conditions which might occur when a lidar is operated remotely.

■ Why an Etalon and not a Fizeau interferometer was chosen for the Laser pulse spectrometer? E.g. in „An absolute frequency reference unit for space borne spectroscopy ", by H. Schäfer et. al. DOI: 10.1117/12.2536012 a fiber coupled wavemeter using a collimator and a Fizeau wedge is presented to compare the wavelength of the injection seeder with the injection seeded pulse from an OPO – they even omitted means of chopping out the cw signal of the injection seeder due to different integration times.

We have experience with the use of etalons in our lidar since more than 20 years, so it was obvious to choose an etalon. Schaefer et al. describe a system for space borne spectroscopy to be used in the MERLIN mission, which was certainly subject to completely different design criteria compared to our device. The block diagram of their frequency reference unit (figure 1) shows that the electro-optic components are connected by optical fiber and the signal distribution is done by tap couplers and optical switches. Most likely the cw signal of the seed diodes is blocked by means of the fiber switches when the OPO pulses are measured by the wavemeter. Otherwise the sum of cw and pulsed light would be processed, which we prevent in our device by using the mechanical chopper.

Further literature to be considered:

■ Fizeau wavemeter for pulsed laser wavelength measurement, Mark B Morris, Thomas J. McIlrath, and James J. Snyder, https://doi.org/10.1364/AO.23.003862

1984: cw wavelength accuracy $2x10^{-7}$, pulsed resolution 10^{-6} (10 Hz, 100 pulses average), not real-time

■ Low-cost wavemeter with a solid Fizeau interferometer and �ber-optic input, Benedikt Faust and Lennart Klynning, https://doi.org/10.1364/AO.30.005254

1991: accuracy 10^{-6}, 10 Hz, not real-time

■ A simple real-time wavemeter for pulsed lasers, Ja-Yong Koo and I Akamatsu, https://doi.org/10.1088/0957-0233/2/1/009

see above

We will add these references to the manuscript.

Further minor questions the authors should consider:

■ Why a FSR of 1 GHz was chosen for the Etalon (line 107)?

The spectral width of the Doppler broadened iodine line 1109 is ~2 GHz and we want to achieve high spectral resolution in this area (will be added to the manuscript).

■ What was the reflectivity of the mirrors of the Etalon?

93% at 532 nm (will be added to the manuscript)

■ How is the seed laser light coupled out of the fiber (line 111) – is there a collimator used?

We use a bi-convex lens having a focal length of 40 mm to produce a minimum beam diameter in the plane of the chopper blade (will be added to the manuscript).

■ What is the beam size of the laser and the seed laser on the diffuser?

~ 15 to 20 mm (will be added to the manuscript)

■ Where is the ground glass diffuser (line 113) depicted in Figure 1?

The schematic contains only key components of the system (line 47), but we will add this component.

■Where is the 500mm lens depicted in Figure 1?

The schematic contains only key components of the system (line 47), but we will add this component.

■ Is the chopper necessary? (E.g. Schäfer et. al. did not need this)

Yes, see our answer to a previous question.

■ In line 113 the authors describe the lens is imaging the interference patterns. Actually, it transforms the angular interference pattern into a spacial interference pattern. An angle of 1mrad is transformed into a displacement of 0.5mm. So, 0.8 mrad would be 0.4mm ~57-66 pixels for a 6-7 µm camera pixel pitch.

We will be more precise at this point.

■ A line camera would not require such "overkill" hardware like a FPGA running RT-Linux and resource hungry LabVIEW... of course a small FPGA could evaluate a line camera in real time with a defined latency. The authors should focus on describing the technical necessities or concepts and then the details of their implementation (as implementations might changes – but keeping in mind the review criteria:

Scientific significance:

Does the manuscript represent a substantial contribution to scientific progress within the scope of Geoscientific Instrumentation, Methods and Data Systems

(substantial new concepts, ideas, methods, or data)?.

E.g. in line 126 the authors write: "Then, for each peak of this function the position and amplitude of the maximum as well as the full width at half maximum (FWHM) are determined. ". The accuracy of the frequency estimation is dependent on the FWHM and the SNR of the measurement – the authors should give a Cramer-Rao limit for their estimator and compare their observations with this.

We do not consider our solution to be overkill, but rather as state of the art. The technical concepts are described in the manuscript and for the motivation behind this implementation see our answer to a previous question. As proof of the functionality and sensitivity of the device we have compared data measured by the spectrometer with data measured by the seed laser setup. These are completely independent measurements with different methods. The seed laser setup determines the laser frequency variations using physical properties of a molecule (iodine), the spectrometer determines the same variations using the property of coherent light to form temporally stable patterns through interference. Both data sets are compared simultaneously 100 times per second, which is a very strict comparison. The results are shown in the upper panel of figure 5 as „naked eye proof" and in the lower panel for statistical evidence. The corresponding sensitivity of approx. $5x10^{-10}$ at a measurement rate (pulse repetition rate) of 100 Hz is significantly higher than the values reported in the references (manuscript and reviewer additions). Furthermore the spectrometer has proven it's ability in regular lidar operations since several years.

For these reasons we indeed consider the content of the manuscript to be a substantial contribution to scientific progress within the scope of this journal and do not see the point of any additional statistical investigations.

We will add the processing chain for the FWHM calculation to the manuscript, see below.

4.1 Calibration

The method is well described.

4.2 Sensitivity

■ The authors should state which slope is used for stabilization of the seed-laser. I suppose the increasing slope in the figure 4 (UT 12:16) is used. Here the type of evaluation (fitting/center of gravity measurement etc...) is important, since a sub pixel evaluation is performed and plotted in figure 5. The chosen criteria in lines 165 and following do not express anything about thermal drift within the Etalon. There is no place where the authors discuss the sensitivity of the laser pulse spectrometer on pressure and temperature. Because it is used for relative measurements, this does not matter too much.

Yes, we use the increasing slope of the absorption line. We are not sure whether we understand the reviewer correctly here („type of evaluation“). If the question concerns the method of FWHM determination to obtain sub-pixel resolution for the spectrometer we refer to our response to a corresponding question from review 1. Here is a copy:

- Determine peak maxima (integer) and background level in the 1-d array of intensity as function of radius in pixel coordinates.
- Following the intensity values from a peak maximum in left and right direction until the background level is reached yield arrays for the left and right slopes of the peak.
- For each slope array: find the two intensity values between which the half maximum value of the peak lies.
- Linearly interpolate the half maximum value using fractional pixel values yield left and right positions of the FWHM value. The difference between these positions yields the FWHM value in fractional pixels.
- The sum of the left position of the FWHM value and the half of the FWHM value yields the position of the peak maximum in fractional pixels.

We have addressed the topic of temperature / pressure impacts in lines 129 – 132: „The pixel difference in the peak positions of seed and power laser light is a measure for their frequency difference. Such pixel differences are calculated for each power laser pulse acquired in one second with respect to the seed laser light acquired in the previous second. This procedure eliminates the impact of changes in etalon parameters caused by drifts in temperature and air pressure that generally occur on much larger timescales.“ In the end, only temperature and pressure changes within a time period of two seconds can impact the determination of the frequency difference between seed and power laser, which is negligible.

But for the sensitivity the bandwidth of the laser might be important, the bandwidth of the cw seed laser is small compared to the bandwidth of the 10-12ns pulses q-switched laser. The bandwidth of the q-switched laser with 10-12ns is 50-100 Mhz (dependent on the time bandwidth product of the pulse). With a Finesse of 20 and an FSR of 1 GHz the Airy linewidth of the interference pattern is approximately 50 MHz, therefore the expected peak FWHM of the lase pulse including the instrument function of the Etalon would be 2-3 times higher than the peak FWHM of the cw-laser. This would decrease the 'sensitivity'.

The FWHM of the power laser pulse is higher compared to that of the seed laser. The screenshots of the LPS client user interface (figure 3) show the FWHM numbers for this particular laser pulse (ArrPeakFwhm): power laser ∼7.5 pixels, seed laser ∼3.5 pixels, power/seed laser ∼2.1. Figure 7 shows the numbers for a time period of 10 minutes.

5 FCaM Performance

■ In line 180 the authors note:"The individual measurements of the power laser frequency stability reproduce the sinusoidal variation of the cavity length nearly perfectly." and in line 209 the authors write: "The imprinted cavity length modulation for the BuT minimization method results in approx. ±10 MHz frequency modulation around the mean frequency of the power laser, which potentially can be reduced."

The authors should discuss why they do not consider using the measured frequency offset with the spectrometer for cavity control. E.g. in DOI: 10.1117/12.2536012 this is the proposed way for a space bourne system. It is a much cleaner signal which is not subject to build-up-time jitter (due to residual inversion etc..).

We agree with the reviewer that the spectrometer data could also be used for the cavity control, but this is out of the scope of the current manuscript. The power lasers and their cavity control are in operation since 2018, but the spectrometer is a more recent development. So the implementation is a question of cost and benefit.

■ In lines 189 ff. the authors begin to speculate about a single event – whether the numerical evaluation worked properly cannot be determined without the raw data of the event.

The sentence: "Destructive interference of adjacent longitudinal modes (mode beating) could explain the observed reduced pulse intensity but should result into a spectral broadening instead of narrowing. In the end, it is unclear which process led to the observed behavior." could/should be verified by opening the control loop of the laser and scanning the Piezo over a full spectral range (532 nm). With a frequency deviation of 40MHz~1/4 FSR detuning I would expect mode beating between two adjacent modes – furthermore I would expect a lower energy/intensity in the main peak. How stable is the FWHM fit when the intensity is reduced and a second peak appears 160 Mhz away from the main peak? - The peak should be still separated but close to each other due to the finesse and spectral width of the pulse.

Therefore, I would advise the characterization of the measurement setup for all possible detunings of the laser cavity.

During this event we found indeed decreased peak maxima by ∼6% (see line 193).

To support our arguments we have added a supplement containing some unpublished figures (measured 2024).

The numerical evaluation should work quite stable even with low intensities as the FWHM determination does not involve fitting of functions which could fail, see the procedure given above. If the FWHM determination was impacted by 2 close-spaced peaks we would not expect a smaller value compared to the value of an isolated peak during normal single-mode laser operation. Figure 1 in our supplement shows a screenshot of the LPS client user interface taken by chance when the power laser was not working single-mode. Here the inner interference ring shows 2 close-spaced peaks which are separated by 10 pixels. At this area on the camera chip one pixel corresponds to approx. 13.5 MHz, resulting in a peak difference of 135 MHz. In this example the numerical evaluation should have calculated the correct (broad) FWHM value by covering both peaks.

Figure 2 in our supplement shows a scan of the piezo over several resonance conditions of the power laser cavity (pulse build-up time as function of piezo position in terms of control voltage), similar to the right figure in the appendix given by the reviewer. Figure 3 in our supplement shows temporal courses of the laser pulse during the piezo scan near and outside a resonance condition. The photos taken from the oscilloscope display contain several laser pulses, the oscilloscope was triggered by the Q-switch sync pulse.

Appendix: Unpublished measurements of a laser with the legendary Lightwave Electronics 101 injection seed laser (measured 2005)

Influence of the laser resonator length on the impulse form and spectrum (Image in the supplement.pdf)

The left figure shows the temporal intensity of q-switched pulses of an injection seeded laser with a resonator length of approximately 80 cm. The pulses were measured using a photodetector with ~2GHz bandwidth. The cavity length is controlled using a Piezo translator where the cavity end mirror is mounted on. Additionally, an unseeded laser pulse is generated by blocking the seed laser.

In the middle the Fourier transform power spectra of the measured pulses is displayed. The laser pulse with the lowest build up time shows the least mode beating. As the cavity is more detuned higher order mode beating appears.

In the right figure the measured laser build-up-time (the rate is approximately 0.05 V/ns) by the injection seeder electronics for different cavity detuning is shown. The measured pulses are indicated by horizontal lines.

We thank the reviewer for sharing this information.