Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2018-389-AC1, 2019

Atmospheric Measurement Techniques Discussions
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Interactive comment on "Laser frequency stabilization based on an universal sub-Doppler NICE-OHMS instrumentation for the potential application in atmospheric Lidar" *by* Y. Zhou et al.

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Received and published: 19 January 2019

Zhou et al. present a system for laser stabilization based on NICE-OHMS. Instead of directly feeding back to the laser, they use a single-sideband modulator as a frequency actuator. This increases the flexibility of the system, as demonstrated by the similar performance achieved with two different lasers. While the system is well designed and implemented, I'm not sure that the results presented relevant enough to the atmospheric community or novel enough for publication in AMT.

Answer: Thanks to the reviewer's comment. NICE-OHMS has been widely used to the fields of metrology, trace gas detection, ion detection and molecular spectroscopy since it has been invented. This manuscript is, for the first time, the intention to apply this technique to the LIDAR-based air monitoring. For the LIDAR system, such as for the detection of CO2 in the upper atmosphere, the laser frequency should be exactly locked to the center of target transition and kept stability in short-term and long-term to ensure an accurate measurement. NICE-OHMS is a good candidate for this purpose due to its unique advantages, such as the properties of ultra sensitive spectroscopy measurement and detection ability of sub-Doppler spectrum. More importantly, the utilization of single sideband modulator (SSB) makes sub-Doppler NICE-OHMS system more universal and compatible with different type of lasers. Therefore we think the involved works open a new vision to the atmospheric community and novel enough for the publication in AMT.

For the applicability to the atmospheric community, more details need to be provided about the potential application to LIDAR: First, what frequency stability is required for LIDAR and why?

Answer: Thanks to the reviewer's comment. In ideality, the better the frequency stabilization of laser frequency, the more accuracy of the result of LIDAR. In reality, the required frequency stability is ranging from hundreds of kHz to dozens of MHz, which depends on the linewidth of the target gas spectrum, [Applied Physics B Vol. 90, 593–608 (2008)]. For example, Jet Propulsion Laboratory in USA has designed a Lidar system with frequency error of $\sim$2 MHz for detection of ν1+ν3 band of acetylene (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.4790&rep=rep1&type=pdf); The group in University of Maryland designed a system with frequency stability better than 0.3 MHz for the detection of CO2 at the wavelength of 1572 nm [Applied Optics, Vol. 50, No.7, 1047-1056, 2011].

My initial thought is that NICE-OHMS is overly complicated for this application. The motivation for using NICE-OHMS was not well justified. What performance has been achieved with a wavemeter and with other schemes such as WMS/FM spectroscopy in a cavity? Why is NICE-OHMS necessary?

Answer: Thanks to the reviewer's comment. Benefiting from the modularized fiber laser and integrated fiber components, NICE-OHMS instrument is getting more and more compact than its inception. On the other hand, molecular transitions are the best frequency reference especially for the long-term laser stability since the frequency accuracy of a wavelength meter is normally in the order of tens MHz and meanwhile strongly relies on the ambient working conditions. In this paper we suggested a sub-Doppler spectrum, which is more sensitive to frequency excursion from transition center than Doppler broadened spectrum, to be applied to the high-performance frequency stabilization. For the LIDAR-based air monitoring system, the absorption path length is normally in the order of tens kilometers. A weak transition for the target gas has to be selected to ensure the laser power can not be fully absorbed in the measuring height range. In order to get a frequency stabilized laser, a highly sensitive laser absorption spectroscopy technique should be employed to get a high SNR error signal for laser frequency locking. As you suggested that a cavity can be used to perform a high sensitive measurement together with the techniques of WMS and FMS. However, WMS can only be used with the OA-ICOS or other cavity enhanced techniques without frequency locking but with a relatively low signal to noise ratio [Applied Physics B Vol.75, 755 (2002)]. By the way, NICE-OHMS, also named as cavity enhanced frequency modulation spectroscopy, is just based on the combination of FMS and cavity enhanced absorption spectroscopy, which can obtain ultra sensitivity and high intracavity buildup power to get sub-Doppler signal of weak transition.

What gas is expected to be used for the LIDAR application (C2H2 is not the most atmospherically relevant)? How will the performance compare (i.e., what are the linestrengths, expected linewidths, etc.)?

Answer: Thanks to the reviewer's comment. I agree C2H2 is not the most atmospherically relevant. In the LIDAR-based gas monitoring applications, CO2, CH4, N2O et al. in the atmosphere are normally monitored [Applied Physics B Vol. 90, 593–608 (2008)]. In this sumitted paper, C2H2 is used to demonstrate the feasibility of our NICE-OHMS system, just like the works in Jet Propulsion Laboratory (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.4790&rep=rep1&type=pdf). As we know that the amplitude of saturation spectroscopy relies on the pump laser power and dipole moment of target transition. The dipole moment can be calculated by use of linestrength, partition function and life time et al. The linewidth of the obtained sub-Doppler saturation spectroscopy is normally in the order of several MHz.

For the novelty, the included Gatti et al. reference has already demonstrated a wide bandwidth PDH lock using a single sideband modulator. This fact should be clarified in the current paper and the differences between this and the Gatti work should be discussed (e.g., the feedback bandwidth was higher in Gatti et al). Also, why was a lower bandwidth VCO used for VCO1? Demonstrating the ability to use a DFB or ECDL would make this a stronger paper.

Answer: Thanks to the reviewer's comment and suggestion. The published paper by D. Gatti et al. do provide a good suggestion to the frequency locking of laser to an external cavity based on a single sideband modulator. However NICE-OHMS is a systematic work, which includes not only a technique of frequency locking, but also other techniques and methods such as DeVoe-Brewer locking, frequency modulation spectroscopy and spectrum analysis. The paper's novelty is obvious. Actually, this paper extends the application of the technique suggested by D. Gatti et al. to the NICE-OHMS. We will change the sentence "It would be possible to increase the bandwidth of this PDH servo to 3 MHz if a high bandwidth VCO would be employed (Gatti et al., 2015)." to "As suggested by D. Gatti, et al., the bandwidth of PDH servo can be increased to 5 MHz if a higher bandwidth VCO and a good PID servo would be employed (Gatti et al., 2015)" in the final version. Actually, we are devoting ourselves to find a VCO with narrow linewidth and wide bandwidth right now. Definitely, a NICE-OHMS system based on DFB or ECDL by use of a single sideband modulator with wide bandwidth PDH locking would be considered as a technique improvement.

In addition, before publication the language could use some editing. Finally, I have some more specific comments/questions as well: 1. "DVB" and "F-P cavity" are not defined in the caption to Figure 1

Answer: Thanks for the reviewer's suggestion. The revisions will be done in the final version.

2. Why were OAPs used instead of lenses?

Answer: Thanks to the reviewer's comment. The substitution of lenses by OAPs is aimed to relieve the generation of etalon noise, which is caused by the reflection between two optical surfaces. The previous work has proved its validity. [Journal of the Optical Society of America B, Vol. 32, No. 10, 2104-2114 (2015)].

3. For the LIDAR output, will the frequency need to be tuned, e.g., to do an online/ off-line measurement? If so, how will this be accomplished?

Answer: For a differential absorption LIDAR, the wavelength should be switched on or off target gas resonance. [Proceedings of The IEEE, Vol. 77, No. 3, March 1989]. However the technique introduced in this paper is aimed to the gas measurement with fixed optical frequency.

4. For Figure 2, it would be better to give the noise PSD. Also, I assume that this is an in-loop measurement? This should be clarified. In addition, I believe that this should be corrected for the cavity low-pass filter effect (e.g., Fig 5 in Gatti et al)?

Answer: Thanks for the comments and suggestion. The noise power spectrum is measured by a electronic spectrum analyzer under the in-loop condition. In this submitted paper, the figure 2 is mainly used to demonstrate the similarity of our system for the two applied lasers by showing its robust restrain of frequency noise in low frequency region, the servo bandwidth of 200 kHz and its universality. As a consequence, the modification of y-scale is not significant. In order to more clearly describe the presented noise properties, the RBW and VBW in the measurement are inserted to the paper. On the other hand, the low pass filter effect should be used to correct the noise power spectrum for the analysis of frequency derivations at different Fourier frequencies. In this paper, we don't care so much on this point due to the noise immune properties. Therefore, "Figure 2 shows frequency noise spectra of the error signals for PDH locking. The black and red lines represent the situations for the EDFL and the WGM lasers, respectively, measured without any change of servo parameters for the PDH locking." will be changed to "Figure 2 shows the frequency noise spectra of the in-loop error signals for PDH locking, which is measured by a electronical spectrum analyzer (FSW, Rohde&Schwarz, Germany). The black and red lines represent the situations for the EDFL and the WGM lasers, respectively, measured without any change of servo parameters for the PDH locking. Both the Video Bandwidth (VBW) and Resolution Bandwidth (RBW) in the measurement are 30Hz." in the final version.

5. What causes the upturn in the Allan deviation past 200 seconds?

Answer: Thanks to the reviewer's comment. "The upturn of Allan deviation is due to the residual amplitude modulation of fiber EOM, the not perfect design of PDH servo and etalon noise in the beam path." will be inserted to the last of section 4 in the final version.

6. What was the temperature stability of the lab? How would the performance be affected by reduced temperature stability?

Answer: Thanks to the reviewer's comment. The lab is not temperature controlled and strongly depends on the air temperature outside the lab. Generally, the room temperature can change 0.5 degrees Celsius during a day. The reduced temperature stability will absolutely improve the long-term performance of the system, because the residual amplitude modulation of fiber EOM and etalon noise in the beam path are easily influenced by the temperature.

Please also note the supplement to this comment:

https://www.atmos-meas-tech-discuss.net/amt-2018-389/amt-2018-389-AC1-supplement.pdf

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2018-389, 2018.