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Atmospheric Measurement Techniques Discussions

Interactive comment on "A Compact Rayleigh Autonomous Lidar (CORAL) for the middle atmosphere" *by* Bernd Kaifler and Natalie Kaifler

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We thank the reviewer for the in-depth review of our manuscript. There are several aspects which we missed and which need more careful explanation to make our intentions clear and our description concise. We address the comments below and will add missing information in the revision of the manuscript.

1 However, I have several restrictions in the present form and I consider that this manuscript requires some critical improvements. The first one concerns the missing references for many aspects while a lot of works has already been done by the research community. Auto-citing needs to be balanced by work performed by the international research community. The second one concerns the technical choices. No alternatives are presented and this is missing to convinced readers that the choices performed by authors are the results of an optimum scientific choice and to avoid part of the manuscript being a technical note rather than a scientific contribution.

It is our intention to describe our system and convey its advantages. Discussing all developments which happened in the past would significantly change the focus of the manuscript and likely turn it into a review style paper. The latter is not our aim nor do we feel qualified to write such a paper since our experience with lidar systems covers only the last decade.

We agree that we should discuss alternative methods for beam tracking since the conscan method is a new concept in mesospheric lidars, and we should point out the rationale for using a bistatic transmitter/receiver configuration. Apart from those modifications, we believe our lidar setup is fairly standard for contemporary mesospheric Rayleigh lidars. It is our opinion that by now e.g. the benefits of using diode-pumped lasers are widely recognized within the community and no explanations are needed any more. It was our desire to keep the manuscript short and focused rather than discussing technological choices which we think are nowadays obvious.

2 Finally, the capabilities of the lidar need to be discuss and mainly regarding the automatization issues. How this mode does not perturb nominal capabilities, and what are the proxy used to check the temperature retrieval quality. No comparisons with other observations are presented. While operators introduce some uncertainties in the quality of the observations, automatic mode main also introduce some bias. How can we check this issue?

We are not entirely sure what the reviewer means by "nominal capabilities". If manual operation is meant, like it is done with non-automatic systems, then this mode of operation is still possible with CORAL. The autocontrol software can be stopped and control switched to remote control by an operator at any time. Moreover, manual operation by throwing switches inside the container is also possible.

In the manuscript we show comparisons with approximately co-located SABER measurements and ECMWF profiles (see Fig. 8). Ehard et al. (2018) present a detailed comparison of lidar temperature profiles and ECMWF data which reveal an almost perfect agreement up to $\sim$50 km where ECMWF starts to diverge (see their Figure 2). We agree that the section discussing the temperature retrieval is rather short and may need expansion, in particular with regard to assumptions made in the retrieval and with regard to quality checks of the data.

We are not sure what kind of biases an automatic measurement mode should introduce. The automatic measurements are exactly the same as manually controlled measurements with regard to data acquisition. Automatic measurements allow regular probing of the atmosphere at marginal weather conditions, conditions which are usually avoided when operating lidars manually. That may lead to, for example, enhanced gravity wave potential energy densities in those measurements because stormy conditions are thought to favour excitation of mountain waves. We are in the process of studying this potential effect in detail. Actually, within the lidar community there is a long standing discussion whether lidar measurements are biased towards fair weather at-

mospheric conditions. Following that discussion, our automatic measurements may be a path forward to remove that potential bias in measurements. Thus, automatic measurements may actually remove a potential bias rather than introduce one. The study is still work in progress and preliminary results indicate no bias in mean temperatures. In particular, dividing our measurement data into two subsets comprising of long and short measurements, the latter being usually acquired during marginal weather conditions, does not result in any significant deviations in monthly mean temperatures.

3 Line 24 page 1: The comment about the fact that lidar only operate during campaigns is a wrong statement while within the NDACC network routine measurements are performed over many sites around the world. The longest data based is obtained at Observatory of Haute-Provence with more than 40 year of continuous observations. Many publications are related to these long commitments. The only thing true is that these systems do not have fully automatic mode for their operations (some of them have semi-automatic mode with possibility to stop when rain and cloud are coming)and require operators for turning them on and ensuring alignment. For data analyses some NDACC partners have automatic software's to process the data real-time including automatic data cleaning. This statement needs to be modified and a section about the associated works need to be provided while many climatologic works have been performed including trends that were published in international reports for IPCC, ozone assessment or SPARC-WCRP.

We agree that using the word "campaign" may have been misleading. What we meant is that these long-term operated lidar stations generally take routine measurements only during certain days per week when the weather forecast is favorable. For example, at the ALOMAR observatory which with the authors have some experience, no lidar observations are conducted at weekends outside of special campaign periods. The quasi periodic but sparse observations may be sufficient for producing climatologies and estimating trends as mentioned by the reviewer, but clearly are not adequate for studies requiring dense sampling e.g. the investigation of the temporal evolution of gravity wave events. We will change this statement in the revision of the manuscript to make that clear.

4 Page 2 line 26: Many gravity waves climatology were already performed that need to be cited. One of the first I think was performed by Wilson et al. in late 1980's and early 1990's.

We agree that there are many lidar-based gravity wave studies in literature e.g. Wilson et al. (1991); Sivakumar et al. (2006); Rauthe et al. (2008); Li et al. (2010); Mzé et al. (2014); Kaifler et al. (2015). However, non of these studies document the detailed temporal evolution of a mountain wave event lasting several days. It is our point here that automatic instruments like CORAL allow the investigation of the temporal evolution of singular events, which, to the knowledge of the authors, is not possible based on other pre-existing lidar data sets because of the much lower measurement cadence. It was not our intention to indicate that only CORAL-type lidars can produce gravity wave climatologies.

5 Page 2 line 58: Operators are also required for safety reasons and air traffic control. These issues need to be introduced here and information about the capabilities of CORAL can be discuss and documented later on the manuscript. The issue is; how authorities can have confidence of such system?

That is indeed an important topic that we neglected in our manuscript. At the southern tip of South America air traffic is so low that no particular safety measures are requested by the authorities in Argentina. We use an Automatic Dependent Surveillance–Broadcast (ADS-B) receiver for receiving aircraft position information. This information is used by the autocontrol software of CORAL to automatically shut down the laser when an aircraft enters a circle of 800 m radius centered at the location of CORAL. Measurements are resumed when the aircraft leaves the circle. However, within the three years of operation, no single aircraft was detected within the critical zone. At the DLR site near Munich we use a restricted area that is closed for air traffic during lidar operations, and during the Deep Propagating Gravity Wave Experiment (DEEPWAVE, see Fritts et al. (2016)) there was again so little air traffic above Lauder, New Zealand, that no special safety measures were required by local authorities.

For other places we are contemplating the use of a radar system in combination with an optical system for detecting approaching aircraft. The output of the radar would be wired directly to the interlock of the laser to bypass any potential software failures. Still, proving the reliability of such a system is a major difficulty for getting approval by local authorities, and operation of a lidar at locations with heavy air traffic may be even denied regardless of any safety measures. In that regard, the density of expected air traffic may be another relevant factor for setting up a lidar at a particular location.

6 Section 2 about lidar description. The description here requires some arguments about the choice rather in referencing to past work of the team, to work performed by other teams or in providing evidences through graphic or capability comparisons when technical choices are different from what the scientific community has performed.

The biggest departure from ”classical” lidar setups is probably the use of the conscan method for beam tracking. The reason for preferring this method over other methods was missing in the manuscript and is discussed in the following section. We will add this information in the revision of the manuscript. Apart from conscan, the CORAL lidar setup is straight forward and similar to setups used in other lidar systems. Minor changes include the selection of a bistatic transmitter/receiver configuration which eliminates two bending mirrors needed for a coaxial configuration, and consolidation of the lidar electronics in a single custom-developed electronics box.

7 Page 6 section about automatic tracking of the laser beam. This section is well de-scribed and critical for lidar automatization. It requires an introduction explaining the technical choices compare to other methods and also the sinusoidal exploration was not explained. Final capabilities need to be demonstrated. Figure 7 is not so clear for me. Also, the time speed for correct alignment need to be discussed according the sky conditions. This is a critical point while human have a exploration mode that is sometime more efficient while less quantitative. Also the geometry here is coaxial. Is it a requirement or the development described here can be apply to bi-axial systems?

The authors are familiar with two other methods for beam alignment. Manual alignment involves moving the laser beam by hand using motorized beam folding mirrors

in the transmitter optical path. The operator commands the motors while watching the strength of the lidar return signal at a certain altitude and tries to find the optimum position where the signal maximizes. This works well when the sky is clear and tropospheric transmission does not change in time, but is absolutely impossible during conditions of e.g. broken clouds. An automatic autoguiding system is described by Innis et al. (2007). In their setup, a camera looks through the telescope via a pellicle beam splitter and images the laser beam at a certain altitude. Images are analyzed and the position of the laser beam is computed. This position information is then used to compute an error signal relative to a target position, and the error signal is subsequently fed to motorized actuators in order to neutralize any deviation from the target. We have used such a system in the beginning but removed it when it became clear that the conscan method performed much better in marginal weather conditions. One of the main problems with the camera based autoguiding system was thin cloud layers passing through the altitude where the beam is imaged. Because Mie scattering within the clouds is much stronger than Rayleigh scattering, the autoguiding algorithm tended to track features within the clouds rather than the actual beam position. This caused a misalignment of the laser beam and, given our rather small FOV, resulted in incomplete overlap and thus unusable data.

The conscan method does not suffer from this problem because the lidar return signal is evaluated at altitudes well above potential cloud layers. We have added additional panels to Fig. 7 (shown here in Fig. 1) to show the phase, amplitude, and χ^2-signal retrieved from conscan measurements. As pointed out in our reply to Reviewer Comment #1, the conscan signal is impacted by changes in tropospheric transmission caused by clouds and demodulation of the conscan signal may fail sometimes. This condition is detected by the conscan algorithm and the current conscan cycle is aborted without updating the beam position. In most cases aborted conscans can be tolerated as long as a minimum of 1 out of $\sim$10 scans succeeds. Thermal drifts within the lidar system are generally slow, and even a reduced update rate is sufficient to track the laser beam. Fast beam tracking is only needed during the beginning of the lidar operation when the initial position of the laser beam may be far from the optimal position. But even for those cases we find that our conscan implementation achieves nearly perfect beam overlap within 3-6 min. In challenging conditions, e.g. broken clouds, that period may extend up to ~ 10 min.

The performance of our conscan implementation may be assessed from Fig. 1 panels a and b. Within the first hour of lidar operation, the FOV of the telescope drifts by more than 150 µrad which is about half of the FOV. Without beam tracking, we would expect a significant decrease of the lidar return signal (shown in panel b) over time. However, peaks in panel b between 4 and 5 UTC indicate a near constant maximum signal of approximately 8×10^4, a strong indication that the conscan algorithm kept the laser beam centered within the telescope FOV. These peak signals were acquired when the laser beam passed through holes in the cloud layer, while in between the lidar return signal was strongly fluctuating due to scattering within clouds.

We decided to use a sinusoidal modulation of mirror angles because the resulting motion does not require strong accelerations and therefore results in minimal stress on the mirror. Gawronski and Craparo (2002) studied rosette and Lissajous figures in addition to the conscan within the context of spacecraft tracking. In lidar applications, these more complex pattern may also provide advantages in some cases, but a detailed study is needed to assess their potential negative impacts. Gawronski and Craparo (2002) conclude that all three scan techniques have similar properties in the estimation of signal positions and they suggest to use the conscan because of its simplicity.

Actually, our CORAL system uses a bistatic transmitter/receiver configuration. We have never tested the conscan method in a coaxial setup, but there is no obvious reason why it shouldn't work. The algorithm does not assume any particular geometry and the sole requirement is that full geometric overlap between laser and telescope FOV is possible at the altitude where the conscan signal is evaluated.

8 Page 15 section example. In this section comparisons with other observations are required. No additional observations will fully validate the full profile except radiosondes. Also, many comparisons between other Rayleigh lidars and satellite instruments have been performed, is CORAL found similar deviations. Authors mentioned MLS and SABER, recent comparisons were published and can used as comparisons. The main point will be about the demonstration that such alignment does not introduce any bias. Comparison with radiosonde and temperature retrieval right after alignment will be a first demonstration. Within NDACC, lidars ensure their qualification by comparison with a mobile system running by NASA. Many publications have reported about these comparisons. It is out of the scope of this studies but collocated measurements with other lidars will allow to convinced the scientific community about the data quality.

We agree that validation of measurement data is an important step. Unfortunately, a second independent mobile lidar system is not available for cross-validation at the location of CORAL. We show a comparison with SABER and ECMWF profiles in Fig. 8 of our manuscript.

A coincident radiosonde sounding, shown in Fig. 2, was acquired during the Southern hemisphere Transport, Dynamics and Chemistry (SOUTHTRAC) campaign. A $\sim$35 min hole in the cloud layer allowed the retrieval of a temperature profile with 20 min integration time centered at 02:10 UTC on 16 November 2019. The period coincides with the upper part of a radiosonde launched at Rio Grande airport approximately 2 km away from CORAL. Both profiles show a nearly perfect agreement with < 0.6 K mean difference between 28 and 33 km altitude. While differences increase to ~ 2.7 K at the bottom of the lidar profile, we have to keep in mind that the radiosonde crossed these altitudes about 1 hr earlier and atmospheric conditions may have changed. The lidar measurement was acquired in fully automatic mode, demonstrating that the conscan method achieved beam overlap and tracking in less than 10 minutes after a cold start of the system.

When writing the manuscript we initially did not include this comparison because, contrary to the statement of the reviewer, radiosondes can validate only the lower part of a lidar temperature profile, as Radiosondes rarely reach altitudes > 35 km. We will include Fig. 2 in the revised manuscript.

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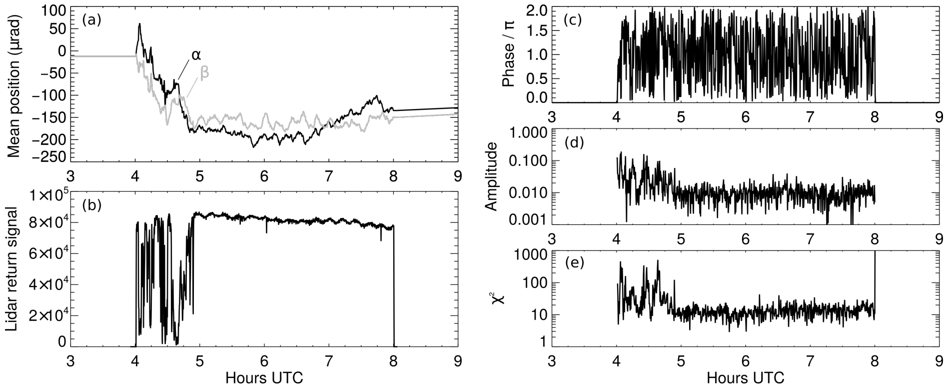

Fig. 1. Performance of the conscan system during the measurement on 3 November 2019, 4-8 UTC. (a) Scan mirror angles, (b) lidar return signal, (c) phase and (d) amplitude of the demodulated signal.

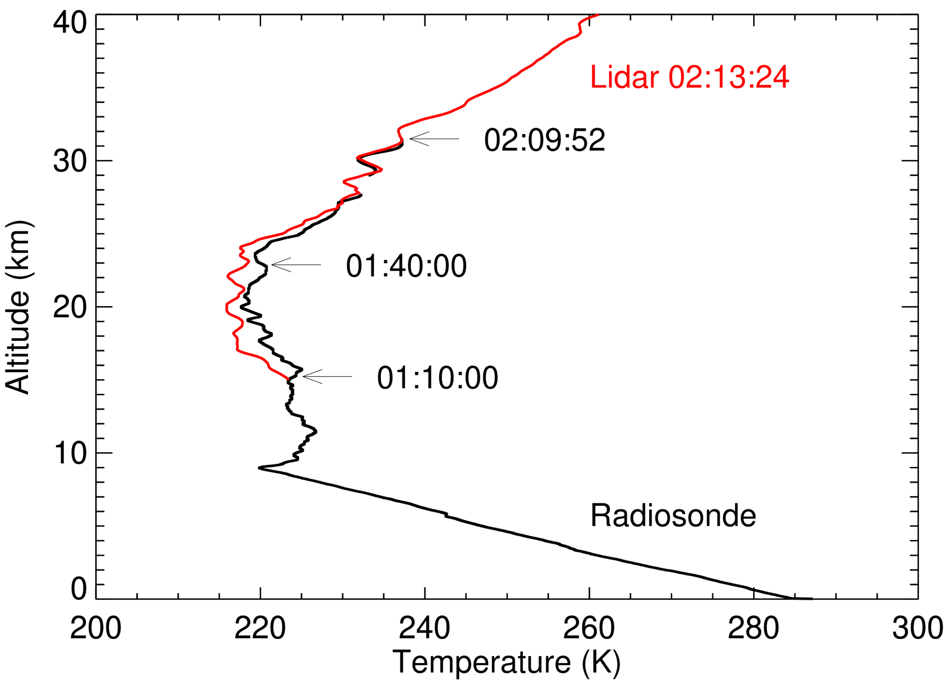

Fig. 2. Radiosonde and lidar profile acquired on 16 November 2019. The arrows indicate the height of the radiosonde at different times. All times are mm:hh:ss UTC.