Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Water Vapor lidar: The Vaisala Broadband Differential Absorption Lidar (DIAL)

ROB NEWSOM[1], DAVE TURNER[2], RAISA LEHTINEN[3], CHRISTOPH MÜNKEL[3]*, JUKKA KALLIO[3], RENO ROININEN[3]

[1] PNNL, RICHLAND, WA, USA
[2] NOAA/ESRL, BOULDER, CO, USA
[3] VAISALA, VANTAA, FINLAND
** RETIRED*

DOE ASR PI meeting, June 10-14, North Bethesda/Rockville, MD

U.S. DEPARTMENT OF ENERGY

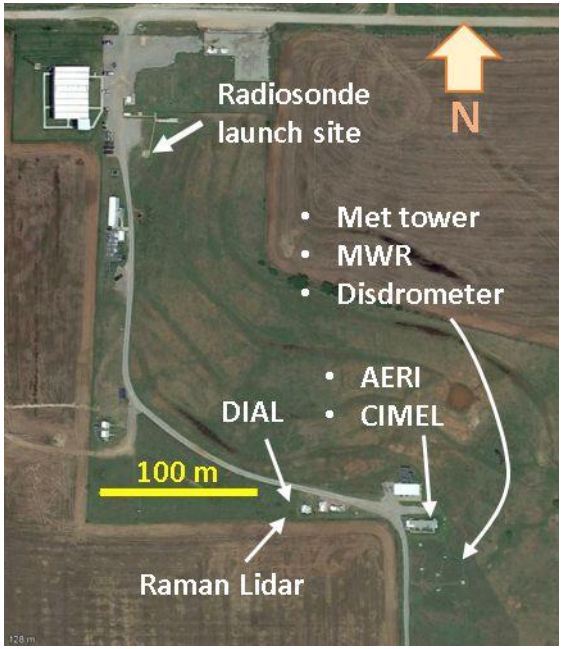
ARM CLIMATE RESEARCH FACILITY

Background

- There is a need for a national network of (small and cheap) ground-based instruments capable of profiling water vapor and temperature in the atmospheric boundary layer.

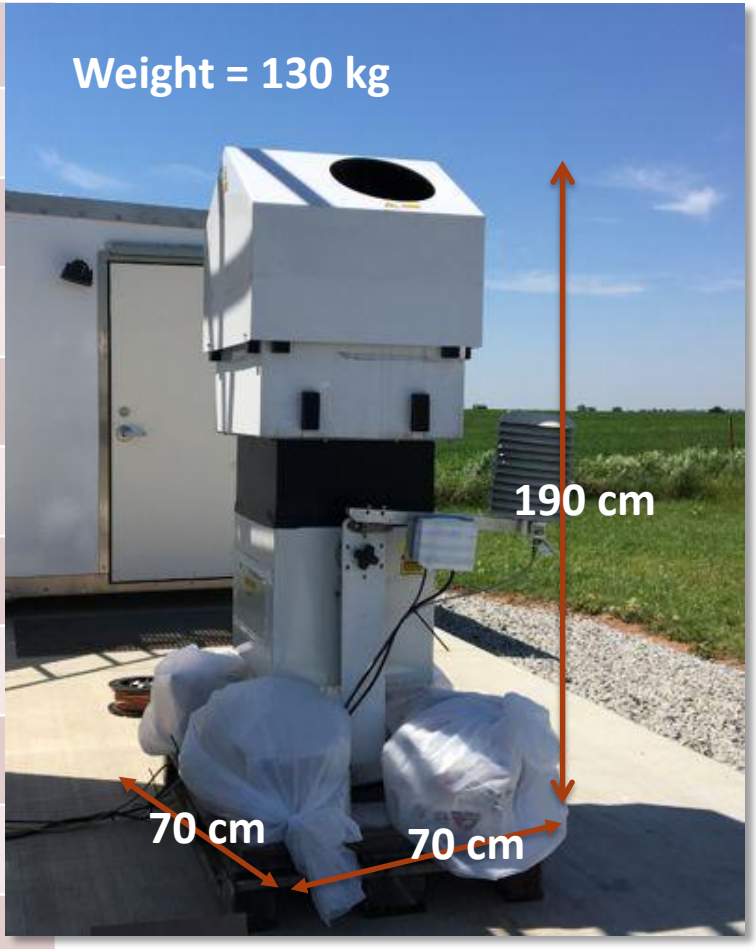
- Back in the spring of 2017, Vaisala approached ARM about deploying their new water vapor Differential Absorption Lidar (DIAL) to SGP for evaluation

- Conducted a field campaign at SGP C1 to access performance the Vaisala DIAL
  - 15 May to 12 June 2017
  - Deployed the DIAL next to the Raman lidar
  - Compared water vapor mixing ratio from the DIAL to
    - Raman lidar
    - Radiosonde
    - AERI



Vaisala DIAL Specs

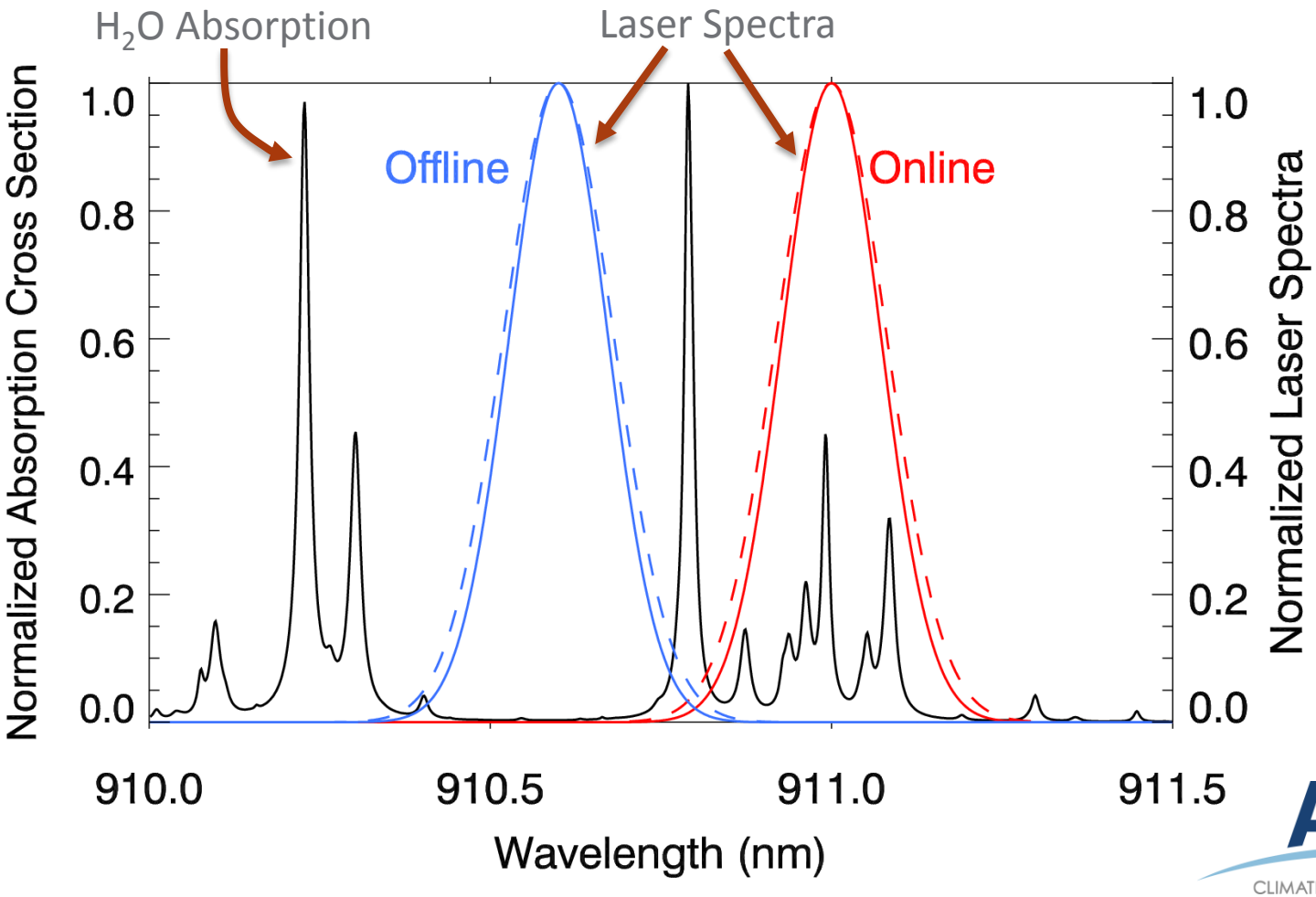
Laser eye-safety classification	**1M**
Averaging time /reporting interval	**20 min / 2 min**
Maximum range	**3000 m reported**
Range resolution	**100 – 500 m**
Average power per unit	44 mW
Pulse energy	5.5 µJ
Pulse peak power	25 W
FWHM pulse width	220 ns (33 m)
Pulse repetition rate	8 kHz
Wavelength (online/offline)	**911.0 nm/ 910.6 nm**
FWHM spectral width (near/far range)	**0.19 nm/0.17 nm**
Telescope diameter (near/far range)	150 mm/280 mm
Receiver detector	APD



The Vaisala Broadband DIAL

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- The Vaisala DIAL is unique in the sense that it uses a broadband approach.



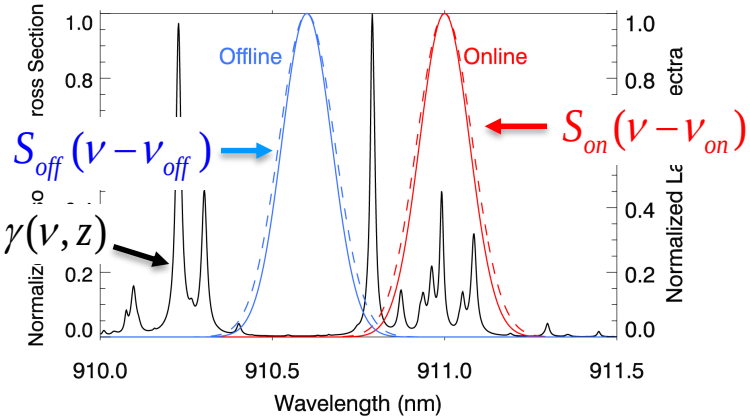
Normalized water vapor absorption cross section at **296K and 1 atm** (black). The normalized laser spectra for **the far-field (solid) and near-field (dashed)** are shown in red for the online laser, and blue for the offline laser spectra.

ARM CLIMATE RESEARCH FACILITY

Water Vapor Retrieval Using the Broadband Approach

- Ratio of the online-to-offline return signals

$$\frac{P'_{\nu_{on}}}{P'_{\nu_{off}}} \simeq \frac{\int_{-\infty}^{\infty} S_{on}(\nu-\nu_{on})T_{WV}^2(\nu,z)d\nu}{\int_{-\infty}^{\infty} S_{off}(\nu-\nu_{off})T_{WV}^2(\nu,z)d\nu} \quad \textbf{(1)}$$



$S_x(\nu-\nu_x)$ = Laser spectra

$$T_{WV}(\nu,z) = \exp\left(-\int_0^z N(z)\gamma(\nu,z)dz\right)$$ = Transmission due to water vapor absorption

  - Assumes aerosol backscatter >> molecular backscatter
  - Online-to-offline aerosol backscatter ratio ~ 1
  - Spectrally flat receiver transmission function
- Goal is to find $N(z)$, the water vapor density, as a function height. In general, a closed-form solution for $N(z)$ is not possible. Instead, $N(z)$ must found using some sort of numerical optimization technique such that equation (1) is satisfied. This is a retrieval problem.

Contrast with Traditional Narrowband Approach

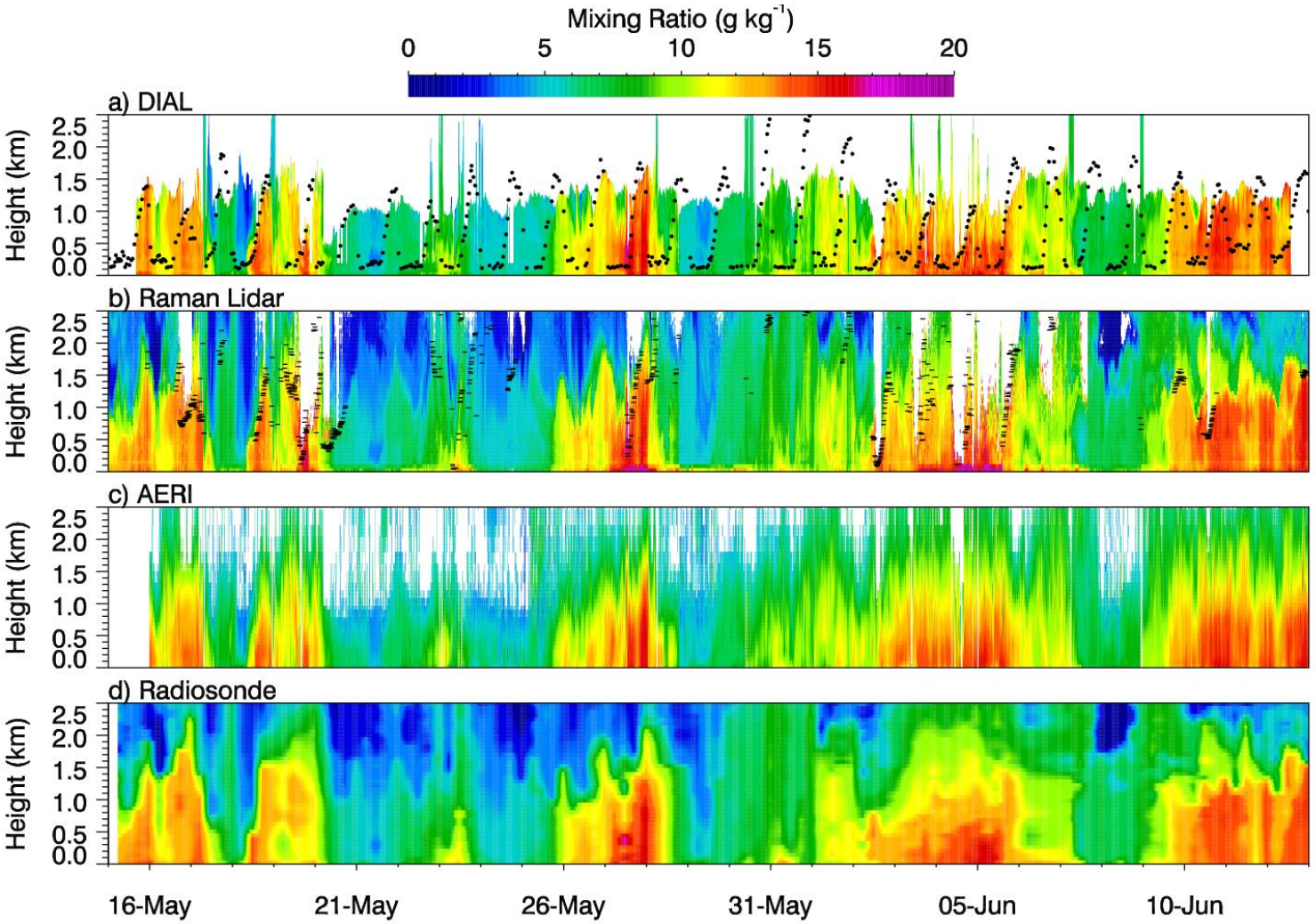
$$\frac{P'_{\nu_{on}}}{P'_{\nu_{off}}} \simeq \frac{\int_{-\infty}^{\infty} S_{on}(\nu-\nu_{on})T_{WV}^2(\nu,z)d\nu}{\int_{-\infty}^{\infty} S_{off}(\nu-\nu_{off})T_{WV}^2(\nu,z)d\nu} \qquad \textbf{(1)}$$

- In the case of narrowband DIAL the laser spectral widths are much narrower than the absorption feature of interest. In that case, the laser spectra can be approximated as delta functions, $S_x(\nu-\nu_x) \rightarrow \delta(\nu-\nu_x)$
- Equation (1) becomes $\frac{P'_{\nu_{on}}}{P'_{\nu_{off}}} \simeq \frac{T_{WV}^2(\nu_{on},z)}{T_{WV}^2(\nu_{off},z)}$
- A closed-form solution for the H_2O density can then be obtained

$$N(z) = \frac{\ln\left(P'_{\nu_{off}}(z)/P'_{\nu_{on}}(z)\right)}{2\left(\gamma(\nu_{on},z)-\gamma(\nu_{off},z)\right)}$$

ARM CLIMATE RESEARCH FACILITY

Qualitative Comparisons



DIAL

Raman lidar

AERI

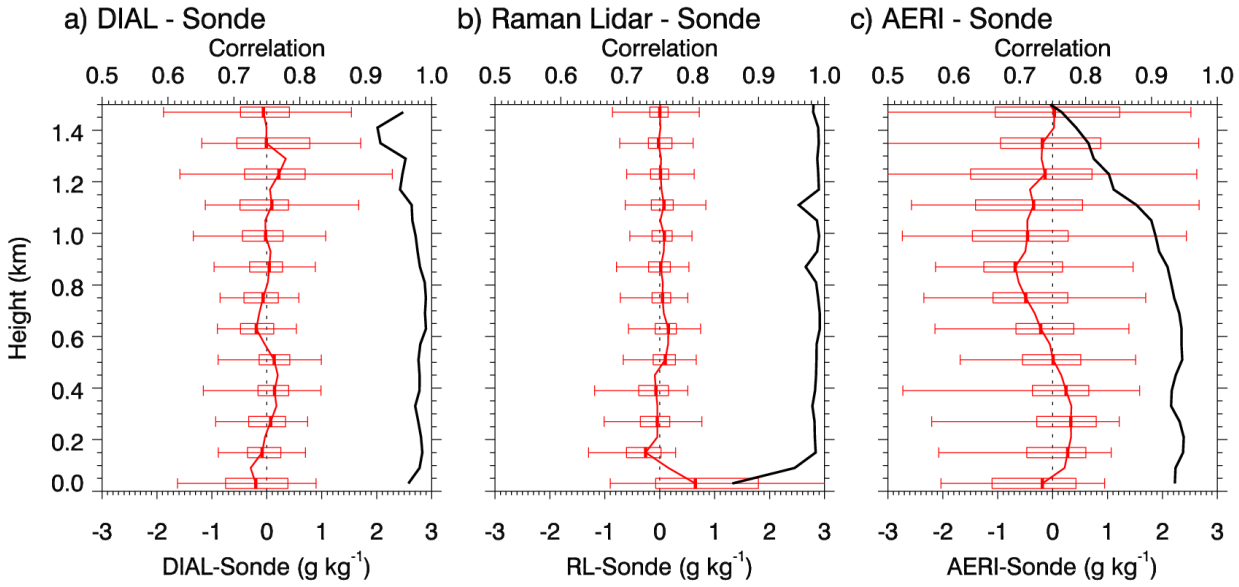
Radiosonde (interpolated)

Quantitative comparisons

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

ARM CLIMATE RESEARCH FACILITY

Profiles

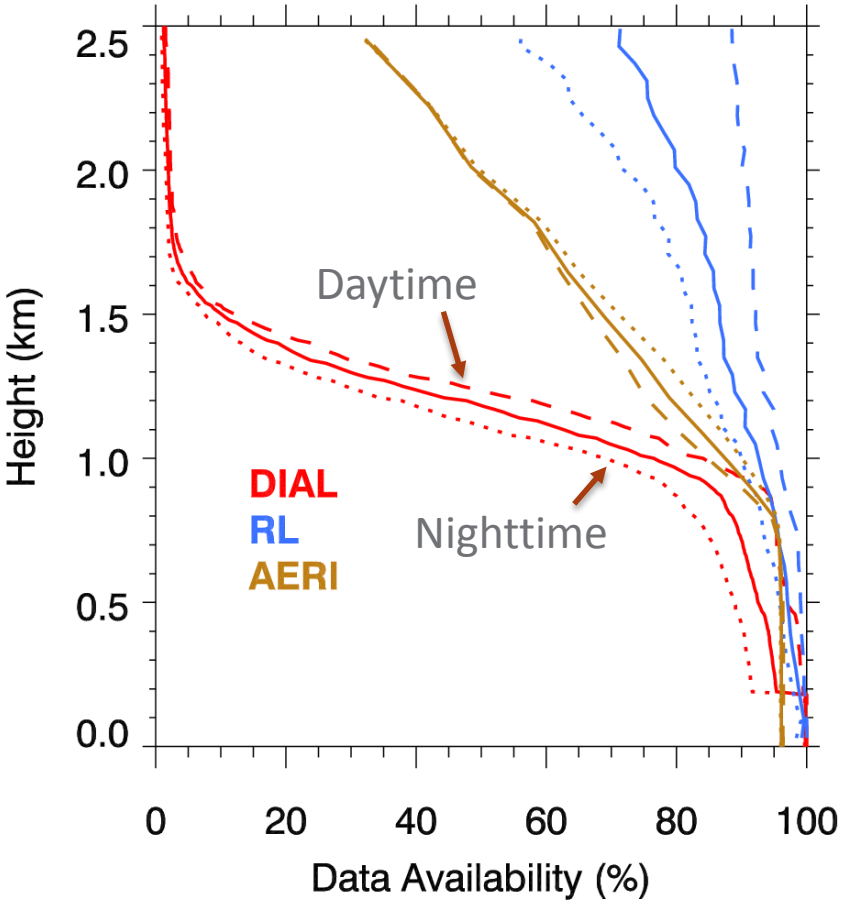


Overall

	DIAL-Sonde	RL-Sonde	AERI-Sonde
Bias (g kg^{-1})	-0.01	0.07	-0.23
StDev (g kg^{-1})	0.65	0.74	1.23
Corr	0.98	0.97	0.92
Mean percent difference (%)	0.42	0.87	-2.0

Data Availability

- Data availability for the DIAL was greater than 90 % below 900 m, but then decreases rapidly with height above this level to less than 10% above 1500 m AGL



Data availability is computed by adding the number of valid samples at a fixed height and dividing by the total number of time samples that were possible.

Summary

- Pros: The Vaisala DIAL showed excellent agreement with the radiosonde (and the Raman lidar) during the SGP field campaign
  - Bias ~-0.01g kg^{-1}, stDev ~ 0.65g kg^{-1}, corr ~0.98
  - Experienced no failures during the campaign
- Cons: The range was somewhat limited
  - Roughly 1.5 km max range
  - 90% data availability below 900 m, but decreased rapidly with height above 900m.
- Calibration?
  - Estimates of the online and offline laser spectral widths were obtained by optimizing the agreement with the radiosonde measurements over the course of the entire experiment. This is essentially a calibration procedure.
  - Linear trend analysis of the DIAL-sonde difference did not show significant drift with time over the course of the field campaign.