Vaisala DIAL Atmospheric Profiler DA10

VAISALA

Technical Paper

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This technical paper discusses the Vaisala DIAL Atmospheric Profiler DA10, which measures water vapor profiles using DIAL technology.
It offers real-time backscatter profiles, cloud data, and continuous operation in all climates, enhancing weather prediction accuracy with high-quality, real-time data.

What is DA10?

DA10 is a state-of-the-art remote sensing instrument that uses differential absorption lidar (DIAL) technology to measure water vapor profiles in the atmosphere. Additionally, it provides real-time attenuated backscatter profiles and cloud data products, offering superior ceilometer-type data quality and signal-to-noise ratio.

Attenuated backscatter and water vapor mixing ratio profiles are monitored in real time, with the device capable of operating 24/7 in all climates. The data clearly shows the vertical structure of humidity in the atmosphere and its evolution, as well as the evolution of the atmosphere in terms of clouds, fog, aerosol layers, precipitating clouds, and precipitation reaching the ground.

DA10 provides continuous, unattended, real-time water vapor profiling, significantly enhancing operational observation networks and advancing numerical weather prediction.

Measurement principle

DA10 uses the laser light detection and ranging (lidar) method where short, powerful yet eye-safe pulses from a diode laser are sent out in vertical or near-vertical direction at two wavelengths:

1. Online wavelength (911.0 nm) in a section of the electromagnetic spectrum that has high water vapor absorption
2. Offline wavelength (910.6 nm) in a nearby section of the spectrum with low water vapor absorption

DA10 alternates the transmission of laser pulses between the online and offline wavelengths. Part of the pulsed signals scatter back towards the instrument from atmospheric particles such as liquid cloud droplets, ice crystals, precipitation, fog, and various aerosols at each height. The rest of the light is either absorbed or scattered in directions not detected by the instrument. The portion of backscattered light at each height is registered by the receiver using an avalanche photodiode detector. These received signals are then translated into vertical profiles of online and offline signals.

The received offline signal is almost free from water vapor absorption, whereas the online wavelength is chosen to ensure high water vapor absorption. Consequently, the profile with the offline wavelength produces more backscattered signal compared to the profile measured with the online wavelength. Therefore, the ratio between the online and offline signals at each height contains information about the amount of water vapor in the atmosphere and its vertical structure.

DA10 uses a broadband DIAL approach, where the spectrum of the online laser output overlaps multiple water vapor absorption lines. Estimates of the water vapor mixing ratio are based on the ratio of the online and offline signals. The retrieval method minimizes a cost function between the measured and modeled online-to-offline signal ratios with respect to the estimated water vapor concentration.

The instrument contains two independent lidar systems: a smaller one optimized for near-range measurements and a larger one for far-range measurements. Each lidar system consists of a lens telescope used for both transmission and reception. The software combines the measurements from both systems, resulting in optimized performance over the full measurement range.

For more information on the measurement principle, see the research article: Evaluation of a Compact Broadband Differential Absorption Lidar for Routine Water Vapor Profiling in the Atmospheric Boundary Layer https://doi.org/10.1175/JTECH-D-18-0102.1.

Data products

DA10 provides attenuated backscatter profiles measured up to 18 km in the atmosphere. Water vapor mixing ratio profiles, along with their uncertainty estimates, are reported from the ground up to 4 km, limited by the boundary layer or cloud top, whichever is lower.

The highest valid data point of the water vapor mixing ratio is reported as the maximum range. Additionally, the ceilometer-type cloud products, diagnostics, and other metadata are reported by the instrument.

Attenuated backscatter profile

DA10 reports attenuated backscatter profiles which correspond to the processed vertical profiles measured with the offline wavelength. Attenuated backscatter is reported with a 4.8 m resolution from the ground up to 18 km, and this data is averaged over one minute by default.

Figure 1 shows the attenuated backscatter profile measurements over one day measured in Germany by Karlsruhe Institute of Technology (KIT). The time in UTC hours is presented on the x-axis, and height above the instrument is presented on the y-axis from ground up to 18 km.

The amplitude of the attenuated backscatter coefficient is presented on a logarithmic color scale in units of 1/(m*sr). Different atmospheric phenomena and structures can be seen in the image.

From 00 to 06 UTC, there is a precipitating cloud between 2 km and 5 km. The precipitation reaches the ground at around 02 UTC. The melting layer can be visually identified at around 1 km in the precipitation layer reaching the ground. The presence of the melting layer can be seen as a decrease in the attenuated backscatter profile, as the scattering properties are changing when ice crystals are melting to raindrops. From 07 to 10 UTC it is mostly clear sky, only a short period of liquid cloud is present at around 3 km. Later in the day, there are ice clouds present between 5 and 10 km, and lower supercooled liquid clouds with falling ice crystals. The planetary boundary layer is visible near the ground, with a residual layer from the previous day and aerosols mixing higher in the atmosphere during the daytime.

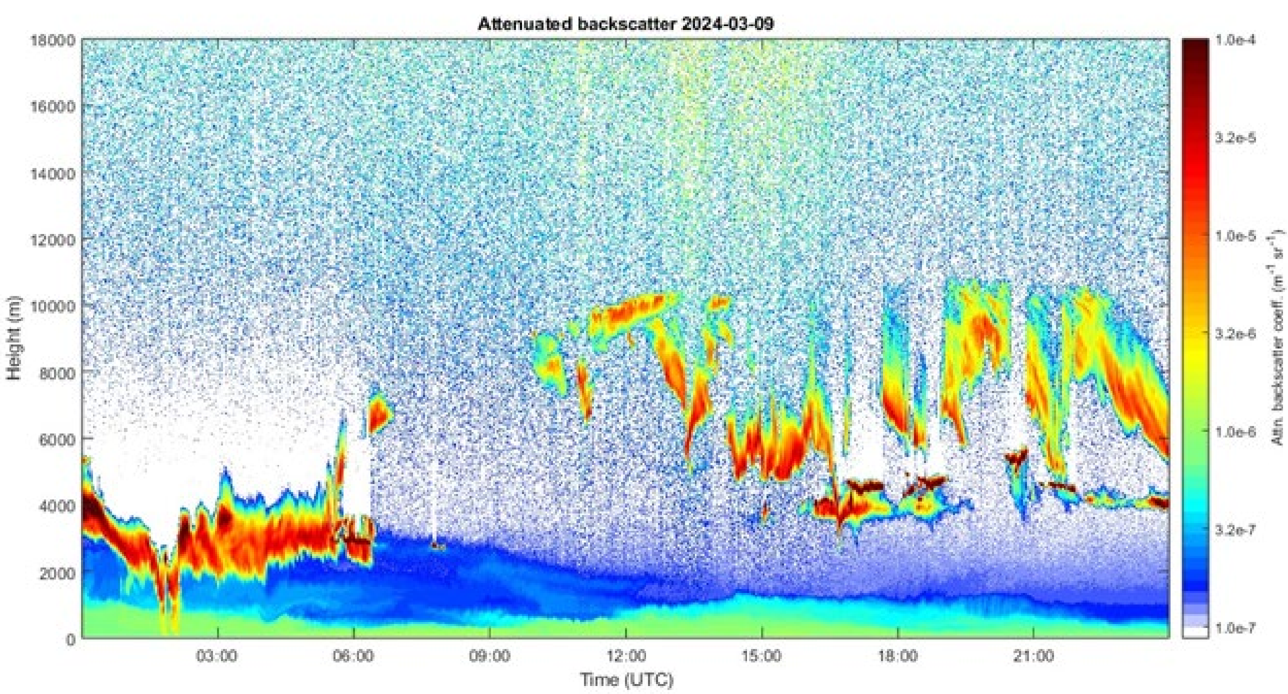


Figure 1: Attenuated backscatter profiles over one day on 9th March 2024, measured in Germany by KIT

Water vapor profile

Water vapor profiles are retrieved using measured online and offline signals. Water vapor profiles are reported with a resolution of 9.8 m, from the ground up to an altitude of 4 km, with an averaging time of 20 minutes.

Figure 2 shows the water vapor mixing ratio measurements over the same day as in Figure 1. Again, the x-axis shows time and the y-axis shows height above the instrument, now from the ground up to 4 km. Water vapor mixing ratio values are presented on a linear color scale in units of g/kg. Water vapor profiles are continuously monitored over time and different structures are visible in the image.

During the first 6 hours of the time period, the maximum range reported by DA10 (representing the highest reliable data point, indicated with black dots) is extending higher, up to 4 km in the atmosphere. Thanks to the precipitating cloud and aerosol layer below, there is enough scatterers up to the height where the signal fully attenuates. During a clear sky event between 07 and 10 UTC, the maximum range is again lower, as there is not enough signal to retrieve reliable water vapor mixing ratio information above approximately 2 km. Later, from 15 UTC onwards, the water vapor mixing ratio retrieval is limited to the top of planetary boundary layer at around 2 km, showing a more humid layer below 1 km and dryer layer above.

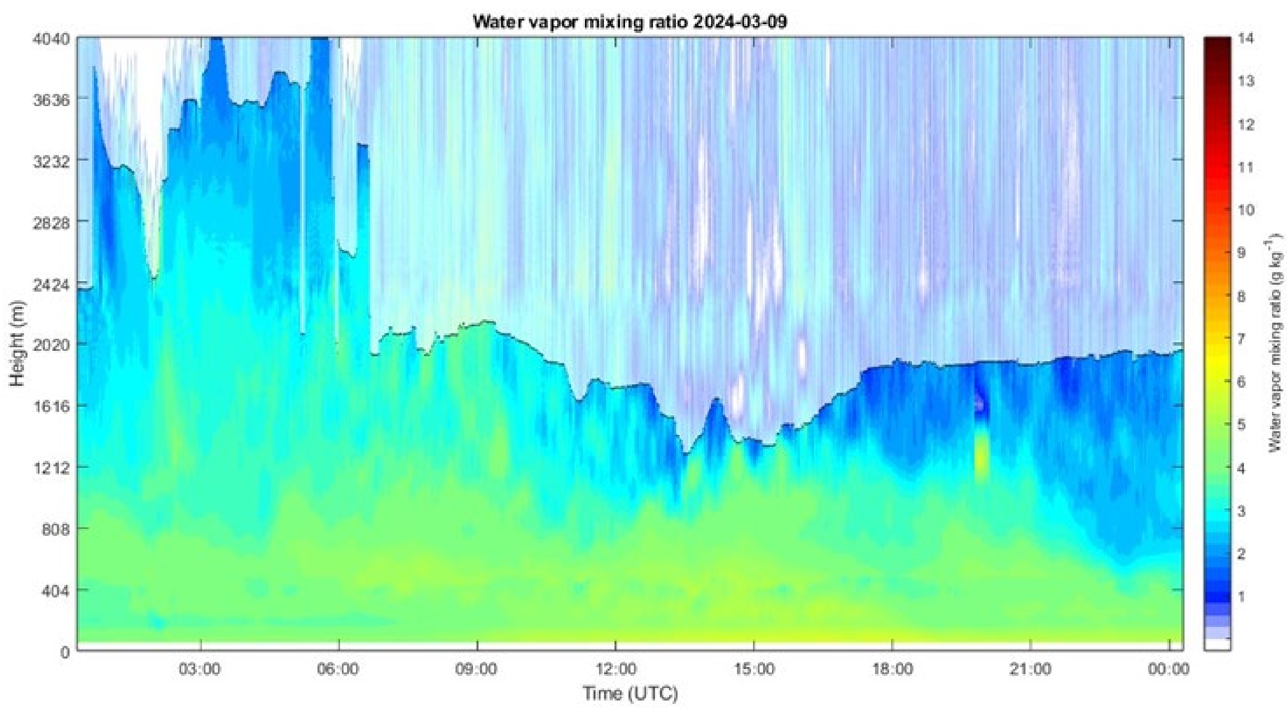


Figure 2: Water vapor profiles over one day on 9th March 2024, measured in Germany by KIT

Water vapor uncertainty profile

DA10 provides an estimate of the measurement uncertainty for each value in the water vapor profile, expressed in units of g/kg. The uncertainty profile is calculated using 2-minute averaged water vapor profiles, which are computed solely for use by internal algorithms.

The standard deviation of the 2-minute averaged data over the total averaging time is computed and reported as the uncertainty estimate. This estimate describes the random uncertainties in the measurement and is valid within the reported maximum range of the water vapor profiles.

Figure 3 shows the uncertainty of the water vapor mixing ratio profile measured on 9th March, 2024 in Germany by KIT. The uncertainty increases with a decreasing signal-to-noise ratio or if outliers are present (around 20 UTC at 1300 m).

Cloud products

DA10 also reports traditional ceilometer data, such as cloud height, vertical visibility, sky condition, fog and precipitation identification, as well as cloud thickness or penetration depth, calculated from the attenuated backscatter profiles. DA10 serves as a powerful lidar ceilometer, offering a higher signal-to-noise ratio.

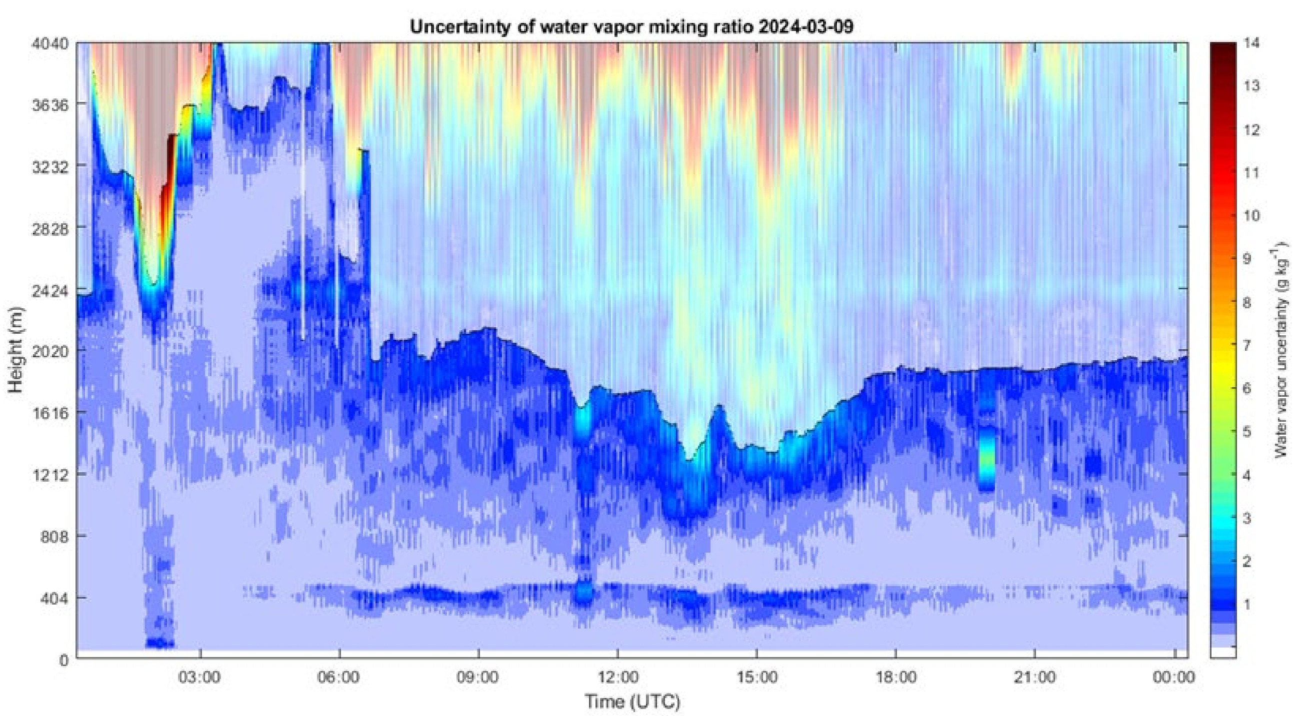


Figure 3: Water vapor uncertainty profile over one day on 9th March 2024, measured in Germany by KIT

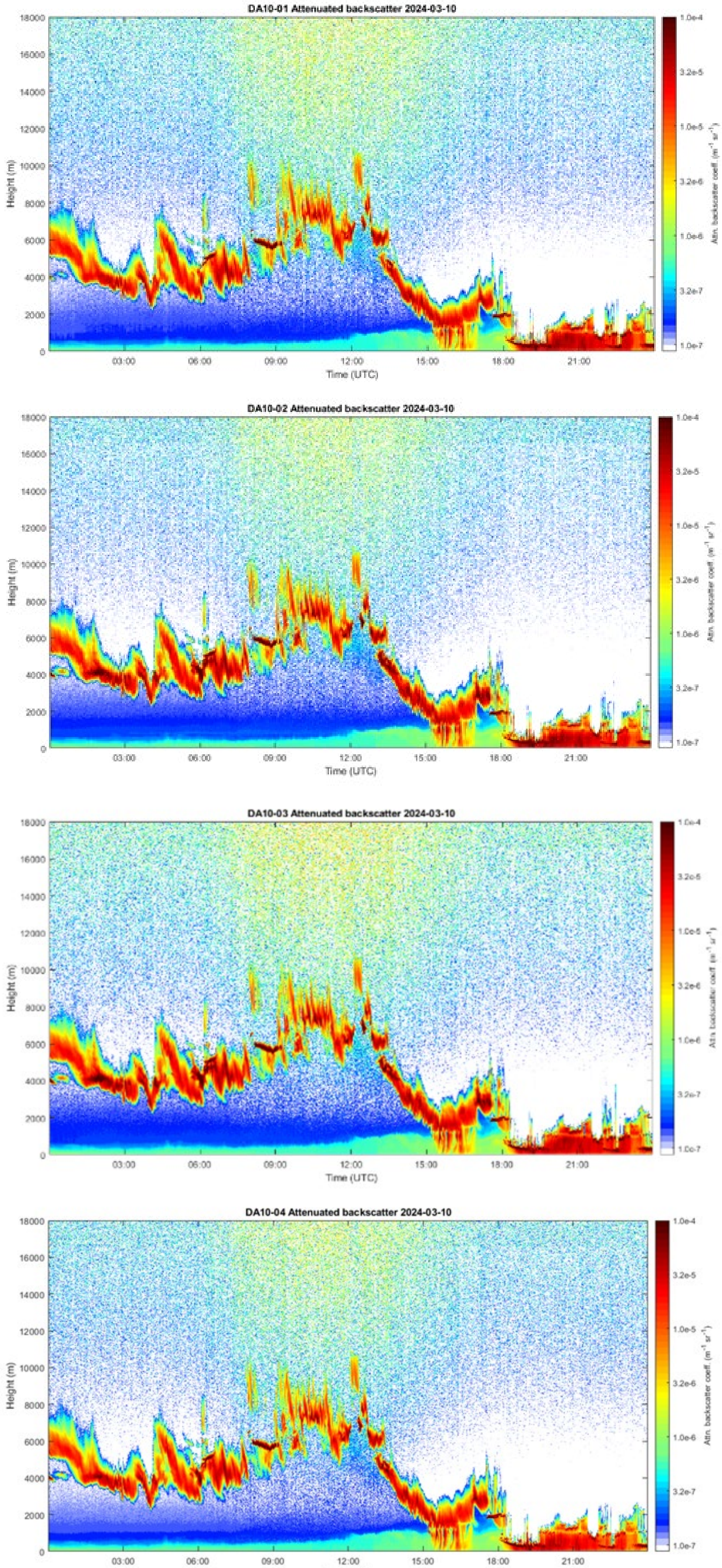


Figure 4: Attenuated backscatter measured over one day on 10th March 2024 at the same location with four separate DA10 units. Data provided by KIT.

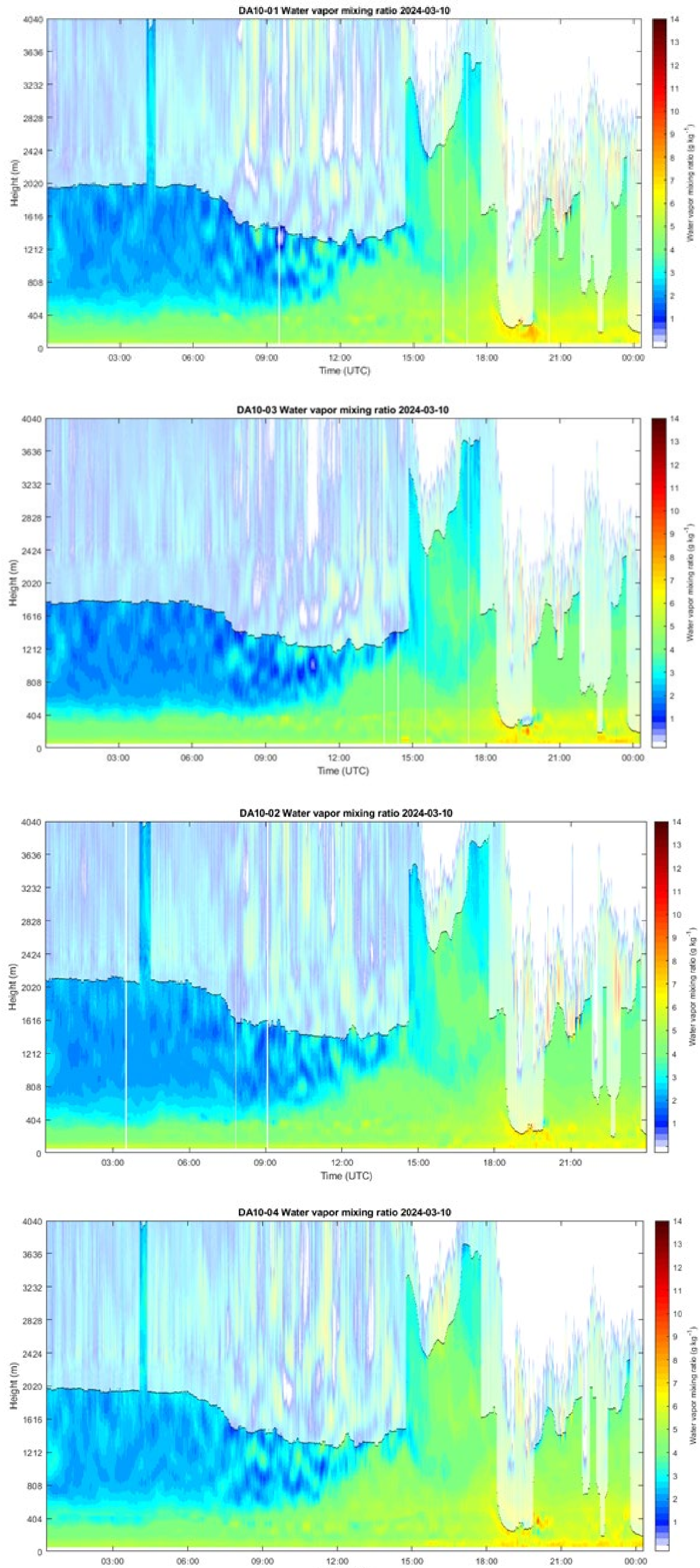
Unit-to-unit variation

DA10 instruments show minimal unit-to-unit variation in both attenuated backscatter and water vapor mixing ratio (Figures 4 and 5). KIT measured the data on 10th March 2024 in Germany using four DA10 units positioned side-by-side.

The attenuated backscatter images taken over one day with the four different units show only minor differences. All units consistently display the same features with similar signal amplitudes.

It is evident from the water vapor mixing ratio profiles measured during the same time period that there is minimal unit-to-unit variation. All the features seen in the images are present in all units, the maximum range is very similar, and the absolute values are very close to each other.

Figure 5: Water vapor mixing ratio measured over one day on 10th March 2024 at the same location with four separate DA10 units. Data provided by KIT.



The patchiness or oscillation in the water vapor mixing ratio profiles, particularly in the dry layer above the more humid aerosol layer, is due to a lower signal-to-noise ratio in the weak return signal from the aerosols. This behavior is characteristic when pushing the DA10 measurement capability to its limit. In such cases, the profile would benefit from heavier averaging, as measurement noise causes some oscillation around the mean value. It is evident that the water vapor mixing ratio retrieval requires a sufficient backscattered signal from aerosols or atmospheric particles to provide reliable information.

Applications

DA10 measurements can be used for various applications, from real-time atmospheric monitoring to different research studies. In observational networks, data provided by DA10 can be used to improve numerical weather prediction models.

DA10 provides continuous, unattended, continuous water vapor profiling suitable for operational networks. It operates 24/7 without the need for on-site instrument calibration. The instrument is easy to use and works in all climates. It provides real-time data that is updated every minute and offers the possibility for real-time monitoring, helping meteorologists follow how the atmospheric situation evolves over time.

With DA10, it is possible to track both the absolute values of the water vapor mixing ratio and their vertical structures, which is crucial for predicting weather patterns more accurately, including the development of severe storms and heavy precipitation. Real-time monitoring systems are a crucial part of early-warning systems for hazardous weather events, such as floods, droughts, tropical cyclones, and thunderstorms.

Humidity is considered one of the most critical atmospheric variables that significantly impacts the accuracy of high-resolution numerical weather prediction (NWP) model output through data assimilation. Improving humidity observations can help to close the gap between the current capabilities of observational networks and the requirements for more precise weather forecasting. Enhancements in severe weather forecasting will further improve early-warning systems and help protect lives and property. Additionally, DA10 data can be used for NWP model evaluation to further improve model development.

Instruments currently providing humidity measurements, such as radiosondes, research-grade lidars, microwave radiometers, satellite observations, and in-situ measurements, do not fill all the gaps needed to resolve water vapor structures in the atmosphere in real-time. Radiosondes are typically launched only twice a day, research-grade lidars are not yet suitable for operational use, microwave radiometers and satellite observations lack vertical resolution, and in-situ measurement cover only one spot at ground level. Thus, there is a lack of humidity profiling capability that functions unattended and is suitable for operational use — a gap that the DA10 can easily fill.

Acknowledgements

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Why Vaisala?

As the global leader in weather and environmental measurements, Vaisala provides trusted weather observations for a sustainable future. With nearly 90 years of innovation and expertise plus customers in 170+ countries from the North and South Poles to Mars, we help provide the most reliable and accurate weather and climate information for better and safer daily lives.

Our instruments and intelligence are known as the gold standard for precision and reliability. As a sustainability leader we enable meteorology professionals to better understand, forecast and explain climate change. We continue to channel our curiosity into climate action and new ways of enabling a better planet for all.