Gerhard Peters, head of R&D, Metek

RELIABLE DATA

Continuous wave lidars can provide more accurate wind measurements with high resolution at short distances

The first reports on lidar-based wind measurements appeared half a century ago, and Doppler wind retrieval by lidar began in the 1980s. Rapid progress of laser technologies, along with the diversity of user requests, has led to a wide range of commercial lidar products being developed, from containerized systems with a greater than 10km (6 mile) range, to portable boxes with ranges of some tens of meters.

PULSED DOPPLER LIDARS

The most widespread method for wind measurement is to transmit pulses and assign a range to the propagation time of the echo signal. The shorter the pulse length, the broader the transmitted frequency band and the finer the range resolution. While there is a lot of competition for radar frequency bands, there is no such issue for optical frequencies. Therefore lidars could be built with extremely short pulses and correspondingly fine range resolution. Unfortunately this freedom cannot be exploited for Doppler measurements due to a fundamental difference from radar signal analysis.

Typical pulse repetition rates of radars are in the range of 10kHz or more. Therefore the change of position of atmospheric scattering centers between subsequent pulses is small compared with typical radar wavelengths (millimeter to meter), and consequently the pulse-to-pulse phase shift of echoes from a given range gate is small ($<<\pi$).

In the left-hand panel of Figure 1, the radar pulses (thick red lines) and echo signals (thin red lines) from range r_1 are depicted in a range-versus-time diagram. The phase of the received signal is indicated by the angle of the black arrows below the time axis. The pulse-to-pulse phase shift is associated with the Doppler shift. The more pulses available for the phase measurement, the better the Doppler resolution.

The assumption of small phase shift between subsequent pulses does not hold for lidars with wavelengths in the µm-range. Therefore the Doppler shift must be extracted from the echo of one pulse.

For the Doppler retrieval it is essential that the transmitted pulse has some spatial extension so that echo signals are received from overlapping ranges during a finite time interval. During this time interval the change of position of scattering centers in the overlapping range slices causes a phase change of the echo signal, which translates into Doppler shift. The finite pulse and the receiving time window for echoes from a range interval centered at r_1 is shown in the right-hand panel of Figure 1.

For better Doppler resolution, the transmitted pulse and the receiving time window must be extended, leading to poorer range resolution. Typical trade-offs for pulsed Doppler lidars are 20m (66ft) range resolution and 2m/s (6.6ft/s) Doppler resolution. Another limitation of pulsed lidars is the smallest observable range, which is about twice the pulse length. The final velocity resolution can be improved by averaging over many pulses. Nevertheless the quest for small minimum range and fine range resolution can lead to unacceptable Doppler resolution.

CONTINUOUS WAVE LIDAR

An alternative ranging method uses focusing the lidar beam at a certain distance. Scattered light is mainly received from the focal point. Since the receiving time is unlimited any Doppler resolution can be achieved. Multiple ranges can be scanned sequentially by varying the focal distance.

With increasing range, the range resolution rapidly becomes worse (Figure 2). Beyond a certain range – depending on the beam diameter at the lidar – the focusing effect vanishes completely. A typical range limit is 200m (660ft). Consequently the preferred use of continuous wave (CW) lidars is measurement at small ranges with fine resolution. Even here certain shortcomings must be kept in mind:

- In the simplest CW lidar realization the observed frequency shift is equal to the absolute value of the Doppler shift. The sign of the wind component is obtained using a ground-based wind vane. Although its output doesn't need to be precise, the method is not

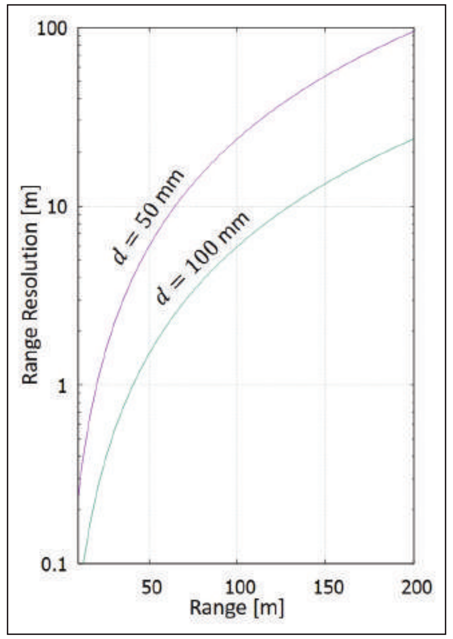

Figure 2: Range resolution of a CW lidar for two telescope lens diameters

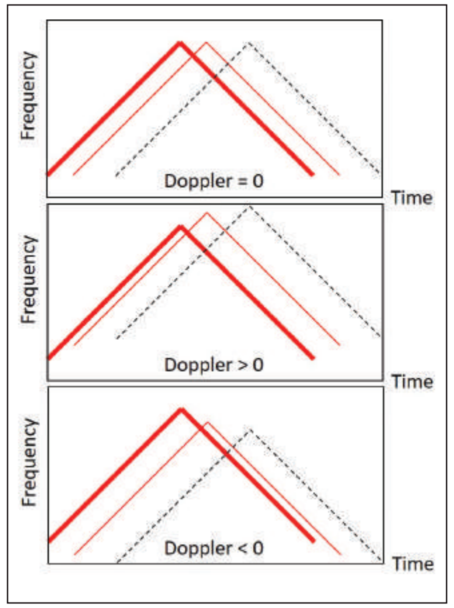

Figure 3: Triangular frequency modulation

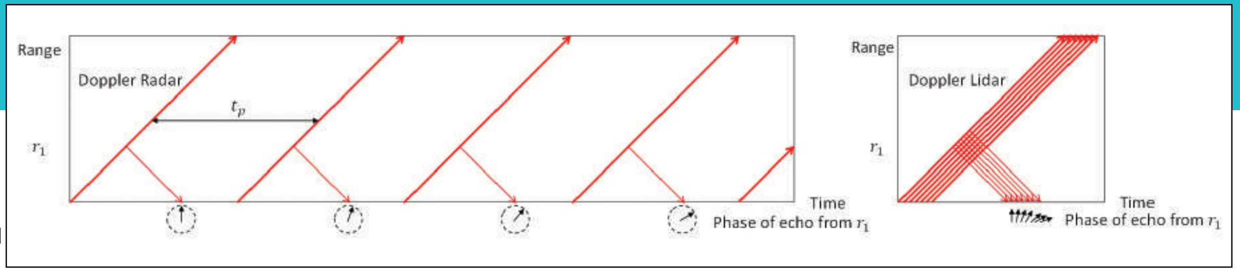

Figure 1: Doppler analysis for pulsed radar (left) and pulsed lidar (right)

reliable for all lidar operation sites, including street canyons, where the surface wind is decoupled from the wind at sounding height.

- Strong returns from a cloud base may dominate the signal, even if the cloud base is distant from the nominal range.
- There is a 'blind frequency range' close to zero. Therefore the basic CW concept is not applicable below certain minimum windspeeds.

There is an extension of the CW concept that avoids these shortcomings. If the frequency is modulated with a triangular pattern, the frequency of the echo signal is not only shifted due to the Doppler effect but also due to the time delay between the transmitted and received signals (Figure 3).

PRACTICALITIES

The sign of the Doppler shift is derived from comparing the modulus of the frequency shifts $|f_+|$ and $|f_-|$ on the rising and falling branch of the triangle. In the top panel on Figure 3, non-moving targets are assumed. Here $|f_+|$ and $|f_-|$ are determined only by the range term, which is equal on both branches. In the middle and lower panels, positive and negative Doppler terms contribute to the frequency shift in addition to the range term. In the first case $|f_+|$ is smaller than $|f_-|$, and vice versa in the second case. Thus $D = |f_+| - |f_-|$, indicates the Doppler shift including its sign.

Signals from outside the focus cause 'wrong' frequency shifts. The frequency of such signals is indicated in Figure 3 by the black dashed lines. If they are strong, they can show up in the Doppler spectra as secondary peaks. They can be recognized as spurious because the sum of the frequency shifts $S = |f_+| + |f_-|$ depends only on the range. Since the nominal range is known due to the chosen focal distance, the associated value of S_n is also known. Comparison with the observed value, S_o, reveals if spectral peaks are spurious.

For zero windspeed there remains a finite frequency shift. So, there is no low wind limitation.

WIND SCOUT AND WIND RANGER

Metek has developed a compact near-range FMCW lidar with fixed or steerable focus distance (Wind Scout, Wind Ranger). For retrieving the wind, vector conical scans are performed around a vertical axis (Figure 4).

Figure 4: Wind Scout/ Wind Ranger

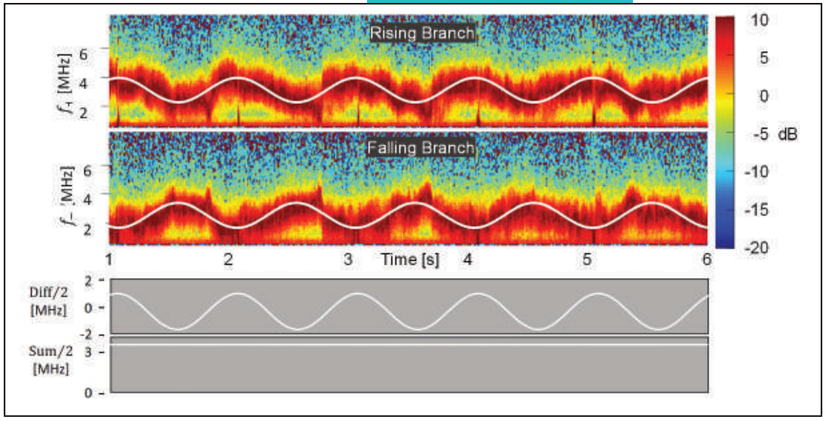

Figure 5: Colored panels – Doppler spectra during five revolutions of the scanner. Gray panels – (top) difference in peak frequencies; (bottom) sum of peak frequencies

The scanner rotates once per second with a 10° zenith angle.

Figure 5 shows spectra obtained on the rising and falling modulation branches for five scanner revolutions. The *y*-axis is the frequency shift (absolute value) and the color shows the relative spectral power averaged over 0.01s. Time is running on the *x*-axis. One recognizes the periodic undulation of the frequency shift with opposite phase for the rising and falling branches, as expected according to the discussion of Figure 3. The white lines represent sinusoidal fits of $|f_+|$ and $|f_-|$. In the lower gray panels, the D and S of the fitted peak frequencies are shown.

As discussed above, D indicates the Doppler shift. The windspeed and direction is derived from the amplitude and phase of the sinusoidal variation of $D(\alpha)$, where α = scan angle. The sum $S_o(\alpha)$ in the lower gray panel is constant. It is not affected by the Doppler shift but depends only on the focus distance. From the modulation parameters it can be inferred that $S_o = S_n$. Therefore spurious spectral peaks originating from outside the focus can be excluded.

PROPERTIES AND FIELD EXPERIENCE

The system can be deployed by a single person and starts running after power-up using either the internal data storage or by transmitting data in real time via the network port. A web-based control interface is available. The system complies with laser safety classification 1M according to IEC 60825-1:2014/EN 60825-1.

Comparisons with ultrasonic measurements are shown in Figure 6 for the windspeed (upper panel) and the standard deviation of the vertical wind component (lower panel). The low bias of the latter is to be expected because the lidar data represents spatial-temporal averages over the full scan circle, with corresponding attenuation of small-scale and high-frequency contributions to the turbulence. The nocturnal minima of the standard deviation provide an estimate of the measurement noise, which is less than 5cm/s.

The gray band in Figure 6 indicates a rain event with rain rates up to 3mm/h. This event obviously did not impair the quality of the lidar wind measurement. ▮

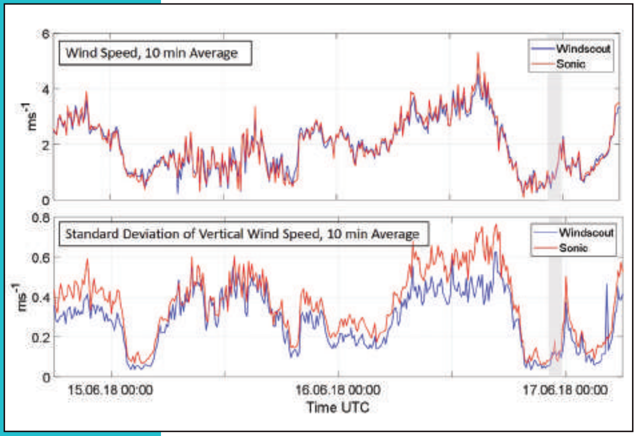

Figure 6: Comparison with sonic anemometer