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Lag-angle compensation technique applied to a fast-scanning long-range Doppler lidar system

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Abstract: The coherent Doppler lidar SKIRON^{3D} is LEONARDO's solution to the problem of identifying dangerous wind hazards at airports. Fast beam scanning while maintaining a long operational range is the key enabler for updating alerts and warnings according to operational requirements.
One downside of fast beam scanning, though, is the decrease of the heterodyne efficiency due to the mismatch between the transmitting and receiving beam caustics. At a typical scanning speed of 12°/s, this leads to a decrease of approximately 20% in operational range. This so-called "lag-angle effect" can be compensated either by a moveable receiver or transmitter. LEONARDO's solution is a continuously tilting piezo-mounted receiver mirror to compensate for the lag-angle losses.
Instrument setup and measurement results for long-range operations using our lag-angle compensation technique (LACT) will be presented in this contribution.

1. Introduction

Pulsed coherent Doppler lidars are powerful instruments when it comes to detection of hazardous wind phenomena like wake vortices and wind shear. For the latter, ICAO (International Civil Aviation Organization) recommends a measurable range of 10 km (at 500 m altitude) within an update rate of 60 s [1]. In practice, however, it is recommendable to be capable of measuring one PPI (Plan Position Indicator) within 30 s, in order to record a whole volume with PPIs at several elevations to get the larger picture while still monitoring the glide path for wind shear with a 60 s update rate.

On days with low aerosol density and high refractive turbulence, the ICAO recommendations are often not met, even with a long-range lidar system with a basic FOM (figure-of-merit) of above 120 mJ√Hz. During our one-year measurement campaign at Frankfurt in 2020, days with a range of only 8 km were observed (except for days with precipitation). A further increase of the pulse energy or the FOM is a possible way to solve this problem but it requires a lot of cost and effort to use more powerful laser amplifiers that necessarily lack the advantages of designs using only single-mode fibers for which this path is barred. Especially from the point of view that we only need to improve the "bad" lidar days, compensation of the lag-angle effect is the more efficient way to gain range especially on days with low aerosol density.

The well-known lag-angle effect results from a mismatch of the transmit and receive beam paths due to the continuous rotational motion of the scanner head and the finite speed of light.

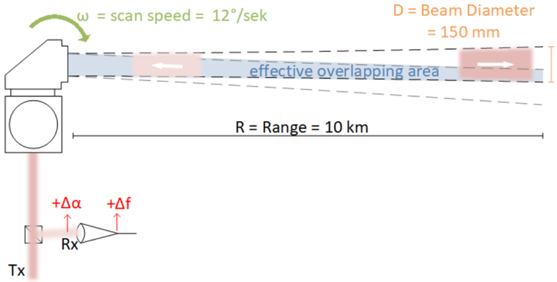

Figure 1. Illustration of the mismatch between the transmitted and received beams when the scanner head moves.

As illustrated in Figure 1, the movement of the scanner in azimuth or/and elevation results in a misalignment. Hence, less power is coupled into the receiver fiber coupler because the focal point is off-axis. The consequence is a higher receiver loss with increasing rotational speed and measurement distance. As described in detail in [2], the lag-angle can be compensated especially for a certain optimized range (target range), using a double-wedge prism or a tip-tilt piezo duplexer as anticipated in [3]. Our solution is to use a tip-tilt mirror (off-the-shelf product) in the receiver path to correct the lag-angle losses.

2. Methodology

LEONARDO’s solution for a fast-scanning long-range Doppler lidar system is the SKIRON^{3D}. This all-fiber pulsed lidar system achieves an FOM of more than 120 mJ√Hz thanks to the multi-channel technique. Figure 2 gives an overview of the system architecture, which is described in more detail in [4].

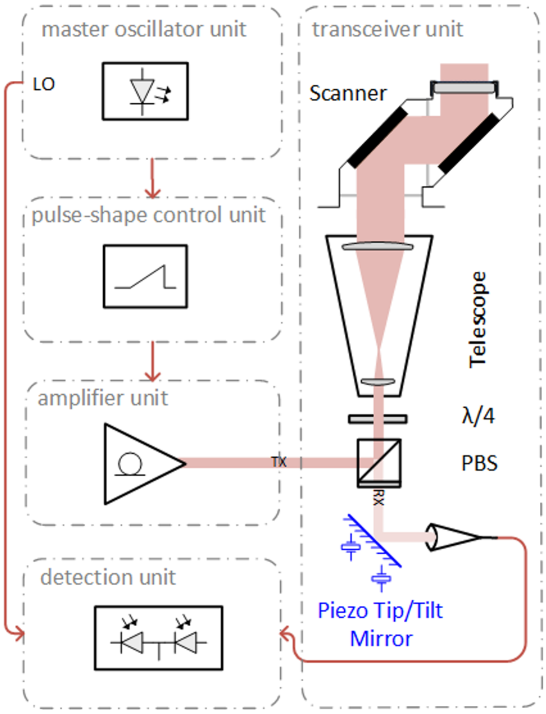

Figure 2. Overview of the multi-channel Doppler lidar system with lag-angle compensation technique (LACT).

The tip and tilting piezo mirror were placed directly behind the polarization beam splitter to move the receiver beam according to the calculated lag-angle. The lag-angle correction can be calculated using the scanning speed ω in both axes, the optimized range R and the telescope magnification A by:

$$\Delta\alpha = \omega \cdot \tau \cdot A = \omega \cdot \frac{2R}{c} \cdot A \qquad (1)$$

where c is the speed of light. The azimuthal motion of the scanner must be converted into a conical motion of the piezo mirror. Therefore, the tip and tilt motion of the mirror is a function of the azimuth velocity, azimut position, elevation velocity, and the scan direction of both axes.

The optimized range can be set manually or automatically by the lidar system. For automatic setting of the optimized range, the LACT uses the estimated measurable range of the lidar system based on the FOM specified in ISO 28902-2 [5]. The estimated range of the Doppler lidar is calculated using the system parameters such as accumulation time, pulse energy, pulse length, system efficiency, and beam diameter.

3. Results

A day with the number of aerosol particles being as little as 3800 (PM03) was chosen to demonstrate the improvement in the maximum operational range at different scanning speeds. The following measurement examples were taken on the 18th of April 2024 at our premises in Neuss. It was a sunny and slightly overcast day. The following measurements were made during daytime, when the refractive turbulence is generally higher. Two lidar systems, one equipped with LACT and one without it, were operated simultaneously to obtain the example measurements presented below. A typical scanning speed in azimuth is 12°/s for airport applications. At this scanning speed and an angular resolution of 1°, the lidar range was as low as 8 km without LACT.

Figure 3 shows two PPIs taken at an elevation angle of 6°. There are some obstacles on the roof of our building that block a certain area in the northwest and southwest. The color code (red positive, blue negative radial velocity) indicates that the wind is blowing from the west to the east. To the south, there are some clouds at about 12 km.

The PPI at the top of the figure was taken by the lidar without LACT and the PPI at the bottom by the lidar equipped with LACT. Observing only angles granting an unobstructed view along the line-of-sight, it emerges that the measurable range was increased by another 3-5 km due to the employment of LACT. For this scan, the optimized range was automatically set to 9.2 km.

Note that if line-of-sights such as a cloud layer or the planetary boundary layer are being hit, there will be no increase of the operational range. Clouds result in a very strong backscatter signal of up to 30 dB higher than clear air but also in very low transmission. Thus, the signal from behind the cloud is very weak, often too weak to detect.

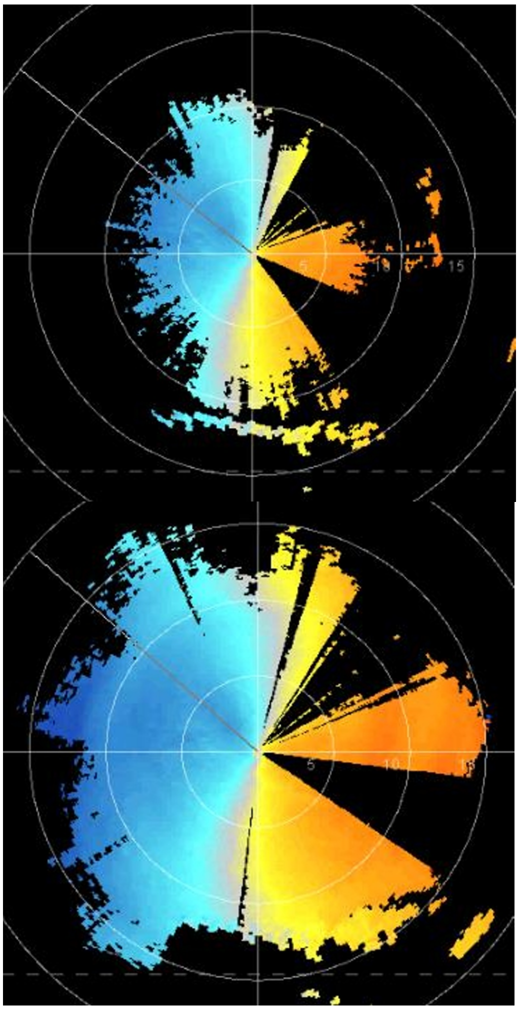

Figure 3. Range comparison for 12°/s without (top) and with LACT (bottom) at low aerosol particle density (5 km range distance per circle).

Using the semianalytic lidar equation [6] and a simplified lag-angle theory based on [2], the increase in operational range is also backed by theory as depicted in Figure 4. Theoretically, at 12°/s, there should be a gain in range of about 2.5 km due to the lag-angle compensation, which agrees well with our measurements.

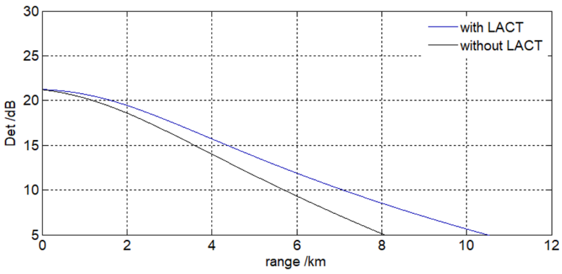

Figure 4. Simulation result using the semianalytic lidar equation with and without compensation of the lag-angle effect.

At higher scanning speeds, the gain in operational range is higher because there is more loss to compensate for. At a scan rate of 40°/s and an angular resolution of 1°, the operational range of the Doppler lidar is about twice as large with LACT than without, as the measurement example in Figure 5 clearly shows. The operational range was increased by up to 5 km. The optimized range for this scan setting was automatically set to 5.3 km.

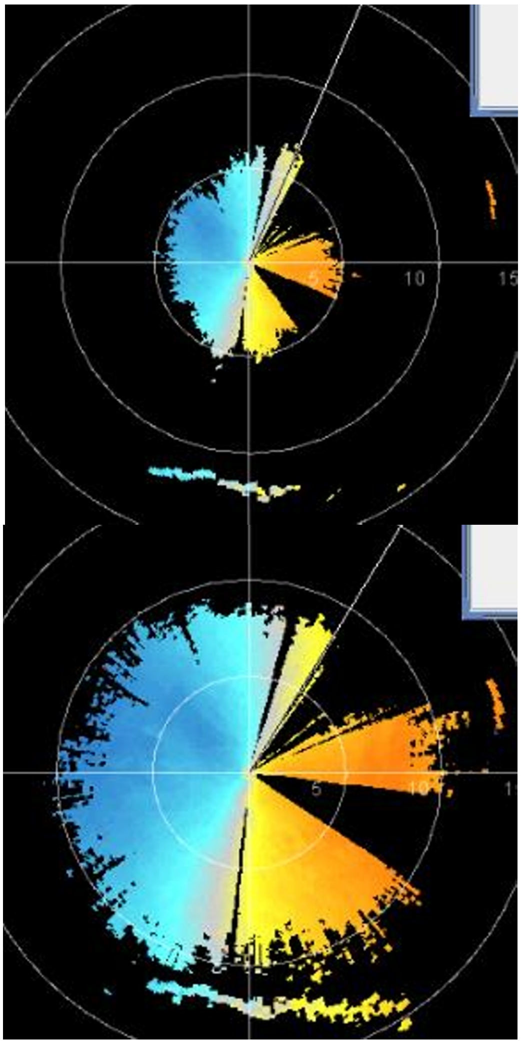

Figure 5. Range comparison for 40°/s without (top) and with LACT (bottom) at low aerosol particle density (5 km range distance per circle).

4. Discussion and Conclusion

LACT is a powerful technique for fast-scanning Doppler lidar systems to significantly increase their operational range. With this technique, all losses due to scanner motion can be compensated for at one optimized range.

This optimized range must be variable, since the maximum operational range of the Doppler lidar strongly depends on the atmospheric conditions and system parameters. We have successfully tested the automatic setting of the optimized range using the ISO-FOM [5] as control variable. The results look very promising with regard to increasing the maximum operational range during time periods with low aerosol particle density to an extent that ICAO requirements are met also in these conditions.

The value of the optimized range has been shown to be adequately estimated by the ISO-FOM as control variable. This will improve the maximum operational range on days with higher aerosol particle concentration but not to the maximum possible. Therefore, the calculation of the optimized range has to be informed by data from the atmosphere. As a first approach to this, we will use the (attenuated) backscatter to adjust the calculated optimized range. This way, the SNR approaches its undisturbed value just where it is needed in order to extend the operational range, i.e. close to the detectability threshold. Therefore, the potential extra benefit of a hypothetical compensation technique that would follow the pulse traveling through the atmosphere and thus would be optimal over the whole range, would not be very large. However, should the necessary hardware be available at reasonable cost, it would be worthwhile trying this.

The next step in the development of our LACT solution will be to conduct a measurement campaign for at least one month to gather information about the reliability of the hardware and the statistics of the maximum operational range improvement.

5. References

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