5.1

TESTING THE PERFORMANCE OF RADAR AND LIDAR VERTICAL WIND SHEAR DETECTION AT FRANKFURT AND MUNICH AIRPORTS

Thomas Ernsdorf*, Björn-Rüdiger Beckmann
German Weather Service, Aeronautical Meteorology Department, Germany

1. INTRODUCTION

Abrupt changes of wind velocity can lead to serious aircraft accidents during landing and take-off. In order to increase air traffic safety low-level wind shear alert systems (LLWAS) have been developed and upgraded from 1976s on at Federal Aviation Administration (FAA) towered airports (USA). The LLWAS are based on wind measurements using a network of remote sensor stations. In general these remote stations contain of several anemometers and radio-telecommunication. Up-to-date systems can consist of over 30 anemometers within the aerodrome boundaries. However, generally remote-sensing wind measurement systems are able to cover also the airspace of the Terminal Maneuvering Area (TMA) which is significant for Air traffic Control (ATC) of approach and departure. Based on volume measurements of a X-band Doppler polarimetric radar and a 1.6 µm Doppler lidar a novel LLWAS has been developed and installed at Munich and Frankfurt Airports in 2013, respectively. These LLWAS are able to detect and quantify on horizontal and vertical wind shear within a large area independent on most weather situations.

In the field of aeronautical meteorology vertical wind information is important to monitor and forecast on atmospheric stratification particularly vertical wind shear. In general, wind measurements of the boundary layer (ABL) profile are based on radiosondes and aircrafts (AMDAR, Mode-S EHS). However, radiosonde measurements are distant thus do not depict the local atmospheric situation at the TMA. On the other hand, the availability of aircraft measurements depends on the number of flight movements.

* *Corresponding author address:* Thomas Ernsdorf, German Weather Service, Aeronautical Meteorology Department, Frankfurter Straße 135, 63067 Offenbach; e-mail: Thomas.ernsdorf@dwd.de

Focus of our investigations are on availability, quality and application of 5 minutes wind profiles (30 m resolution) based on X-band radar and 1.6 µm lidar measurements at Frankfurt and Munich Airports.

2. SYSTEM OVERVIEW

In 2013 a SELEX Meteor 50DX radar and a Lockheed Martin WTX WindTracer lidar have been installed at the international airports of Munich (MUC) and Frankfurt (FRA). They are collocated on top of a parking deck in the middle of the airport (MUC and FRA; Figure 1).

The radar is a X-band system and the lidar emits 1.6 µm IR radiation. In general both instruments radar and lidar measure physical variables of the atmosphere in which the propagation time of the impulses is used to determine the distances. In case of X-band radar the emitted radio signals theoretically interacts with drops whereas in case of lidar the emitted IR light basically interacts with aerosols. By using the Doppler shift of reflected/backscattered signals radial velocity vector fields are determined.

In order to obtain similar high resolution measurements of both sensors lidar and radar the sampling rate has been adapted individually. Consequently, radar scan speed is set up faster than lidar scan speed (Table 1). The scan strategy is adapted to detect horizontal (microbursts, gust fronts, and runway-oriented wind shear) and vertical wind shear. Every minute a 3° PPI glide path scan is performed (radar and lidar); by varying elevations a 3D volume is captured every 5 minutes. In addition, a long distance overview scan (150 km) at 0.5° elevation (azimuthal, radar) and 1 (MUC) to 2 RHI scans (FRA) along the runways (lidar) are performed.

3. DATA PROCESSING

LLWAS products are based on filtered measurements. Hannesen et al. (2014) found that for insects the wind bias and RMSE are almost one order of magnitude larger. In order to remove reflected radiation of non-meteorological tracers an echo classification method is applied on radar data using a DFT clutter filter and a multi-trip-echo filter. However, lidar data are selected using modified wind standard deviations. Effects of filter applications on radar as well as on lidar data are shown in Figure 2. Due to drizzle in both cases radar and lidar data are available.

Thereafter, aimed at vertical wind shear detection wind profiles are retrieved by the Volume Velocity Processing (VVP) method of Waldteufel and Corbin (1979). This method is based on a multivariate regression which fits a simple wind model to the observed radial velocities of the volume scans. In a model the local wind velocity components *U*, *V*, *W* in the vicinity of the radar and the lidar (at x = 0 and y = 0) are approximated by:

$$U(x,y,z) = u_0 + x\frac{\partial u}{\partial x} + y\frac{\partial u}{\partial y} + (z - z_0)\frac{\partial u}{\partial z}$$

$$V(x,y,z) = u_0 + x\frac{\partial v}{\partial x} + y\frac{\partial v}{\partial y} + (z - z_0)\frac{\partial v}{\partial z}$$

$$W(x,y,z) = w_0 + (z - z_0)\frac{\partial w}{\partial z}$$

Using a uniform wind field and a constant tracer velocity, the radial velocity V_r is a function of azimuth (Φ) and elevation angle (θ):

$$V_r = (w_0 + W_{final})\sin\theta + u_0\cos\theta\sin\Phi + v_0\cos\theta\cos\Phi.$$

The wind information is captured every 100 ft (approximately 30 m) within a 5 minutes update rate. Depending on the count and variance of single measurements four different cases of sensors' data availabilities can be distinguished: (1) radar data are available only, (2) lidar data are available only, (3) radar data and lidar data are available, and (4) neither radar nor radar data are available. In case 3 retrievals from both sensors are merged into a single product. Depending of trusted sensor data a weighted merging is performed, where various quality control parameters influence the weights.

The vertical wind shear vector is calculated until 1600 ft (ICAO, 2007) based on the difference of the horizontal wind vector between two 100 ft layers. A wind shear advice is given automatically when the vector difference exceeds 5 kt (moderate) respectively 9 kt per 100 ft (severe). In total, in 832 (MUC) respectively 344 cases (FRA) a moderate and in 6 (MUC) respectively 2 cases (FRA) a severe wind shear alert was issued between August 2013 and June 2014 (Weipert et al., 2014).

4. DATA AVAILABILITY

Radar and lidar data availability strongly depends on the weather situation. Since clear-sky conditions are dominant at MUC and FRA in general up to 500 m AGL lidar data are available at about 80 % to 90 % on average (Figure 3). According to Weipert et al. (2014) most low-level wind shear events happen in clear nights with low-level temperature inversion and low-level jet. In case of frontal systems linked with precipitation and high wind speed radar measurements are available and used for monitoring of wind shear thresholds. The fraction of radar retrievals increases significantly with increasing wind speed (from 5 % at 4 m/s to 30 %–40 % at 20 m/s). By contrast both instruments lidar and radar are not able to detect low-level wind within fog. Figure 4 shows a reduced data availability as a fact of 17 fog days in December 2013.

Systems' sensitivity allows vertical wind to be derived simultaneously from both sensors lidar and radar at about 5 % to 8 % on average (until 800 m AGL) at MUC and FRA. Depending on cloud type, height and coverage different cases for overlapping of lidar and radar data are possible. Examples of different availability of radar and lidar VVP wind retrievals are shown in Figure 5:

1. Drizzle lead to radar and lidar wind detection within the whole profile (panel 1, top left).
2. As a fact of Stratus Fractus clouds the lidar impulse does not transmit beyond 900 m MSL (panel 2, top right).
3. Radar reflectivity begins to be strong enough to receive the wind field from the Stratus cloud base at approximately 1100 m MSL (panel 3, bottom).

5. VERIFICATION

5.1 INTER-COMPARISON

Quality studies of lidar and radar wind measurements are based on inter-comparison. Inter-comparisons are performed when wind measurements of radar and lidar exist similar in time and space. For these cases basically reflectivity (radar) and Signal-to-Noise Ratio (SNR; lidar) as well as standard deviations of the wind measurements are small on average (drizzle, steady and uniform wind field). In general, three more cases can be distinguished:

1. The intensity of the returned signal is high and the velocity standard deviation is small.
2. The intensity of the returned signal is high and the velocity standard deviation is high.
3. The intensity of the returned signal is small and the velocity standard deviation is high.

In case 1 data are available basically from one sensor only. The quality of the wind measurement is higher than the quality tested by our inter-comparison studies. In case 2 data are available from one sensor only, too. Due to a fixed standard deviation threshold of 2 m/s the quality shall be at least as high as the quality checked by our inter-comparison studies (Holleman, 2005). In case 3 data are available basically neither from radar nor from lidar.

Measurements within range distances until 6 km are crucial for calculation of VVP retrievals. In general, the monthly mean radial velocity RMSD and bias hardly increase with increasing range until 6 km (Figure 6). The bias is generally smaller than 0.25 m/s for range distances lower than 6 km, and positive, that is the radial velocities from the radar are slightly higher than those from the lidar. Peaks of RMSD at very low range might be caused in clutter near instrumentation location. After 6 km the differences grow with rising range up to 2.5 m/s (RMSD) and -0.4 m/s (bias) at 12 km range. Similar values are reached for high radial velocity (about 15 m/s; Figure 6). As a fact of tight detection of zero velocity lines there exists a local RMSD maximum near zero velocity. According to Holleman (2005) velocities close to zero can be rejected.

In general, radar and lidar VVP wind show a good agreement. There is a clear correlation between radar and lidar wind speed, rather independent on heights and wind speed (Figure 7). The mean bias of wind speed and u wind component is close to 0 m/s, the mean RMSD is 0.5 m/s at all heights until approximately 800 m AGL (Figure 8). Basically westerly wind is dominant at MUC and FRA (70 % to 80 % for August 2013 until June 2014) which cause in a great challenge to detect north-south components of the wind field. At MUC and FRA a small v wind component discrepancy – the v wind component from lidar is slightly higher than from radar – leads to increase the v wind component and wind direction bias with increasing height. However, the maximum bias is smaller than 0.5 m/s respectively 4° (at 800 m AGL) which reveal still a good system's performance; according to the WMO (2008) *Guide to Meteorological Instruments and Methods of Observation*, the required accuracy of upper-air wind speed measurements from surface to 100 hPa is 1 m/s and that for upper air wind direction measurements is 5° and 2.5° for wind speed below and above 15 m/s, respectively.

Due to the mean wind speed increases with height, similarities to those of Figure 8 (lidar–radar bias and RMSD as a function of height) can be seen for increasing wind speed (see Ernsdorf et al., 2014 for detail). Situations of high wind speed (above 25 m/s) are rare at MUC and FRA influencing much the mean quality values. Grand biases and RMSD at high wind speed are because of non-uniform wind fields of individual situations of high wind speed.

5.2 COMPARISON WITH MODE-S EHS WIND

A novel method to measure wind is related to tracking and ranging by an EnHanced surveillance (EHS) air traffic control (ATC) radar (e.g. De Haan, 2011; Sondij 2013). An EHS radar interrogates all aircraft in sight in a selective mode (Mode-S), on which the aircraft replies with a message containing, for example, magnetic heading and airspeed (http://mode-s.knmi.nl/). From this information wind can be extracted. An aircraft can stay airborne when it has a sufficient speed relative to the air, the so-called airspeed. The atmospheric wind alters the flight track of the aircraft and thus by calculating the difference between the expected flight path and the actual (ground) track, an estimate of the wind can be obtained.

Our comparisons are based on 15 minutes Mode-S EHS data covering the LLWAS scan volume used for calculation of VVP profiles. The significance of comparison results depends on the data availability and the atmospheric stratification. In general comparisons can be classified as valid for high number of flight movements as well as a stationary and uniform wind field. Figure 9 shows an example comprising 130 Mode-S EHS data points. In general, the differences between LLWAS and Mode-S EHS vertical wind are small (standard deviation of 1.8 m/s). The mean Mode-S EHS wind profile and the VVP wind profile is clearly correlated (correlation coefficient of 0.95).

6. CASE STUDY

At Munich and Frankfurt Airports vertical wind shear events are caused mostly by temperature inversions and low-level jets (Weipert et al., 2014). Commonly temperature inversions occur during night when radiation from the surface exceeds the amount of radiation received from the sun. As a fact of increase of sun radiation in the morning the inversion can decrease continuously from the surface on.

In general at the upper border of the inversion layer (mixing layer height) the wind field changes abruptly. At this height wind shear events can appear easily. Figure 10 shows an example of a lifted inversion with a pronounced temperature gradient. The wind direction changes from east (mixing layer) to south within a thin layer.

7. SUMMARY AND CONCLUSIONS

Abrupt changes of wind velocity can cause serious aircraft hazards. Wind shear poses a great danger during climb-out and approach operations since aircraft air speed and height are near critical values, thus rendering the aircraft susceptible to the adverse effects of wind shear. In order to detect, quantify and alert on the presence of vertical and horizontal low-level wind shear a novel combined system based on X-band Doppler polarimetric radar and 1.6 µm Doppler lidar measurements has been developed and installed at the international airports of Frankfurt and Munich. As a fact of the combination of both sensors the wind field can be observed in rain as well as in clear air conditions.

In general, wind measurements of the atmospheric boundary layer (ABL) profile at aerodromes using radiosondes are not possible. However, wind profiles derived from aircraft measurements (AMDAR, Mode-S EHS) depend on the number of flight movements. Focus of our investigations is on comparison of one year lidar and radar high-resolution wind profiles (approximately 30 m vertical resolution) of the lower atmosphere (up to 800 m vertical) at Frankfurt and Munich airports. Prior to the data processing, non-meteorological and ambiguous echoes are removed from the measurements using various echo classification techniques (radar) and modified wind standard deviation and signal-to-noise thresholds (lidar). Thereafter, aimed at vertical wind shear detection wind profiles are retrieved from the 5 minutes Doppler volume scans (radar: 11 PPIs from 1° to 60°, lidar: 5 PPIs from 1.5° to 20°) using the established volume velocity processing (VVP) method. In the last step, retrievals from both sensors are merged into a single product depending on the availability of trusted sensor data from lidar only, radar only or both lidar and radar (weighted average depending on the count of single measurements and standard deviation). Based on the difference of the horizontal wind vector between two 100 ft (about 30 m) layers the vertical wind shear vector is calculated. A wind shear advice is given automatically when the maximum vector difference exceeds 5 kt (about 4.63 m/s) per 100 ft (ICAO, 2007).

In most cases vertical wind shear events appear in clear nights and mornings as a fact of low-level temperature inversion and low-level jets. For these events high availability of lidar measurements is important. In general, for the crucial heights up to 500 m AGL lidar data is available in about 80 % to 90 % on average. Radar wind availability strongly depends on hydrometeor reflectivity of the emitted radiation (wave length of 3.2 cm). For bad weather situations linked with precipitation and high wind speed (differences/shear) radar measurements are available and used for monitoring of the wind shear thresholds. The fraction of radar retrievals increases significantly with increasing wind speed (from 5 % at 4 m/s, to 30-40 % at 20 m/s). However, the availability of wind data depends on seasonal effects. During fog events at Munich airport sensor measurements have been available neither from lidar nor from radar.

Depending on the weather situation in light precipitation the systems' sensitivity allows wind and wind shear data to be derived simultaneously from both sensors lidar and radar. In most cases during light rain measurements of both sensors pass the quality-control process and then are merged into a single product. At Frankfurt and Munich airports about 5 % to 8 % of the measurements on average vertical wind data retrievals combine both sensors. Inter-comparisons of wind from lidar and radar are the baseline for verification/quality analyses (see following). Vertical wind of both systems at Frankfurt as well as at Munich is correlated clearly. At all heights the mean difference of radar and lidar wind speed is small (bias close to 0 m/s, root mean square difference RMSD smaller than 0.5 m/s). In general, wind speed difference increase slightly with increasing wind speed to a maximum bias of 0.2 m/s on average. However, this still means a much better quality performance than recommended by EUCOS the ground-based or non-satellite observing system designed for EUMETNET members.

In comparison with aircraft wind data the LLWAS wind measurements have a higher resolution (temporal and spatial). In case of increasing number of flight movements Mode-S EHS processed data become more important for verification of LLWAS profiles. Case studies show a good agreement of mean Mode-S EHS and LLWAS wind during stationary and uniform wind conditions. Nevertheless, inter-comparison is preferred for verification.

High-frequently and high-resolution wind profile measurements could advance mesoscale forecasting. In order to improve weather forecasts the quality controlled low-level wind data are foreseen to assimilate in high-resolution NWP (numerical weather prediction). Next step could be on adaption of ICAO (2007) wind shear thresholds depending on absolute wind speed. In addition, the development of further products is possible depending on the scan method (e.g. EDR for detection of wake vortices, turbulences). However, measurements of the LLWAS X-band radar can be used as back-up of measurements of operational radars.

ACKNOWLEDGEMENTS

This study has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under the grant number 314237 (UFO). Mode-S EHS wind was made available by KNMI (Koninklijk Nederlands Meteorologisch Instituut).

REFERENCES

De Haan, S., 2011: High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar. *Journal of Geophysical Research*, 116, D10111, doi:10.1029/2010JD015264, 1–13.

Ernsdorf, T., B. Stiller, B.-R. Beckmann, A. Weipert, S. Kauczok, and R. Hannesen, 2014: Inter-comparison of X-band radar and lidar low-level wind measurement for air traffic control. *8th European Conference on Radar in Meteorology and Hydrology*, Garmisch-Partenkirchen, Germany.

Hannesen, R., S. Kauczok, and A. Weipert, 2014: Quality of clear-air radar radial velocity data: Do insects matter? *8th European Conference on Radar in Meteorology and Hydrology*, Garmisch-Partenkirchen, Germany.

Holleman, I., 2005: Quality Control and Verification of Weather Radar Wind Profiles. *Journal of Atmospheric and Oceanic Technology*, 22, 1541–1550.

ICAO, 2007: Meteorological Services for International Air Navigation. *Annex 3 to the Convention on International Civil Aviation*, Vol. 16.

Sondij, J., and S. De Haan, 2011: Aircraft as a Sensor: Using Modes-S EHS data to derive upper air wind and temperature information. *Meteorological Technology International*, August 2013, 24–28.

Waldteufel, P., and H. Corbin, 1979: On the analysis of single Doppler radar data. *Journal of Applied Meteorology*, 18, 532–542.

Weipert, A., S. Kauczok, R. Hannesen, T. Ernsdorf, and B. Stiller, 2014: Wind shear detection using radar and lidar at Frankfurt and Munich airports. *8th European Conference on Radar in Meteorology and Hydrology*, Garmisch-Partenkirchen, Germany.

WMO, 2008: Guide to Meteorological Instruments and Methods of Observation. No. 8, 7th edition, Secretariat WMO.

TABLE

Table 1: Specifications and scan strategy of radar and lidar.

Parameter	Radar (SELEX Meteor 50DX)	Lidar (Lockheed Martin WTX WindTracer)
Wave length	3.2 cm (X-band)	1.6 µm
Tracer	Hydrometeors	Aerosols
Polarization	Dual	Linear
PRF	2000:1600 Hz	750 Hz
Scan speed	18°/sec (3D scan up to 36 deg/sec)	14°/sec
Scan range	75 km	12-15 km
Radial resolution	0.15 km	0.10-0.12 km
Azimthual resolution	1°	≈ 2.5°
Scan per minute	PPI @ 3°	PPI @ 3°
Scan once per 5 minutes	3D scan (11 PPIs 1.0-60.0°) PPI scan @ 150 km range @ 0.5°	3D scan (5 PPIs 1.5-20.0°) 1-2 RHI scans

FIGURES

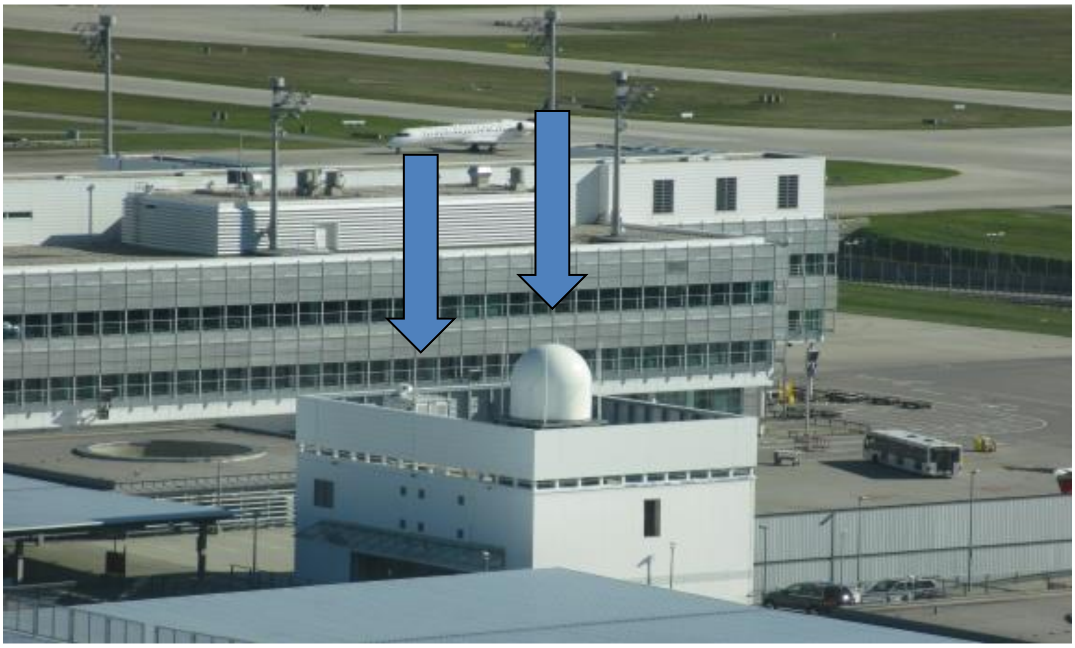

Figure 1: Lidar (left) and radar (right) at Munich Airport (October 2014).

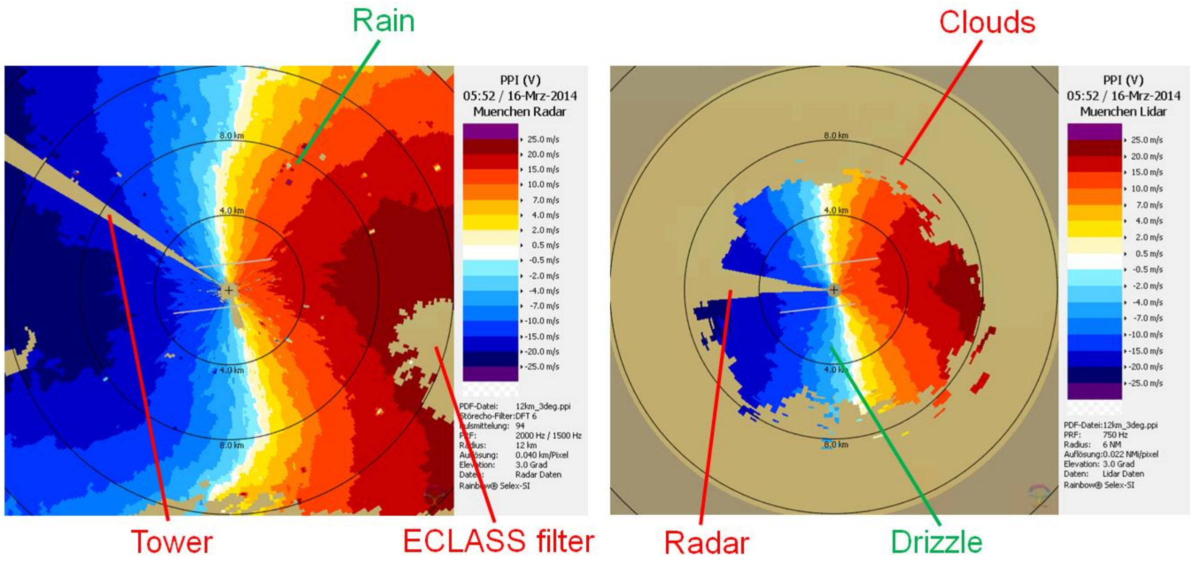

Figure 2: Radar (left) and lidar (right) 3° PPI radial velocity.

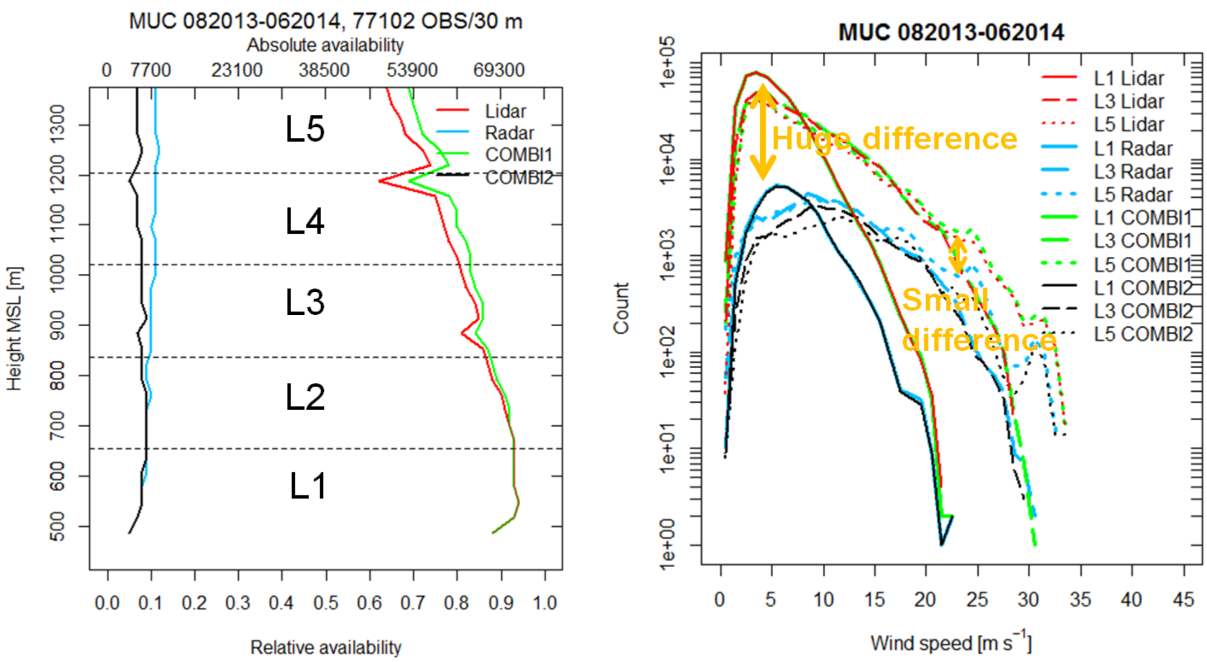

Figure 3: Availability of VVP data from August 2013 until June 2014 at Munich Airport; as a function of layer height (left) and as a function of wind speed (right). COMBI2 represents cases where both sensors provide valid data and COMBI1 where at least one sensor provides valid data.

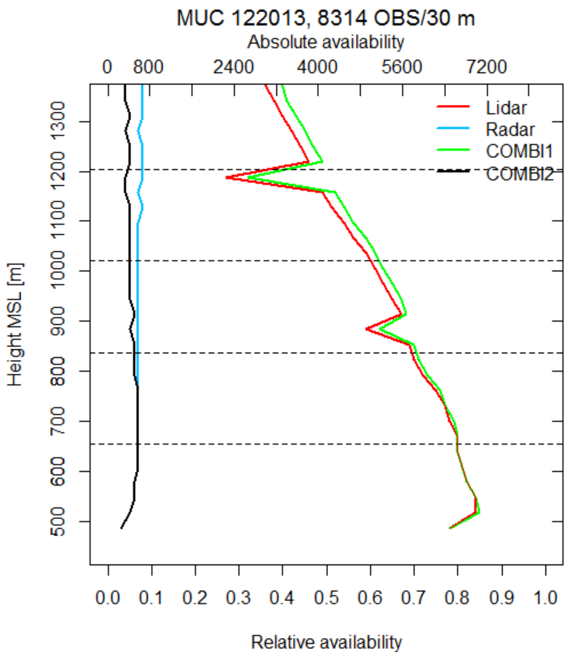

Figure 4: Availability of VVP data for December 2013 at Munich Airport; as a function of height.

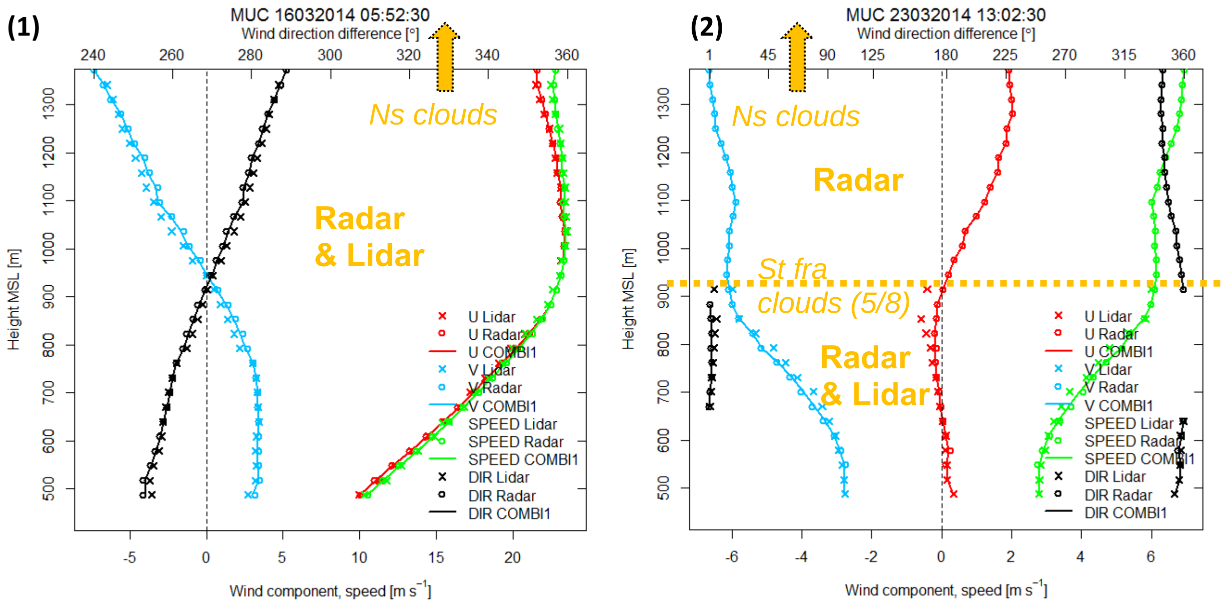

Figure 5: VVP vertical profiles of U and V wind components, wind speed (SPEED) and direction (DIR) of lidar, radar and the combination of both sensors (COMBI1) at MUC. Dates: (1) 16 March 2014, 5.52 UTC; (2) 23 March 2014, 13.02 UTC.

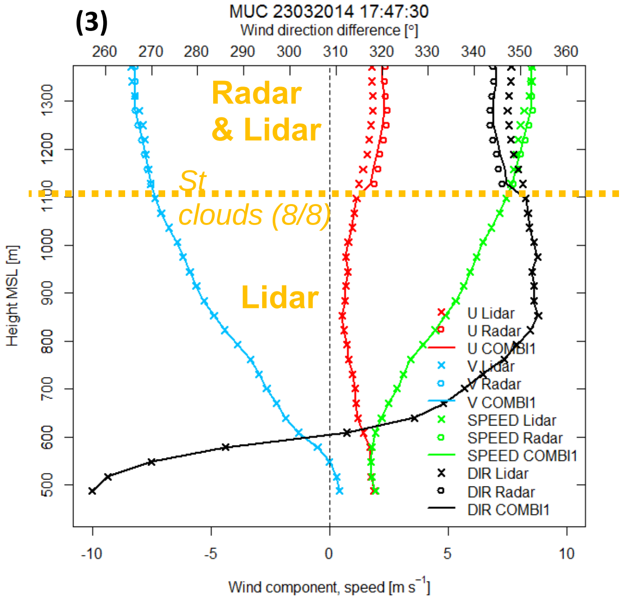

Figure 5 (continued): (3) 23 March, 17.47 UTC.

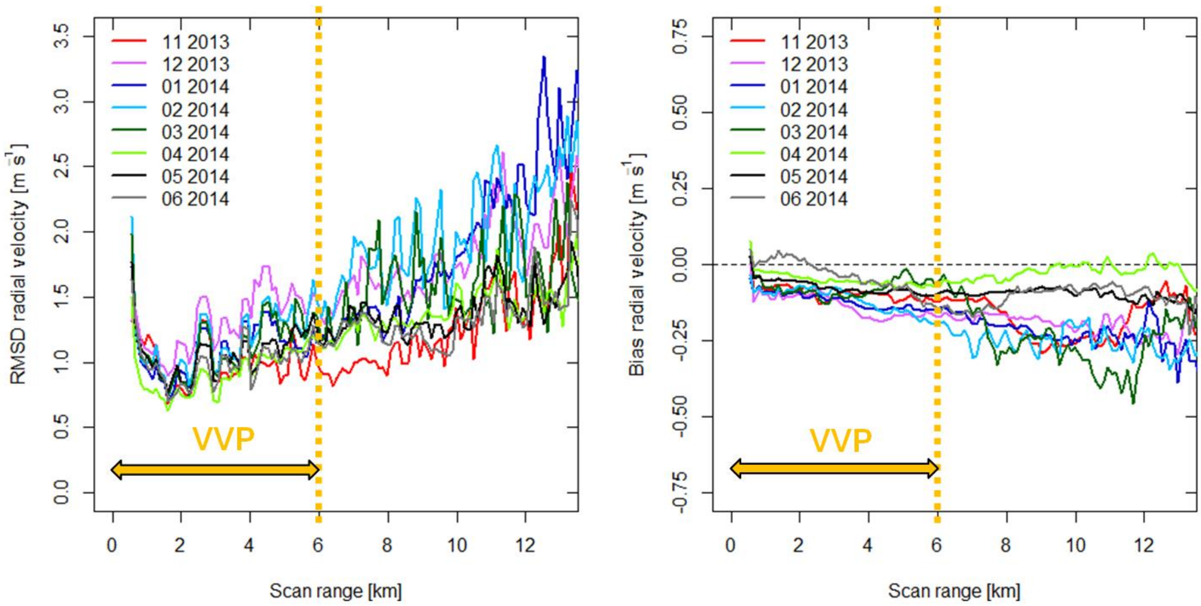

Figure 6: Mean monthly lidar–radar RMSD (left) and bias (right) of 3° PPI radial velocity for FRA; as function of range.

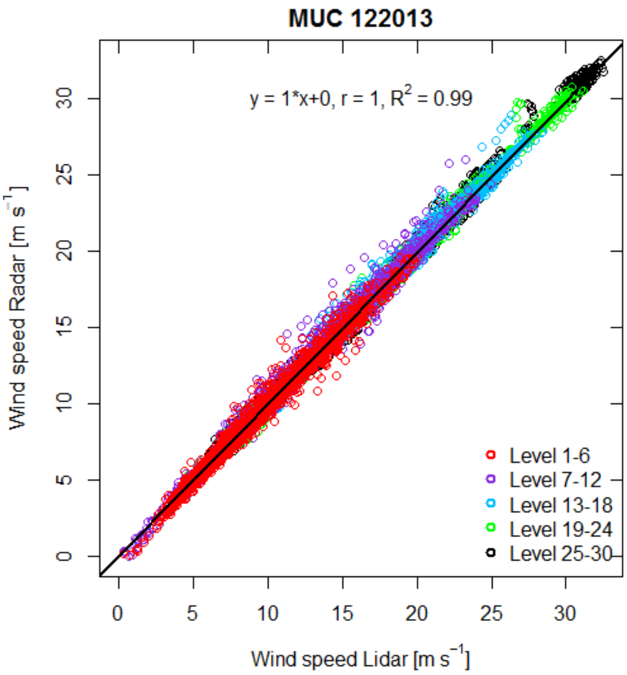

Figure 7: Scattergram of lidar and radar wind speed for December 2013 at MUC.

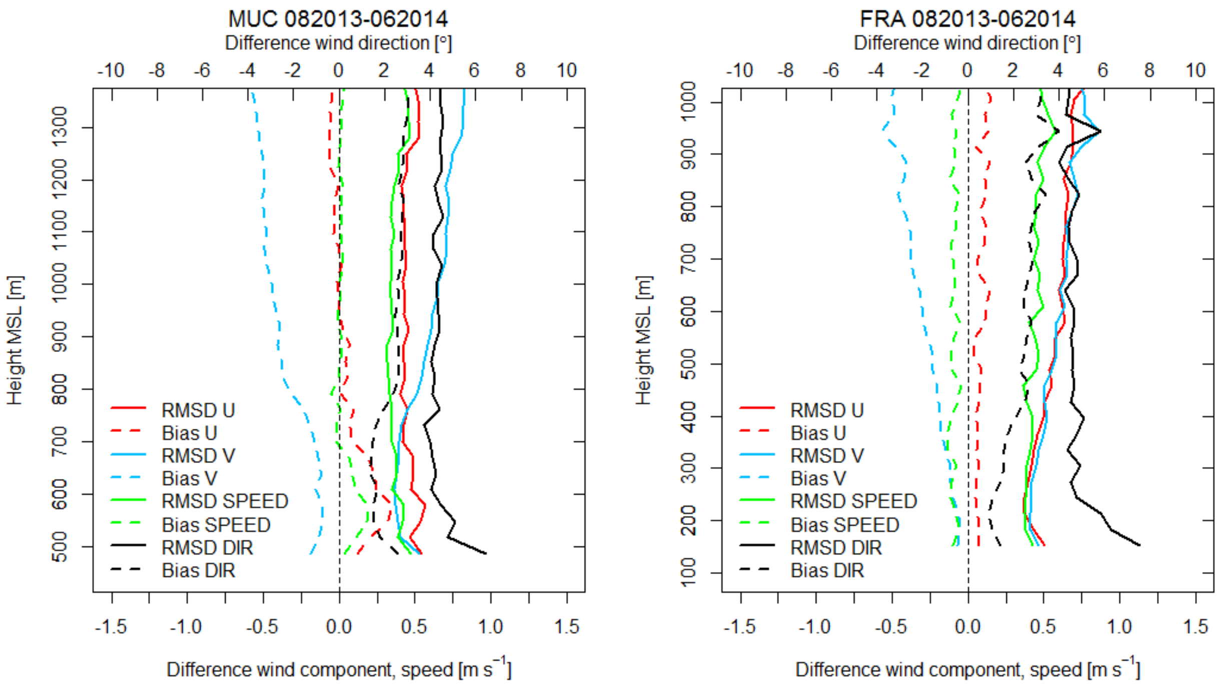

Figure 8: Mean lidar–radar RMSD and bias of VVP U and V wind components, wind speed (SPEED) and direction (DIR) from August 2013 until June 2014 for MUC (left) and FRA (right); as a function of height.

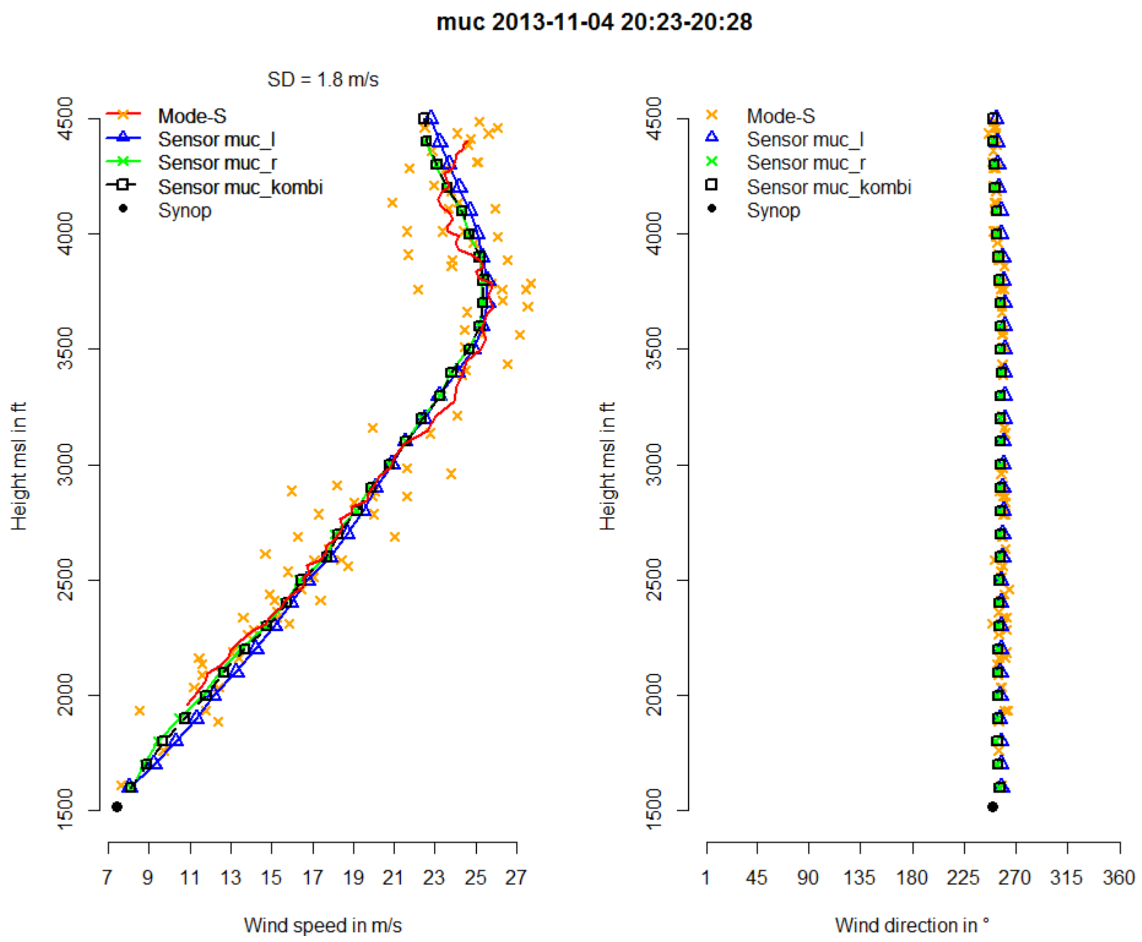

Figure 9: Vertical profiles of wind speed (left) and direction (right) of lidar (muc_l), radar (muc_r), the combination of both sensors (muc_kombi) and of Mode-S EHS (Mode-S) at MUC. Date: 04 November 2013, 20:23 UTC till 20:28 UTC for LLWAS wind and 20:18 UTC till 20:33 UTC for Mode-S EHS wind.

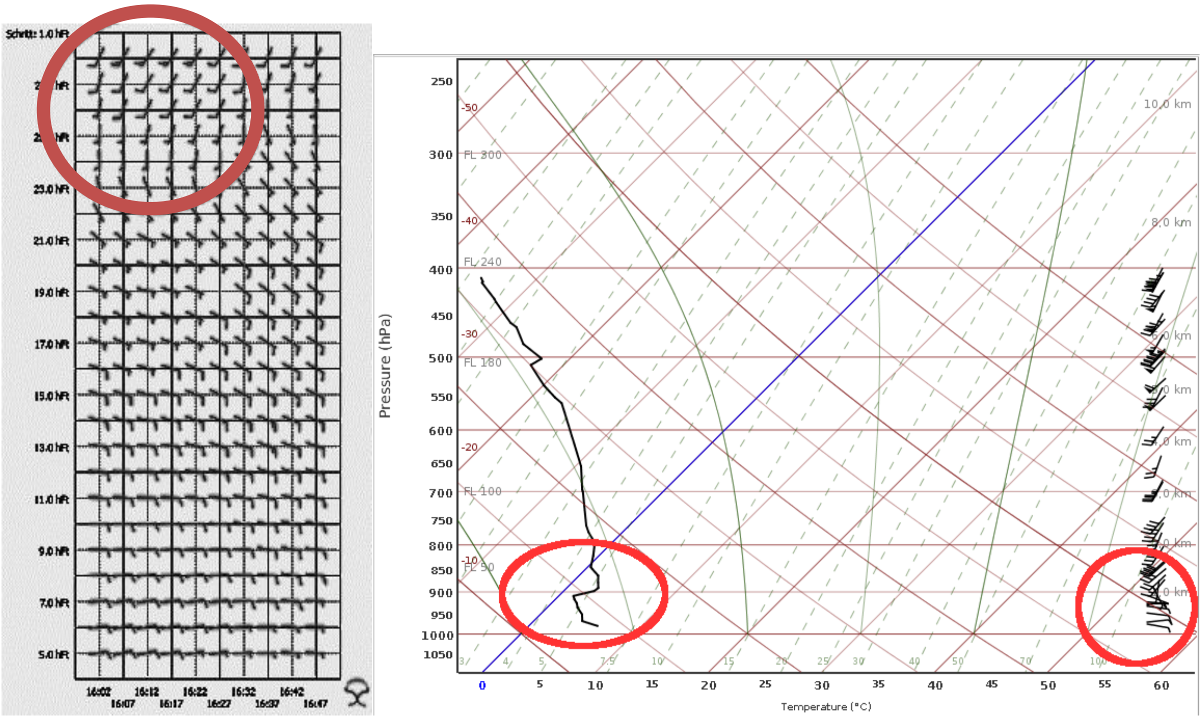

Figure 10: LLWAS VVP wind barb profiles (left panel) and AMDAR temperature and wind barb profile (right panel) at MUC. Date: 17 February 2014, 16:02 UTC till 16:47 UTC for LLWAS wind and about 16:45 UTC for AMDAR temperature and wind.