# Inter-comparison of X-band radar and lidar low-level wind measurement for air traffic control (ATC)

Thomas Ernsdorf[1], Bernd Stiller[2], Björn-Rüdiger Beckmann[1], André Weipert[3], Sebastian Kauczok[3] and Ronald Hannesen[3]

[1]*Deutscher Wetterdienst, Flugmeteorologie, Frankfurter Str. 135, 63067 Offenbach am Main, Germany*
[2]*Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Fernmessung, Am Observatorium 12, 15848 Tauche/Lindenberg, Germany*
[3]*Selex ES GmbH, Raiffeisenstr. 10, 41470 Neuss, Germany*

(Dated: 23 September 2014)

Thomas Ernsdorf

## 1 Introduction

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 low-level wind shear a novel combined system based on X-band Doppler polarimetric radar and a 1.6 µm Doppler lidar measurements has been developed and installed at the international airports of Frankfurt (FRA) and Munich (MUC). 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) at Terminal Maneuvering Areas (TMA) are based on aircraft measurements from AMDAR (Aircraft Meteorological Data Relay) and Mode-S EHS (Selective Mode Enhanced Surveillance). However, wind measurements of the new radar and lidar system at Frankfurt and Munich airports cover a conic volume including the glide paths rather independent on number of aircraft movements. On the other hand the availability of lidar and radar measurements depends on the classification process of reflected/backscattered pulses which cause in limited measurement ranges (Weipert et al., 2014). Basically during clear air conditions lidar data are available until 10 km and radar data are available from rain echoes rather independent of range distance. Depending on weather conditions and application of filtering techniques there may exist overlapping between X-band radar and lidar measurements which are the baseline for our studies.

In order to improve Air Traffic Management (ATM) high-quality wind measurements are required as input for wind and wind shear analysis and forecasts. Focus of our investigations is on verification by inter-comparison of one year radar and lidar low-level wind measurement for MUC and FRA. After selecting idealized cases of weather situations when both radar and lidar wind measurements are available comparisons of radar and lidar wind are performed depending on scan range, height and wind speed. With regard to horizontal and vertical wind (shear) the studies are based on radial velocity observations of single elevations (PPIs) as well as on vertical wind profiles covering the whole scan volumes.

## 2 Instrumental setup and observation method

A Low-Level Wind shear Alert Aystem (LLWAS) based on measurements of a collocated 3.2 cm (X-band) polarimetric radar (Selex Meteor 50DX) and 1.6 µm (IR) lidar (Lockheed Martin WindTracer) have been installed in spring/summer 2013 at MUC and FRA. General radar and lidar instrument specifications are shown in Table 1. 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 a lidar the emitted IR light basically interacts with aerosols. By using the Doppler shift of the reflected/backscattered signals radial velocity vector fields are determined.

*Table 1: Specifications of radar and lidar.*

| Parameter | Radar | Lidar |
|---|---|---|
| Wavelength | 3.2 cm | 1.6 µm |
| Polarization | Dual | Linear |
| PRF | 2000:1600 Hz | 750 Hz |

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 2). Focus is providing concise information on the observed or expected existence of wind shear which could adversely affect aircraft on the approach path or take-off path (ICAO, 2007). For the purpose of monitoring wind (shear) along the glide paths and vertical wind (shear) as well as atmospheric convergences and divergences in the field of sensors view both instruments radar and lidar perform a 3° PPI scan every minute and a volume scan every 5 minutes using several elevations (Table 2). The scan process consists mainly of small elevations to detect horizontal wind at low-level of high accuracy. In addition, a long-range PPI scan and a RHI scan (MUC) respectively two RHI scans (FRA) in runway directions are performed within the 5 minutes scan interval.

*Table 2: Scan strategy of radar and lidar.*

| Parameter | Radar | Lidar |
|---|---|---|
| Scan speed | 18°/sec (3D scan up to 36°/sec) | 14°/sec |
| Scan range | 75 km | 12 – 15 km |
| Radial resolution | 0.15 km | 0.1 – 0.12 km |
| Azimuthal resolution | 1° | approx. 2.5° |
| Scan once per minute | PPI @ 3° | PPI @ 3° |
| Scan once per 5 minutes | 3D scan (11 PPIs from 1 – 60°) | 3D scan (5 PPIs from 1.5 – 20°) |
| | PPI scan @ 150 km range @ 0.5° | 1 – 2 RHI scans |

## 3 Wind retrieval

Using the Doppler technique, the radial velocity – the component of the velocity vector line of sight – is extracted from the motion of atmospheric tracers basically of rain drops (radar) and aerosols (lidar). Lidar returns are dominated by aerosols even in case of rain drops which anyway do not bias the horizontal velocity (see radar). However, as shown by Hannesen et al. (2014) active tracers lead to erroneous measurements. Their results demonstrate that radar derived wind vectors from insects can differ by several meters per second from the true wind. In order to suppress non-meteorological and ambiguous radar echoes different filter techniques are applied: DFT (Discrete Fourier Transform) clutter filter, multi-trip-echo filter and an interference filter. Our studies are based on filtered radial velocity data.

Under the assumption of a linear wind field, profiles of the horizontal wind speed and direction are retrieved from the radial velocity volume data by the established Volume Velocity Processing (VVP) method (Waldteufel & Corbin, 1979). The VVP method extracts the parameters of the local wind field by a multidimensional linear fit of the radial velocity equation to the observed Doppler volume data. 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 ($\Phi$) and elevation angle ($\theta$):

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

In order to derive vertical wind profiles the VVP technique is applied for 100 ft (approximately 30 meters) layers of 5 minutes volume data within a range distance of 6 km. Results are considered valid only if a sophisticated quality control was passed (Selex, 2013). 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 of the measurements). Based on the difference of the horizontal wind vector between 100 ft layers the vertical wind shear is calculated. A wind shear advice is given automatically when the maximum vector difference exceeds 5 kt (about 2.57 m/s) per 100 ft defining the threshold of moderate wind shear events and 9 kt (about 4.63 m/s) per 100 ft defining the threshold of severe wind shear events. According to ICAO (2007) recommendations focus is on the atmospheric boundary layer (ABL) until 1600 ft (about 500 m) above runway level.

## 4 Data availability

At MUC and FRA in general for small ranges up to 3 km lidar data are available at more than 90 % on average (Weipert et al., 2014). For larger ranges, this figure decreases rapidly (below 50 % at more than 10 km distance). Radar data from meteorological echoes are available about 10 % of the time, rather independent of the range. Based on the presence of passive tracers basically light precipitation there may exist overlapping between radar and lidar wind measurements. Measurements are available together from radar and lidar at 5 % to 8 % of the time until a range of 3 km. For larger ranges the quantity of overlapped data from radar and lidar decreases in accordance to decrease of lidar data availability. In Figure 1 for example 3° PPI radial velocity data are available from radar and lidar as a fact of drizzle until a radius of 5 km – 6 km covering the VVP range (Figure 2, panel 1). Measurement sectors are masked due to ground clutters and non-meteorological echoes.

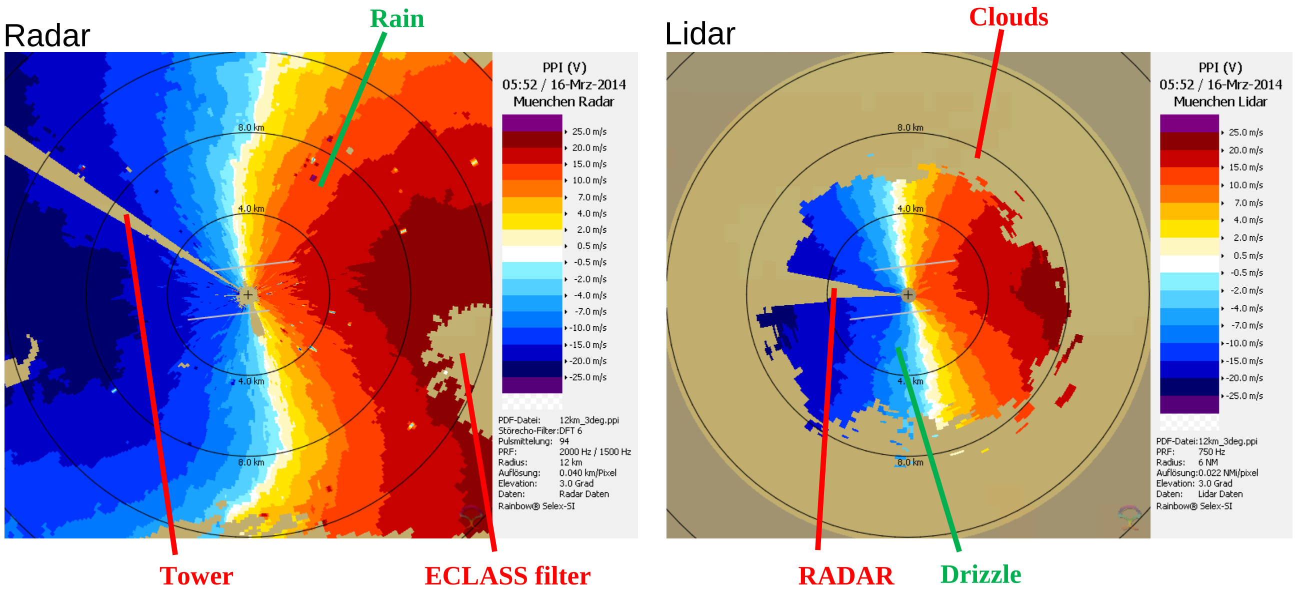


*Figure 1: Example of radar (left) and lidar (right) 3° PPI radial velocity data availability at MUC on 16 March 2014, 5.52 UTC.*

As a consequence of seasonal effects and different weather situations data availability of each sensor differs clearly. 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 (Weipert et al., 2014). 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.

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 2:

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).

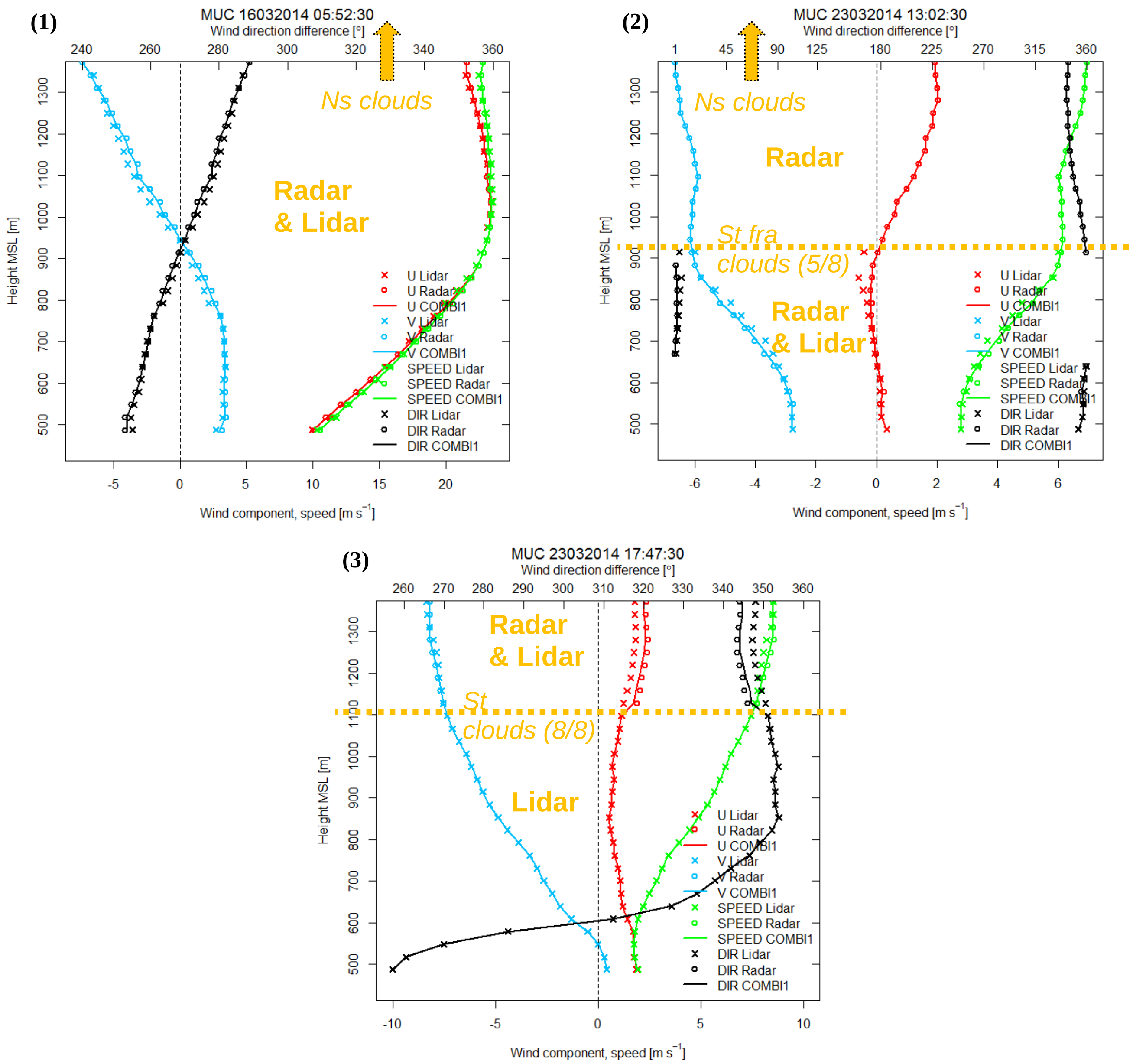


*Figure 2: VVP vertical profiles of U and V wind components, wind speed (SPEED) and direction (DIR) of lidar, radar and the combination of both sensors (COMBI1) at MUC. Dates: (1) 16 March 2014, 5.52 UTC; (2) 23 March 2014, 13.02 UTC; (3) 23 March, 17.47 UTC.*

## 5 Verification

Our 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.

### 5.1 Radial velocity

As a fact of both systems lidar and radar perform 3° PPI scans every minute quasi-simultaneously radial velocity measurements of these scans are compared to each other. In general, radar and lidar wind differences are small and distributed uniformly revealing a good measurement performance (Figure 3). The monthly mean bias is close to 0 m/s and the Root Mean Square Difference (RMSD) varies from 1 m/s to 1.4 m/s for MUC and FRA. Cases of high differences might be occurring because of speckles. Due to removal of speckles after a lidar noise scan in November 2013 at MUC the counts of high biases decreases (Figure 3). However, unambiguous velocities of single radar PRF (2000 Hz, 1600 Hz) lead to peaks at ±12 m/s and ±16 m/s.

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 4). 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 5). 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.

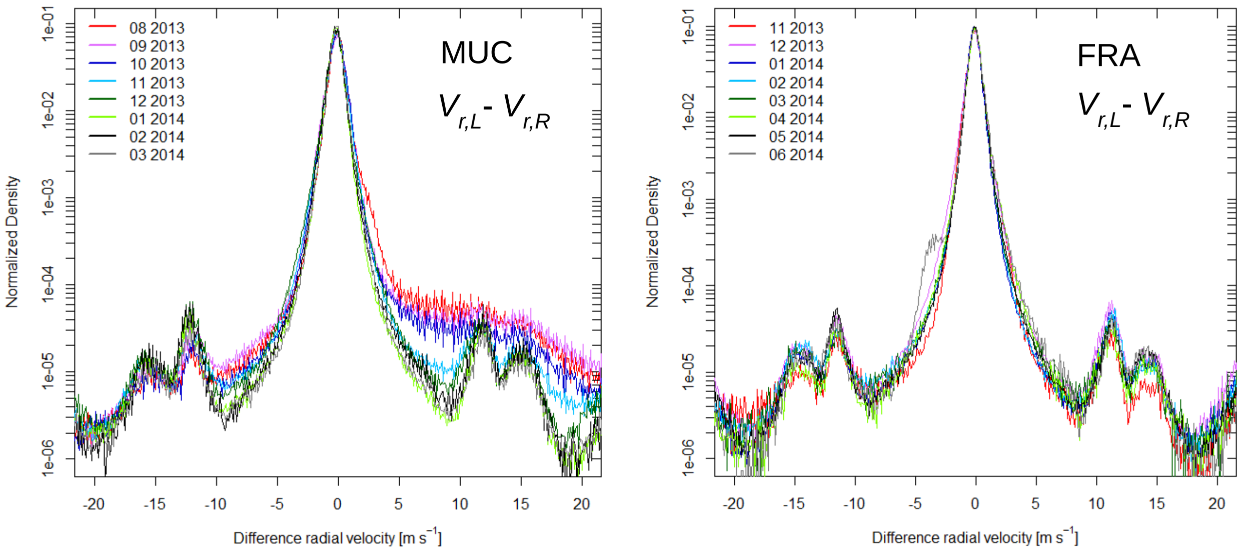


*Figure 3: Normalized density of monthly lidar–radar radial velocity differences for MUC (left) and FRA (right).*

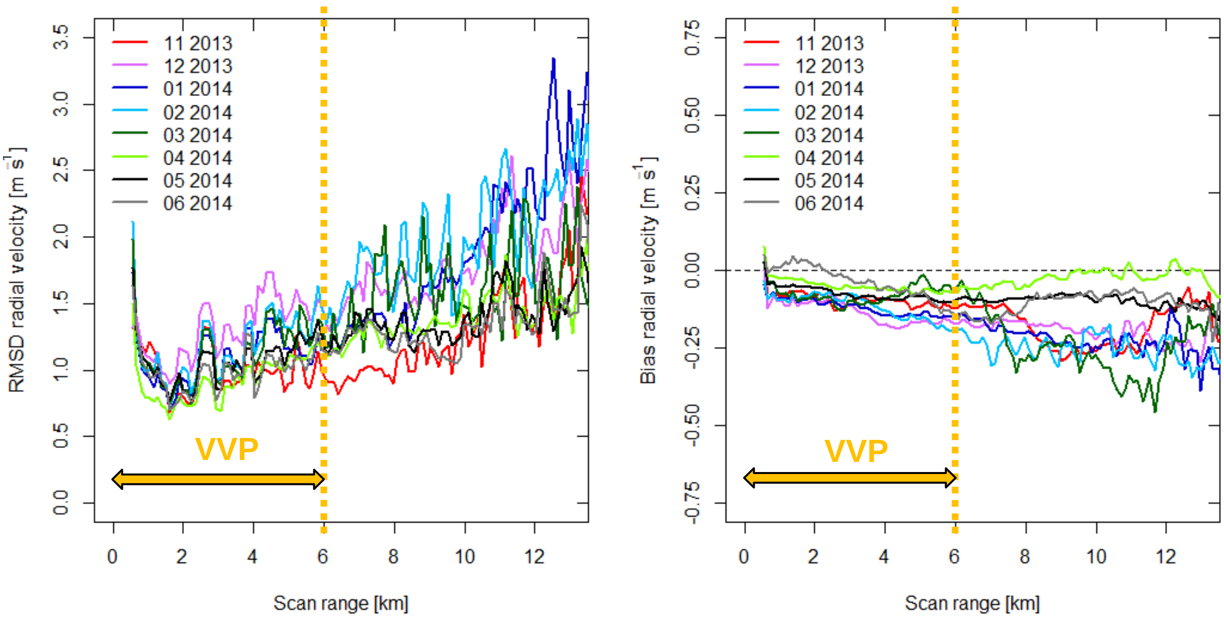


*Figure 4: Mean monthly lidar–radar RMSD (left) and bias (right) of 3° PPI radial velocity for FRA; as function of range.*

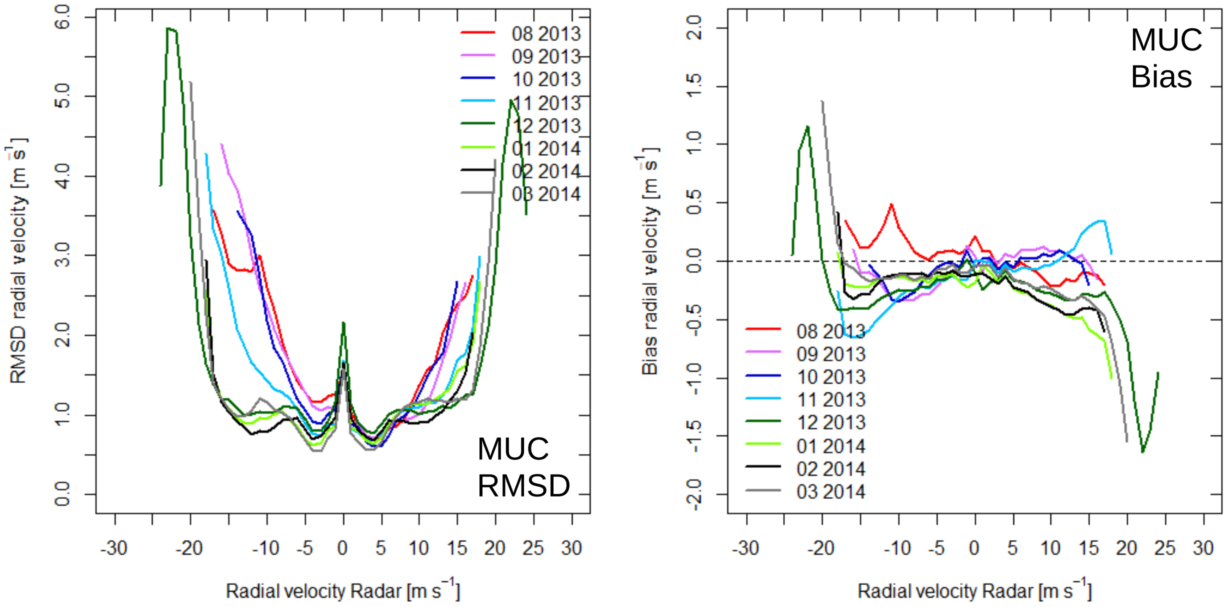


*Figure 5: Mean monthly lidar–radar RMSD (left) and bias (right) of 3° PPI radial velocity for MUC; as function of radar radial velocity.*

## 5.2 Vertical wind profiles

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 6). 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 7). 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 7 (lidar–radar bias and RMSD as a function of height) can be seen for increasing wind speed in Figure 8. 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.

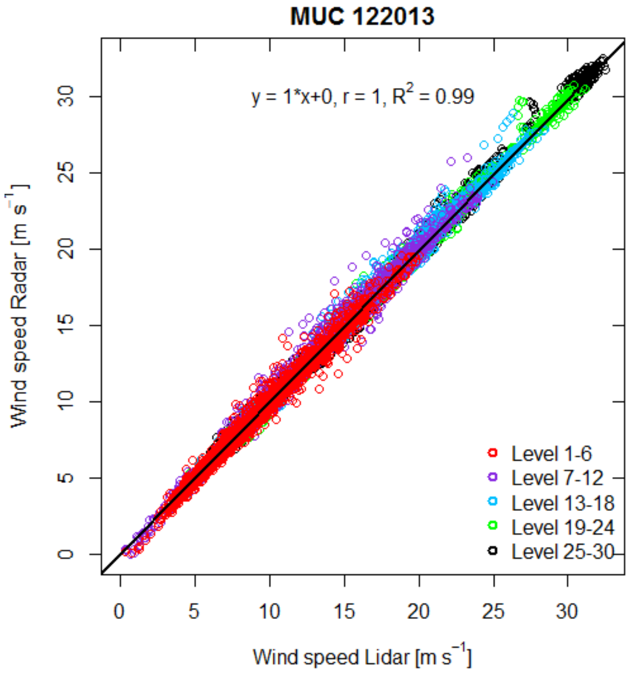


*Figure 6: Scattergram of lidar and radar wind speed for December 2013 at MUC.*

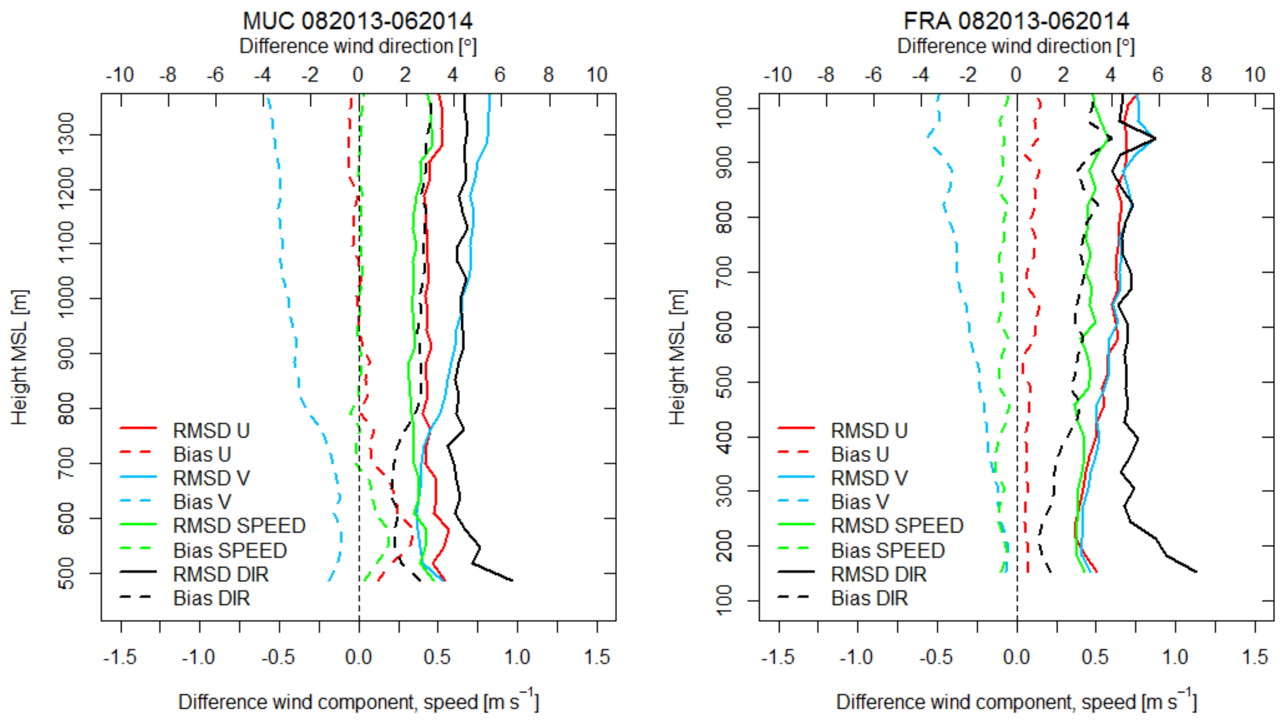


*Figure 7: Mean lidar–radar RMSD and bias of VVP U and V wind components, wind speed (SPEED) and direction (DIR) from August 2013 until June 2014 for MUC (left) and FRA (right); as a function of height.*

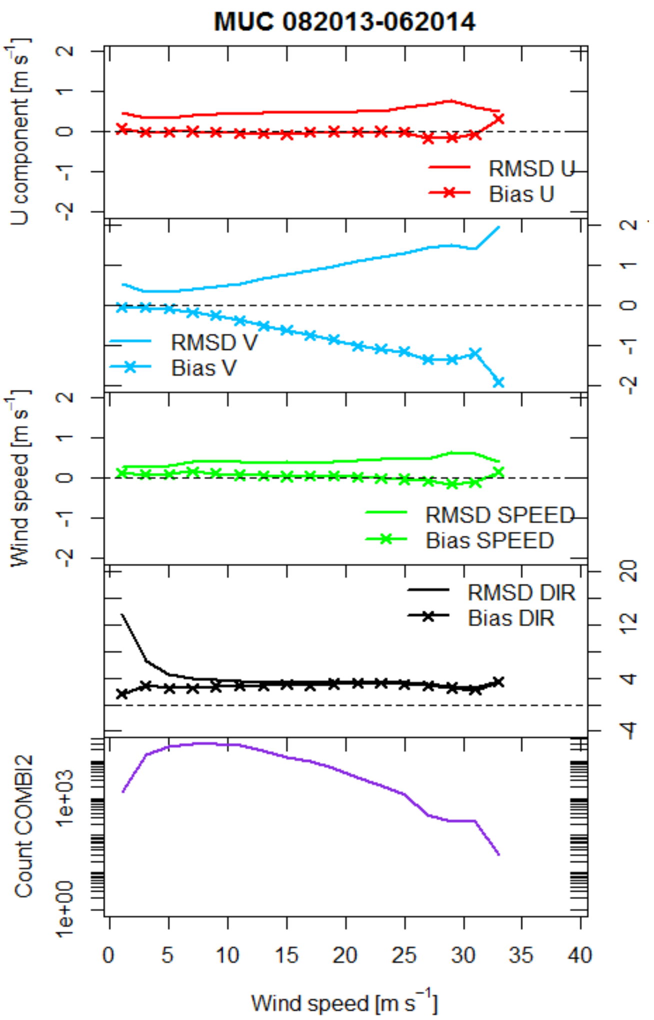


*Figure 8: Mean lidar–radar RMSD and bias of VVP U and V wind components, wind speed (SPEED), direction (DIR) and counts of inter-comparisons from August 2013 until June 2014 for MUC (left) and FRA (right); as a function of wind speed.*

## 6 Summary and conclusions

Observations of low-level wind are vital to the safety, economy and ecology of aircraft operations at TMA and essential for operational weather and wind shear forecasting. In order to detect wind and wind shear (vertical and horizontal) during rain and clear-air conditions a X-band radar and a IR lidar has been installed at the international airports of Munich (MUC) and Frankfurt (FRA). Never before in Europe there exist high-frequently and high-resolution wind measurements of new X-band radar and lidar systems like at MUC and FRA. Our studies are based on one year data of radar and lidar low-level wind measurements. Prior to the data processing, non-meteorological and ambiguous echoes are removed from the measurements using various echo classification techniques (radar) and modified signal-to-noise thresholds (lidar) and wind standard deviation (radar and lidar). Based on the filtered radial velocity data from 1 minutes 3° PPIs covering the glide paths and 5 minutes volume scans (several PPIs of different elevation) wind shear is determined. Aimed at vertical wind shear detection vertical wind profiles are retrieved from the volume data 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 together.

In order to check the quality of each system's measurement inter-comparison studies are performed. The inter-comparisons are based on simultaneous availability of radar and lidar measurements. Basically motion of light rain (mainly drizzle) can be used as wind tracer for both sensors radar and lidar. However, the availability range and height of each system is typically limited by clouds. In general, at MUC and FRA about 5 % to 8 % on average data are available from both sensors radar and lidar until a range distance of 3 km (3° PPI) as well as until a height of 800 m AGL (VVP). Thus, about 40,000 to 65,000 times within one year 5 minutes mean wind is available every 100 ft (approximately 30 m) vertically (until 800 m AGL) from both sensors.

In general, radar and lidar radial velocity and vertical wind profiles show a good agreement similar at MUC and FRA. For radial velocity, the monthly mean bias is close to 0 m/s and the Root Mean Square Difference (RMSD) varies from 1 m/s to 1.4 m/s. Commonly, the difference of radar and lidar radial velocity increase slightly by increasing range distance and velocity (maximum monthly mean bias of 0.5 m/s at 12 km and 0.7 m/s at 15 m/s). Basically, the data quality is affected positively by noise scans and staggering based on different radar PRF. For vertical wind profiles, the maximum mean bias is smaller than 0.5 m/s respectively 4° (at 800 m AGL) which reveal a good system's performance according to WMO (2008). As a fact of absolute wind variability is higher for non-uniform wind fields linked with high wind speed maxima, the difference of radar and lidar wind velocity is significantly higher for those individual cases. By comparing each data point the RMSD may exceed 5 m/s (radial velocity above 20 m/s), for the vertical VVP mean wind the RMSD may exceed 2 m/s (wind speed above 25 m/s). Due to the calculation method of horizontal wind is based on the component of the velocity vector line of sight, wind components perpendicular to the prevailing wind (tracer) directions are difficult to calculate. Consequently, at MUC and FRA (mostly westerly wind) the bias and RMSE of the v wind component is slightly higher than of the u wind component.

Based on our inter-comparison investigations wind and wind shear measurements from the combined X-band radar and lidar system can be valued qualitatively. Quality statements of wind measurements are able to be performed depending on range distance, height, and wind speed. The high-frequently and high-resolution wind measurements will develop mesoscale forecasting. In order to improve weather forecasts the quality controlled low-level wind data are foreseen to assimilate in high-resolution Numerical Weather Prediction (NWP) models.

## Acknowledgement

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).

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