# SCIENTIFIC REPORT

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**Produced by**: Anne Hirsikko (FMI, Finland) and Ewan O'Connor (FMI, Finland)

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**Contribution by**:
Christoforos Halios (University of Reading, UK),
Anne Hirsikko (FMI, Finland),
Sven-Erik Gryning (DTU, Denmark),
Ronny Leinweber (DWD, Germany),
Antti Manninen (University of Helsinki, Finland),
Tobias Marke (University of Köln, Germany),
Ewan O'Connor (FMI, Finland),
Nina Petersen (IMO, Iceland),
Jana Preissler (NUIG, Ireland),
Eileen Päschke (DWD, Germany),

Umar Saeed (Universitat Politècnica de Catalunya, Spain),
Jan Schween (University of Köln, Germany),
Yang Shu (Reykjavik University, Iceland),
Irene Suomi (FMI, Finland),
Minttu Tuononen (FMI, Finland),
Ville Vakkari (FMI, Finland)

**Introduction**

The major aim of this meeting was to summarise the current scientific and technical understanding of Doppler lidar when operating in a meteorological context. The discussion focused on two topics, how to optimally retrieve wind profiles, and how to retrieve turbulent parameters. The expected outcome is a standard operating procedures (SOP) document that details how to deploy and operate a Doppler lidar within an emerging meteorological Doppler lidar network. This document can then be published as a WMO technical document, and distilled into a review paper.

**Wind**

Recent work by members of the WG have shown that the reliability of the retrieval of the vertical profile of horizontal wind (speed and direction) depends on the scanning strategy employed. All single-instrument retrieval methods require an assumption on the homogeneity of the wind flow, and that this can be rendered invalid in the presence of strong turbulence (and other coherent features). The discussion in the meeting highlighted that this had been the general experience of the group.

The DBS method appears more susceptible to turbulence rendering wind retrievals invalid than the VAD method. A number of examples were shown in the meeting. There are retrieval methods that can identify and flag situations where the necessary assumption of homogeneity is not met (Päschke et al., AMT, 2015). However, removal of wind profiles leads to the issue of conditional sampling which was seen as a problem in e.g. climate and wind turbine applications. Therefore, it was agreed to further investigate the influence of turbulence on winds derived from DBS and VAD methods. There are a number of existing wind datasets (from e.g. Limassol, Utö, Hyytiälä, Vehmasmäki, Jülich, Falkenberg) in various environments co-located with in-situ wind observations on tall towers. It was agreed that these data would be made available so that WG2 members could attempt to quantify the impact of turbulence on wind retrievals.

A number of papers have been published that describe the optimum settings for obtaining horizontal winds from a VAD scan under certain conditions, such as assuming homogeneity, and include a rigorous treatment of the impact of measurement uncertainties. However, the discussion and quantification of the impact of turbulence, which may render the homogeneity assumption invalid, is not so thorough and there is no clear message on the relative merits of the various scan strategies at different locations, under different atmospheric conditions. Some preliminary studies suggest that the impact of turbulence can be mitigated somewhat by scanning at lower elevations, although this would not prevent coherent structures from rendering the homogeneity assumption invalid. It was also noted that much of the discussion on Doppler lidar wind retrievals in the literature focused on requirements from a wind energy perspective, i.e. winds at hub height, and that this may not be suitable or applicable from a meteorological perspective.

This culminated in a decision to produce a review paper discussing the relative merits of the scanning strategies for providing horizontal winds from an operational meteorological perspective. The outline of the proposed review paper is given in the appendix. In addition, the WG will prepare an abstract to EMS 2017 in Dublin on this topic, presenting the WG findings to a wider audience.

Minttu Tuononen presented an algorithm to detect low level jets (LLJ) from Doppler lidar wind profile observations (Tuononen et al, in review, 2017). The method has already been tested at a few locations, on different instrument types, and an algorithm package will be distributed to all Doppler lidar sites. Detection of LLJ at levels below 150 m also necessitates VAD scans at an elevation that provides a suitable vertical resolution; this provoked discussion that the optimum VAD elevation angle discussed in the literature may not actually be optimal for LLJ detection and that an 'optimum' scanning strategy should be devised for obtaining winds both close to surface and at upper levels. Sequential VAD scans at two elevations was proposed as the lower elevation scan would enable LLJ detection, and provide some mitigation of the turbulent impact.

Irene Suomi showed how Doppler lidar wind observations can potentially be used to monitor wind gusts (Suomi et al., in review, 2017). This application is of immediate benefit to forecasters. Full characterization of the uncertainty in the measurements is necessary, as the gust definition relies on each individual measurement being accurate when determining the maximum departure from the mean over a specified time window (the mean wind itself is less susceptible to measurement errors).

**Turbulence**

Turbulent properties in the boundary-layer can be obtained with different measurement strategies:

1) zenith-pointing (e.g. O'Connor et al., 2010)
2) VAD scanning (e.g. Vakkari et al., 2015)

An advantage of zenith-pointing observations is that they provide a direct measurement of vertical Doppler velocity variance from which the dissipation of turbulent kinetic energy (TKE) can be retrieved. However, due to instrumental limitations, the minimum distance that most instruments can measure reliably is about

100 m, turbulence at heights below this is not possible to quantify. With VAD scanning, observations at heights below 100 m are now possible, with the minimum height dependent on the elevation angle selected for the VAD scan (note that the minimum *range* limitation remains). The current VAD technique (Vakkari et al., 2015) provides the variance of the radial Doppler velocity which can be used as a proxy for dissipation of TKE. Application of both methods in parallel was seen as beneficial since the VAD technique can diagnose the presence of turbulence much closer to the surface and fill in the gap in the vertical profile.

Since both methods derive the turbulent information from the variance of the Doppler velocities it is vital that the uncertainty characteristics of the Doppler velocity measurement are known and quantified. Since the Doppler velocity uncertainty directly depends on the signal-to-noise ratio of the measurement (e.g. O'Connor et al., 2010), this requires that the received signal and noise are also well characterized. Such characterization has already been performed for a number of HALO Photonics Doppler lidar instruments with a methodology for background noise correction ready for implementation (Manninen et al., 2016; Vakkari et al., in preparation, 2017). Jana Preissler and Yang Shu are investigating and working on a similar characterisation and corresponding correction for Leosphere Doppler lidars.

Evaluation of the turbulent retrievals from a Halo Photonics system has been performed at Hyytiälä, with direct comparison against turbulence measurements made by sonic anemometers mounted on a tall mast. This evaluation will be extended. The tower at Falkenberg also provides an opportunity to evaluate the Doppler lidar retrieved turbulent profiles with in-situ sonic anemometer measurements.

Antti Manninen and Tobias Marke showed recent updates in a classification scheme that identifies boundary layer turbulence and its source. This classification scheme can be routinely applied to both clear and cloudy profiles, although there are some challenges when precipitation is present; velocity variance arising from variations in precipitation terminal fall speed rather than turbulence still require a more accurate diagnosis. Source labelling conventions were reviewed and improvements in naming were agreed upon. LLJ detection using Tuononen (2017, in review) was agreed upon as a useful and necessary improvement in the turbulent source appointment. This classification method will be applicable throughout the network once standard operating procedures and processing have been implemented at each site.

### Data provision

All participants agreed that a central hub for the Doppler lidar network should be implemented, to provide data processing, data storage and data archiving. FMI has the necessary resources and manpower to provide such a central server, and that this is already in operation in principle (since FMI already has a server for its internal Doppler lidar network). The central hub at FMI will implement the full processing chain from background correction applied to raw data, wind and turbulence retrievals, through to additional products such as LLJ and turbulence classification.

There are some specific requirements for provision of data for NWP assimilation (and other forecast applications):

- data must be transferred to NWP within ca. 10 minutes from observation
- algorithms should be written in C to ensure fast processing

To enable further research, testing, and harmonization of the operational methods, it was agreed to create a software repository for sharing retrieval algorithms.

## Tasks for the next WG meeting

The next Doppler lidar WG will be organized in Dublin in September 2017 during the combined MC/WG TOPROF meeting. Based on their experiences, each WG participant will contribute to writing the SOP and the review paper. The drafts of SOP and review manuscript, which supplement this report, include contribution allocation.

The scientific report will be posted on the TOPROF website: www.toprof.eu.

## References

Manninen et al. (2016) A generalised background correction algorithm for a Halo Doppler lidar and its application to data from Finland. *Atmos. Meas. Tech*., **9**, 817–827.

O'Connor et al. (2010) A method for estimating the turbulent kinetic energy dissipation rate from a vertically-pointing Doppler lidar, and independent evaluation from balloon-borne in-situ measurements. *Atmos. Ocean. Technol*., **27**, 1652–1664.

Paeschke et al. (2015) An assessment of the performance of a 1.5 um Doppler lidar for operational vertical wind profiling based on a 1-year trial. *Atmos. Meas. Tech*., **8**, 2251–2266.

Suomi et al. (2017) Methodology for obtaining wind gusts using Doppler lidar. *QJRMS*, accepted.

Teschke and Lehmann (2017) Mean wind vector estimation using the Velocity-Azimuth-Display (VAD) method: An explicit algebraic solution, *AMTD.*

Vakkari et al. (2015) Low-level mixing height detection in coastal locations with a scanning Doppler lidar. *Atmos. Meas. Tech.,* **8**, 1875–1885.

**APPENDIX A**

**Review paper on wind retrieval methods from a meteorological perspective**

The objective is to prepare a review paper on VAD and DBS wind retrievals aiming for submission in early 2018.



1. What are the research questions?
Optimal methods for retrieving winds from a Doppler lidar from a meteorological perspective. The retrievals assume homogeneity; what is the impact of turbulence on the validity of this assumption?

2. Objective of the review paper.
Discuss optimal scanning methodologies for retrieving vertical profiles of horizontal winds from a Doppler lidar? Note that different locations may have different requirements.
Review the literature concerning retrieval methods. Note the particular perspectives that other groups may have (e.g. wind energy) and how this might be different from a meteorological perspective.
Discuss impact of turbulence and measurement uncertainties for different retrieval methods.
Provide recommendations on suitable optimised scanning methodologies for a range of conditions.

3. Why is it an important objective which requires literature review?
No clear message on most suitable scanning methodology. No thorough discussion on the impact of turbulence on the validity of the homogeneity assumption necessary for retrieving wind. What should the requirements be for an operational network? How to harmonise different scanning methodologies across such a network, bearing in mind that each location may have its own particular requirements and hence optimization.

4. Main results of the paper.
Present methodology.
Show impact of turbulence on different retrievals and how to mitigate this.
Intercomparisons between different scan types.

5. What can the results contribute relative to the existing literature?
Show impact of turbulence on different retrievals and how to mitigate this.

Present guidelines for an operational network.

6. What are the implications of these results?
Better exploitation of instrument network
Facilitate exchange between different communities (end-users and data providers)



Possible paper structure:
1) Introduction
2) Retrieval methods
3) Impact of inhomogeneity
4) Intercomparison of different scan patterns
5) Optimal scan methodology
6) Data quality metrics
7) Conclusion

**<u>Introduction</u>**

Review literature. Stress that requirement is for optimal methods for retrieving winds from a Doppler lidar from a **meteorological perspective** and that obtaining a volume-averaged wind measurement rather than a point measurement may be preferable.

**<u>Retrieval methods</u>**

Present the two major scanning methodologies (DBS and VAD) together with their strengths and weaknesses. Show retrieval methods (e.g. Päschke et al., 2015). Show how measurement uncertainties should be incorporated and propagated through to retrieved winds. Discuss ideal elevation angle presented in the literature based on measurement uncertainty considerations (Teschke et al., 2017).

**<u>Impact of inhomogeneity</u>**

All single-instrument retrievals assume homogeneity in the wind flow. What is the impact if this is no longer true? Retrieval may not be valid in:

- turbulent situations
- gravity wave
- orography

Can we test for homogeneity? Yes, using e.g. Päschke et al. (2015), which provides a goodness-of-fit test and a condition number. Also look at individual radial winds compared to the 30-60 minute average.
Show that DBS not valid in strongly turbulent conditions – or coherent structures. Also show that VAD is not immune either
Examples include:

- Limassol
- Utö – test close to surface
- Hyde and Vehmasmäki – compare with tall mast
- Juelich – compare with tower

How often does this happen? How much data must be discarded? Is it the same at all heights?

## Intercomparison of different scan patterns

Show that different scan patterns are affected differently

- compare VAD and DBS
- compare VADs at different elevation angles
- Falkenberg – compare two lidars (one VAD, one DBS) at same time, and with mast

Show formal impact (Schween 2017, in prep.) of turbulent length scales on inhomogeneity and see if theory and observation agree.
Show impact of inhomogeneity on VAD at Falkenberg – compare two lidars (one VAD, one vertical stare) with mast. Also evaluate the vertical component of VAD by comparison with direct vertical measurement.
Expect more impact in the surface layer – scales with height in the surface layer

## Optimal scan methodology

Probably two VAD scans at different elevations since this also allows other products (LLJ, wind gust). Temporal aspect not as important as spatial. VAD scans also provide representativity. Scan selection also dependent on location.

## Data quality metrics

Filtering of data with respect to inhomogeneity and measurement uncertainties will depend on application. For NWP – very conservative (strong) filtering and they also require accurate uncertainty estimation for assimilation. Question:

- if model has good TKE scheme, then provide wind and turbulence profile, can relax strict inhomogeneity test
- if not, strict test must be applied to obtain mean wind profile

Conditional sampling will affect climatology

- important for wind resource, wind energy applications

## Conclusion

Optimal scan methodology is two VAD at different elevations – choice of elevation depends partly on location. Network will expect different scanning strategies so must be capable of harmonisation. Stress that requirement is for retrieving winds from a Doppler lidar from a **meteorological perspective.**

## APPENDIX B

## Standard Operating Procedures Document

Document detailing how to deploy and operate a Doppler lidar within an emerging meteorological Doppler lidar network. This document will then be published as a WMO technical document, and distilled into a review paper.



There are a number of recommendations for operational instruments that can be placed into three main categories: installation, operation, data processing. The outline of the sections in the SOP document is given below, with each section to be expanded on by members of the WG.

### Installation

Power requirements

- Power consumption typically < 1 kW, can use mains electricity (with converter)
- Fuel cells have proven reliable but probably not suitable for long-term operation
- Online UPS should be installed if possible

Location recommendations

- Impact of orography, coastline, city, heterogeneous surfaces

Installation requirements

- Stable platform, with instrument fastened to the platform
- Viewing field of view in elevation and azimuth.
  - Blocked sectors ok if not too large

Scanning quality check

- Hard target check for azimuthal/elevation alignment (repeatability)
  - Accuracy requirement?

### Operation

Cleaning and maintenance

- Check window
- Change mini-UPS batteries if necessary (3 years)
- Change desiccant if necessary (depending on location/instrument)
- Check for internal ice/condensation
- Check amplifier

Internet connection and data transfer/storage requirements

- Save raw/spectral data? Much larger requirements
- Store all diagnostic parameters

Scan strategy

- Location dependent
- Flexible, to take other operational requirements into account



**Data**

Data transfer to data hub

- Robust transfer method – operational check
- Update frequency and format

Processing

- Assessment of uncertainties
- Account for instrument capabilities
- Quicklooks
  - Status reports
  - Visual check
- Products
  - Wind and turbulent retrieval methods
  - LLJ
  - Wind gusts
  - Boundary layer classification

Data quality checking

- Quality flags
- File format/metadata
- Validation and evaluation
- Calibration and quality assurance procedures

Data provision for users