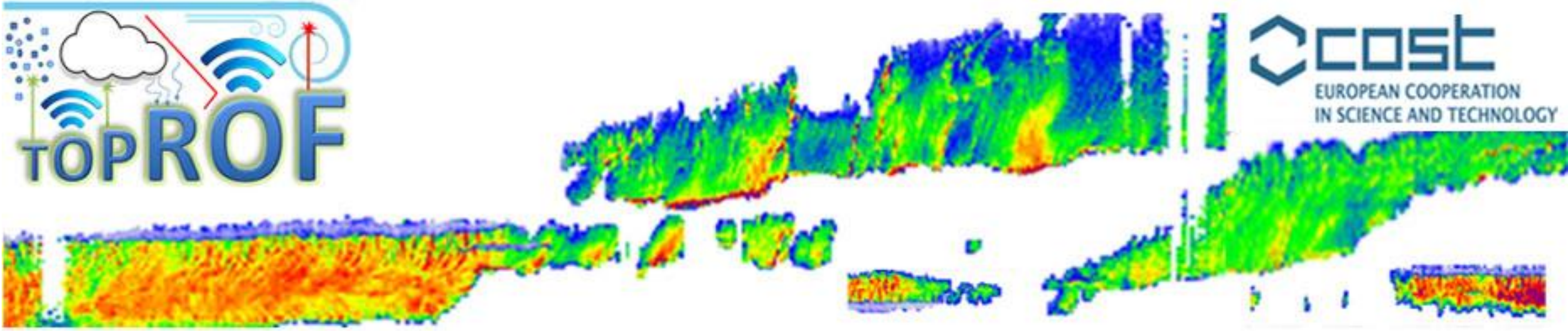

TOPROF EU COST Action ES-1303

Doppler lidar training school

Ewan O'Connor

Doppler lidar

- **Introduction**
  - Instrument and basic theory
- **Measuring wind**
  - Scanning methods
- **Measuring turbulence**
- **Practical applications**

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- **Instruments**
  - Characterise instruments
    - Understand uncertainty
    - Improve sensitivity (background correction)
- **Wind observations**
  - Selection of scanning pattern
  - Impact of turbulence
- **Turbulent properties**
  - Uncertainty is directly implicated in velocity distribution
  - Multiple layers – identify source of mixing
- **Applications**
  - Identify shear, low-level jets, wind gusts
  - Ash /dust resuspension
  - Update classical picture of the boundary layer


WindTracer

WindTracer


WindTracer

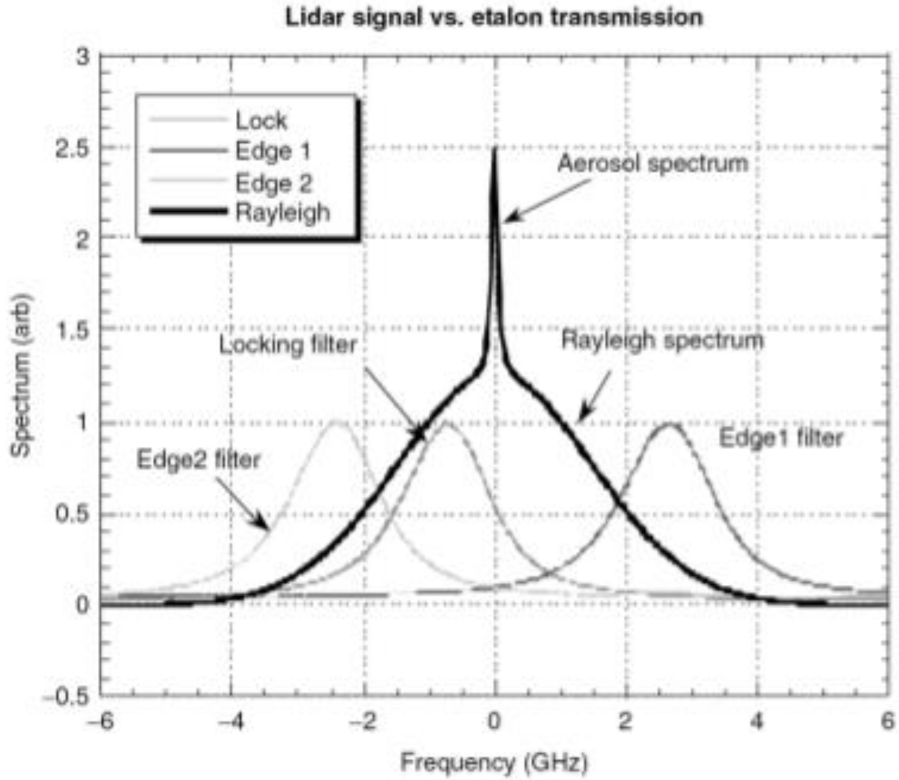

WindTracer®


WINDCUBE
200s

Doppler lidar types

- **Direct detection**
  - Resonance
  - Rayleigh-Mie filter
- **Heterodyne**
  - Pulsed
  - Continuous wave

Single- and Double-Edge Filters



The locking filter channel is to ensure the optimum balance of the Edge 1 and Edge 2 filters (F-P etalons) on the zero Doppler-shifted laser signal.

Coherent Detection
Detecting Doppler Shifts

We can't detect the frequency of light - but we can detect the "beat" (i.e. difference) signal between to light beams of slightly different frequency…

So, we create two beams: a local oscillator (LO) and a power oscillator (PO). The Local oscillator has frequency f_{LO}.

We make sure that the PO has a known frequency offset (i.e. f_{offset} = 10 MHz, 100 MHz) from that of the LO, or $f_{PO} = f_{LO} + f_{offset}$.

This PO beam goes out into the atmosphere. The light that returns (scattering off of aerosols) may have been Doppler shifted by f_{Dopp} for a total frequency offset of

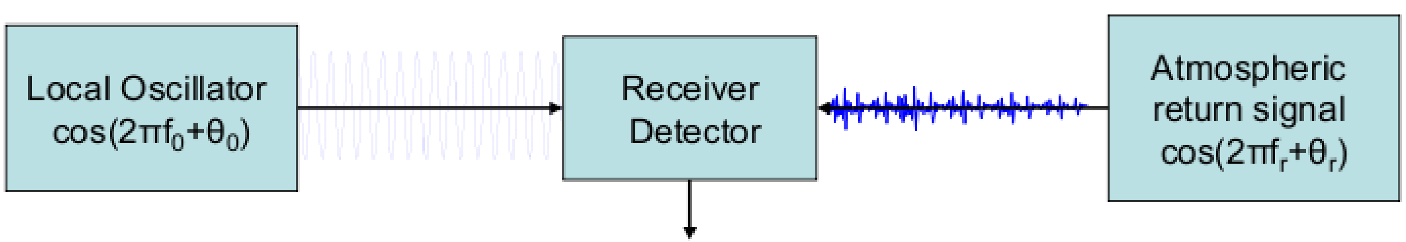
$$f_a = f_{Dopp} + f_{offset} + f_{LO}$$

Coherent Detection

The atmospheric return signal and the signal from the local oscillator are both incident on the detector.

Their electric fields add to create the total electric field incident on the detector:

$$E_a = A_a \cos\left(j2\pi f_a t + \varphi_a\right)$$
$$E_{LO} = A_{LO} \cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$
$$E_{tot} = A_a \cos\left(j2\pi f_a t + \varphi_a\right) + A_{LO} \cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$



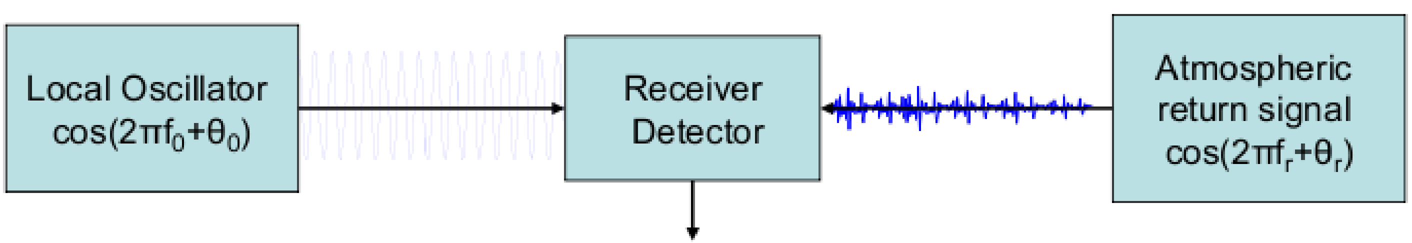
Coherent Detection

The detector actually "sees" optical power or:

$$\begin{aligned}|E_{tot}|^2 &= \left|A_a \cos(j2\pi f_a t + \varphi_a) + A_{LO} \cos(j2\pi f_{LO} t + \varphi_{LO})\right|^2 \\ &= A_a{}^2 \left|\cos(j2\pi f_a t + \varphi_a)\right|^2 + A_{LO}{}^2 \left|\cos(j2\pi f_{LO} t + \varphi_{LO})\right|^2 \\ &\quad + 2 A_a A_{LO} \cos(j2\pi f_a t + \varphi_a) \cos(j2\pi f_{LO} t + \varphi_{LO})\end{aligned}$$

The product of cosines leads to a sum and a difference:

$$\begin{aligned}|E_{tot}|^2 = A_a{}^2 \left|\cos(j2\pi f_a t + \varphi_a)\right|^2 + A_{LO}{}^2 \left|\cos(j2\pi f_{LO} t + \varphi_{LO})\right|^2 \\ + 2 A_a A_{LO} \cos\left(j2\pi (f_a + f_{LO}) t + (\varphi_a + \varphi_{LO})\right) \\ + 2 A_a A_{LO} \cos\left(j2\pi (f_a - f_{LO}) t + (\varphi_a - \varphi_{LO})\right)\end{aligned}$$

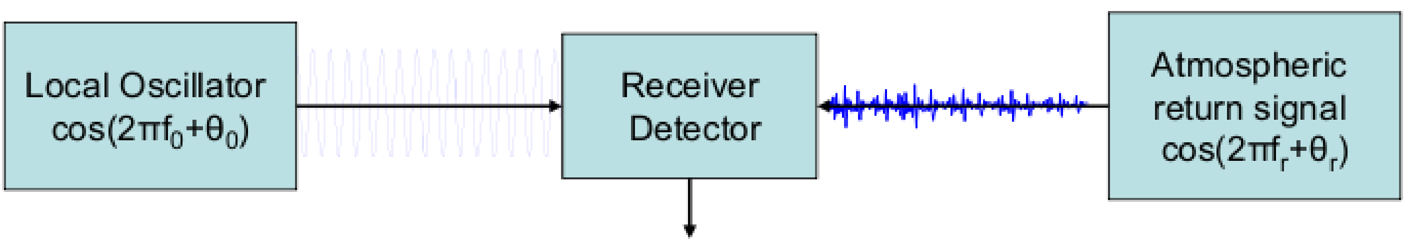


Coherent Detection

The high frequency (i.e. the sum of LO and atmospheric frequencies) is too high to detect. The other terms contribute to a DC offset, and the difference frequency is what gives us our signal:

$$|E_{tot}|^2 = |E_a|^2 + |E_{LO}|^2 + A_a A_{LO} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

In terms of power - the optical power on the detector is given by:

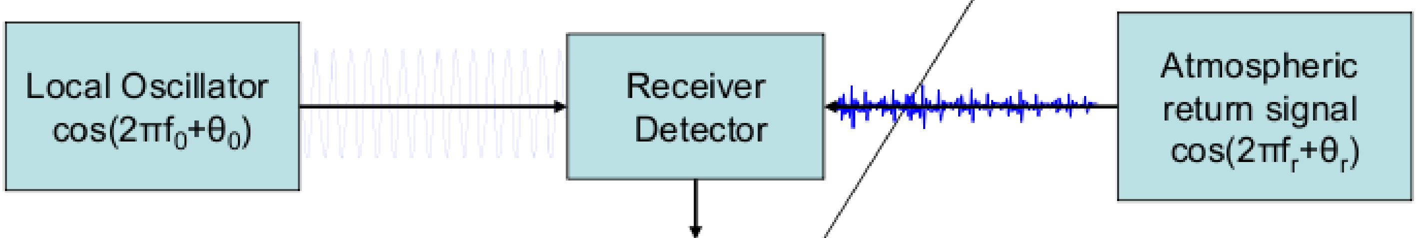


$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

Coherent Detection

The detector current is then given by:

$$i_{sig} = \left(\frac{\eta e P_{sig}}{h\upsilon} \right) = i_a + i_{LO} + 2\sqrt{i_a i_{LO}} \cos\left(j2\pi \left(f_a - f_{LO} \right) t + \left(\varphi_a - \varphi_{LO} \right) \right)$$



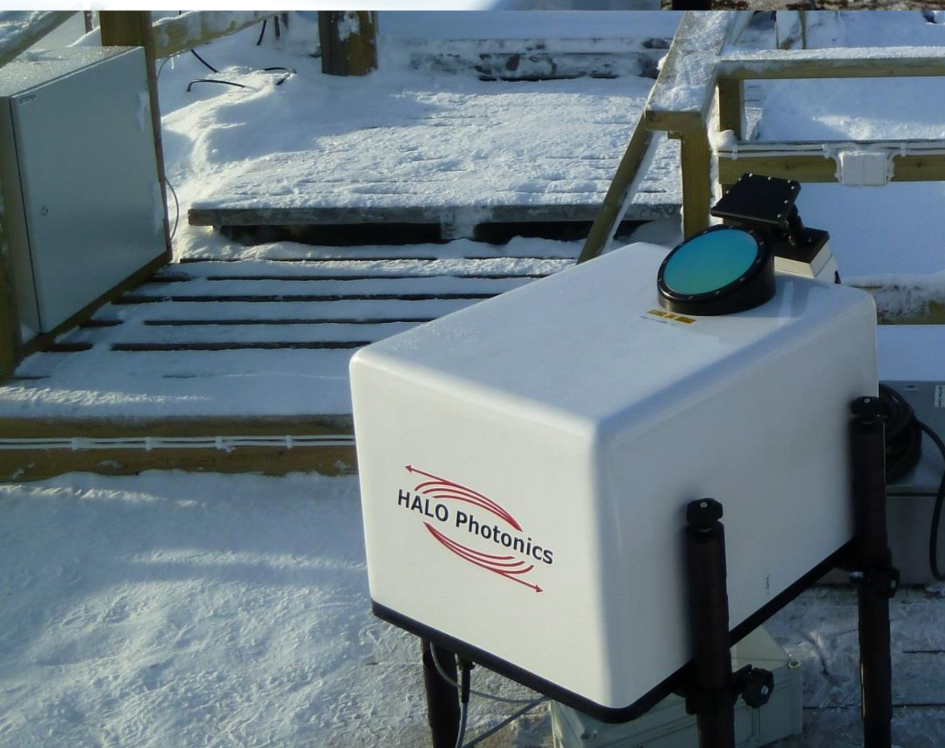
Remember $f_a - f_{LO} = f_{Dopp} + f_{offset} \quad \sim$ Mhz

We know f_{offset}…so we can find the Doppler shift frequency.

Typical Doppler lidar specifications

- Wavelength 1.5 micron
- Low-energy laser (~0.1mJ), high pulse repetition (15kHz) –> eye-safe
- Coherent heterodyne technique
  - Mix signal with local oscillator to get the Doppler shift
- Range 90 m – 10 km, resolution 30-50 m
- Full hemispheric scanning, or limited conical scan
- Continuous operation for months

- **Signal-to-noise ratio**
- **Radial velocity**
- **Attenuated backscatter**
- **Depolarisation**


HALO Photonics

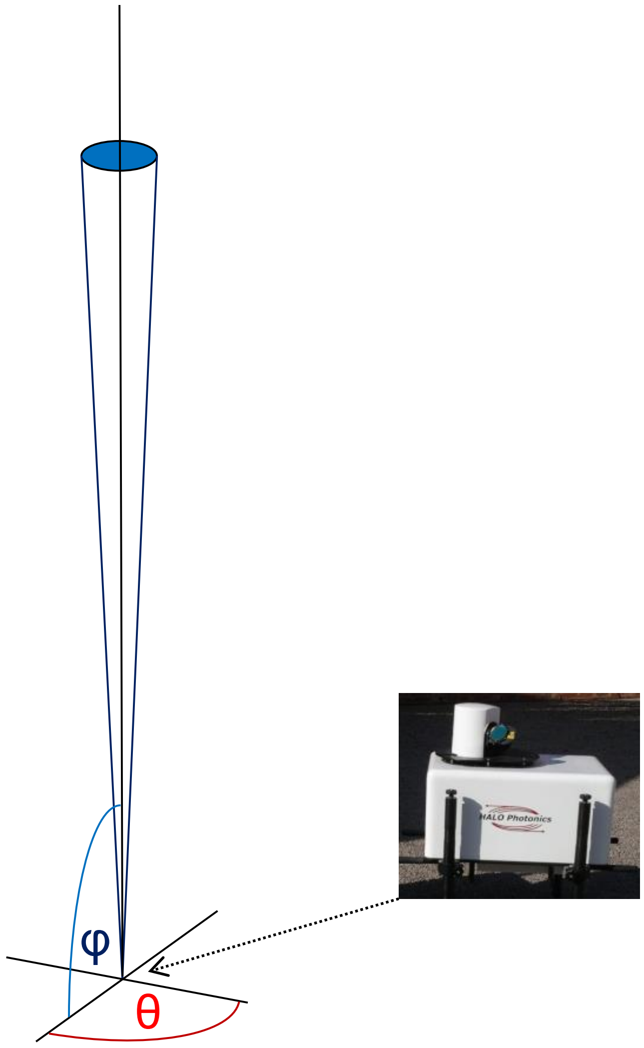

Stream Line

Scan Types

Stare

- θ - azimuth angle
- φ - elevation angle

- **Vertical stare (zenith)**
  - φ = 90º



Scan Types

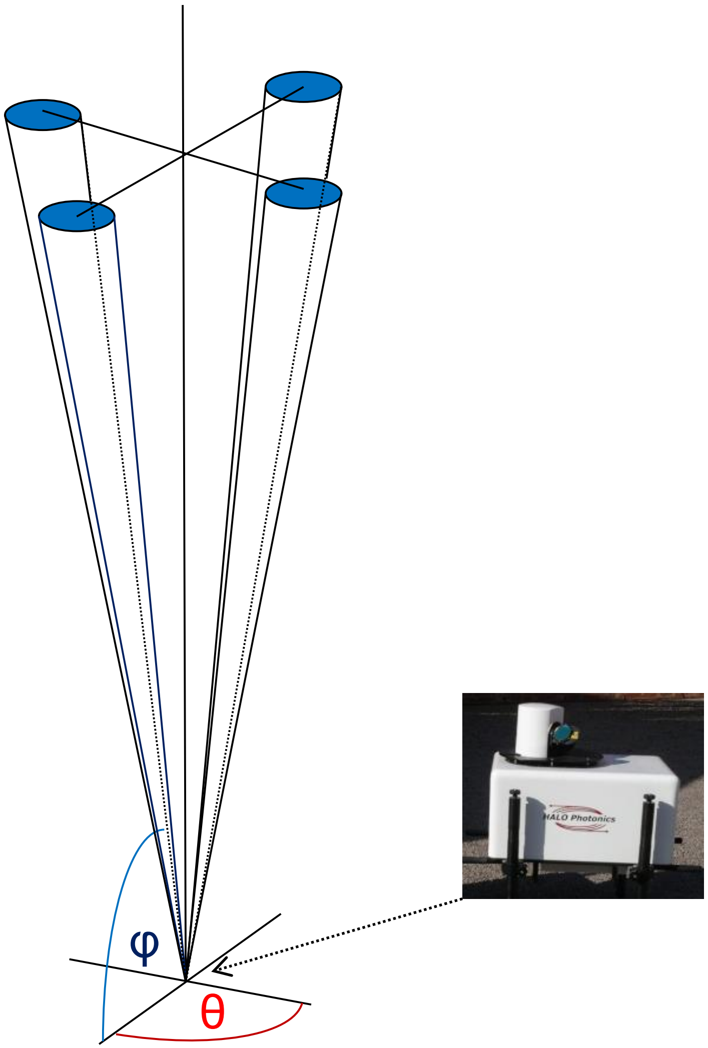
Doppler Beam Swing (DBS)

- **3-beam DBS**
  - 1 zenith (vertical) beam
  - 2 off-zenith beams
    - Orthogonal (e.g. N, E)
  - $\theta = 90^{o}$
  - $\varphi = 70^{o}$ (typically)

Scan Types

Doppler Beam Swing (DBS)

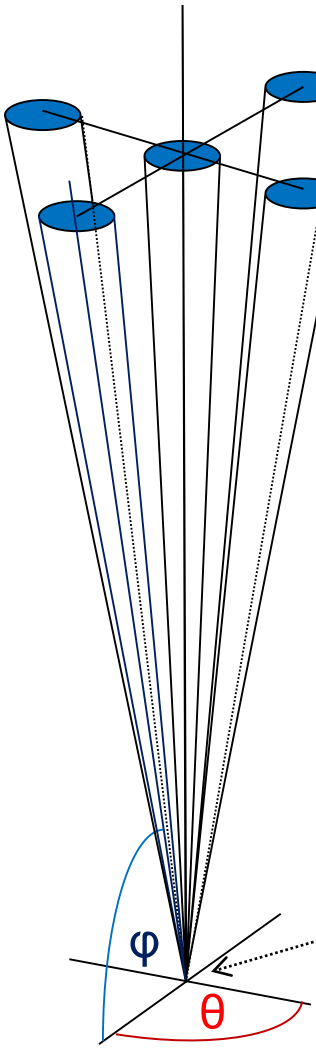
- **4-beam DBS**
  - 4 off-zenith beams
  - θ = 90º, N, E, S, W
  - φ = 70º (typically)



Scan Types

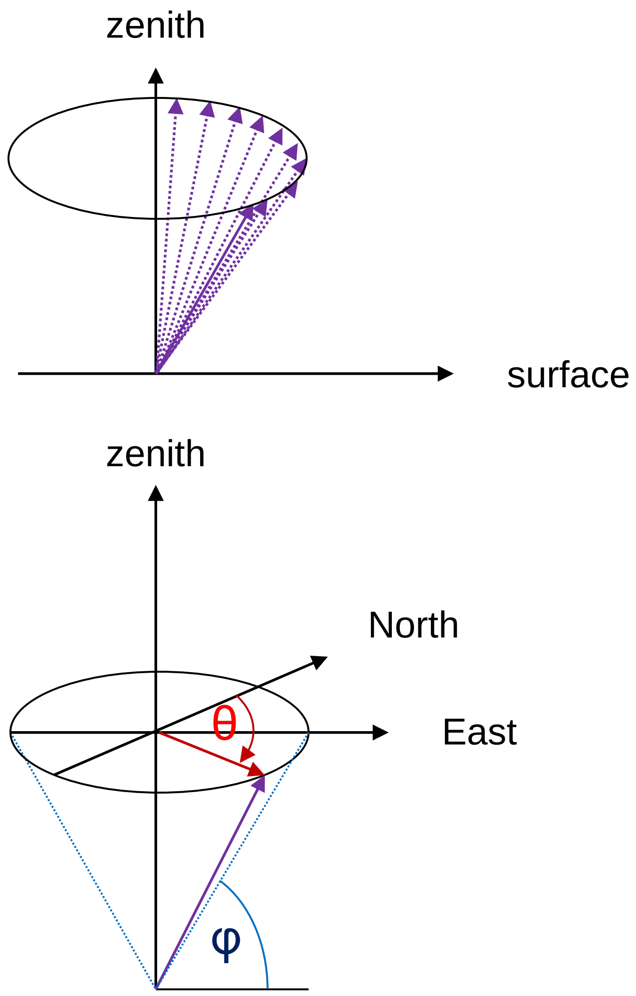
Doppler Beam Swing (DBS)

- **5-beam DBS**
    - 1 zenith beam
    - 4 off-zenith beams
    - θ = 90º, N, S, E, W
    - φ = 70º (typically)



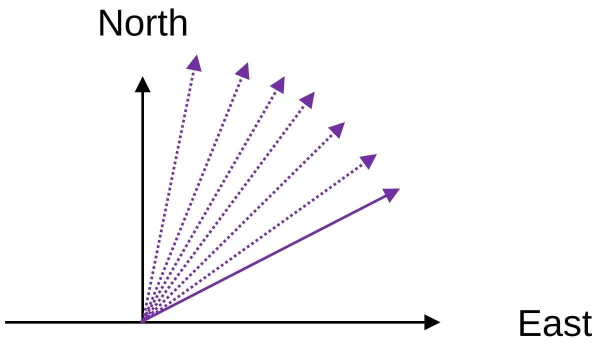
Scan Types

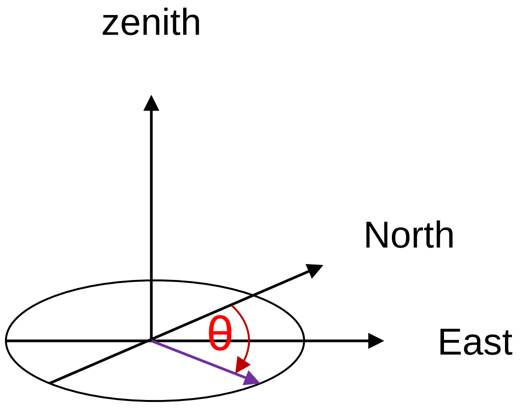
- **Velocity Azimuth Display**
  - VAD
  - Conical scan
  - N off-zenith beams
  - θ = 0:360
  - φ = constant



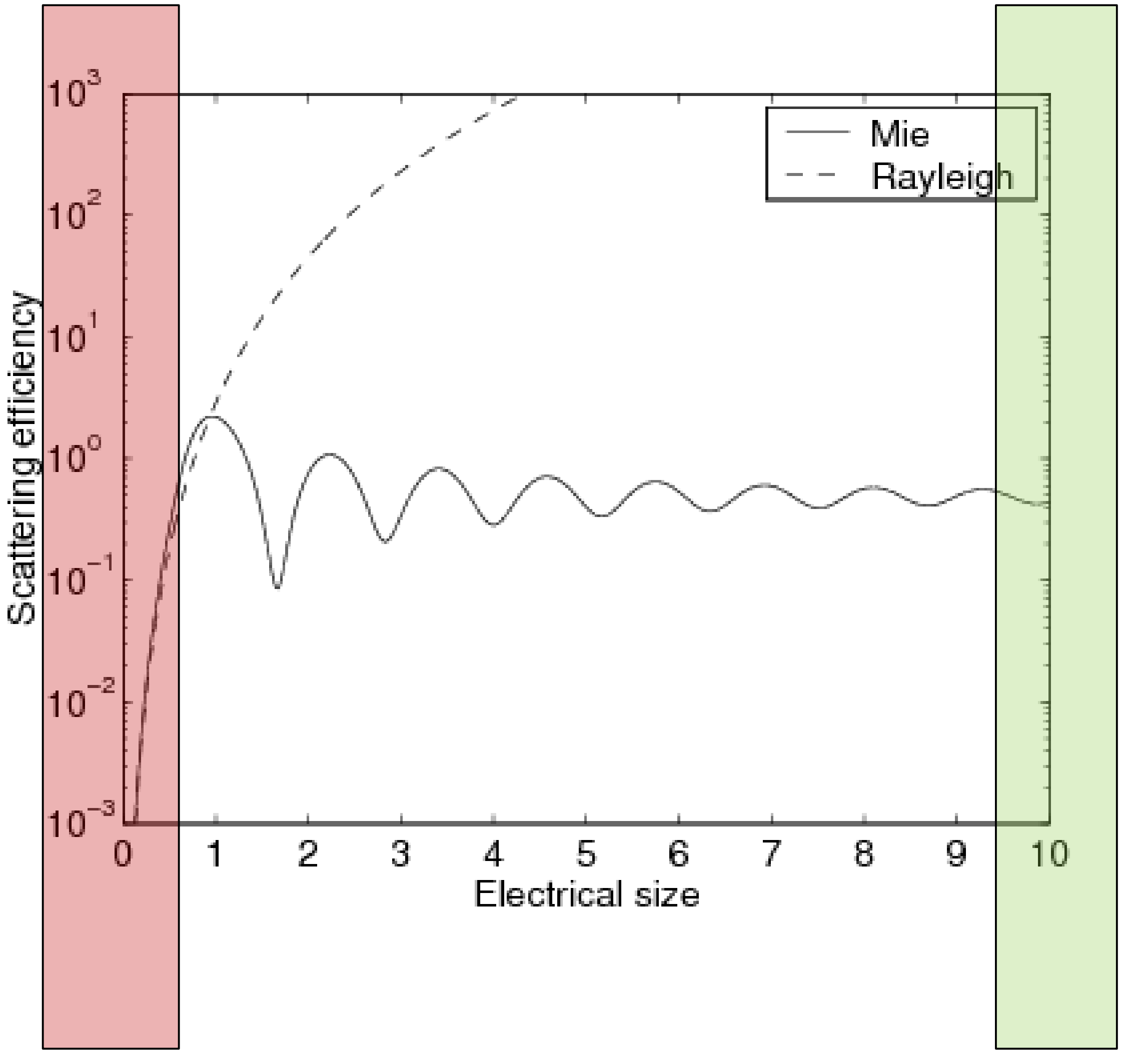
Scan Types

- **Plan Position Indicator**
  - PPI
  - Scan in azimuth at constant elevation
  - Low elevation scan similar to VAD
  - N beams
  - θ = 0:360
  - φ = constant (0 – 5º)





Scattering properties (Mie)



Electrical size = 2πr / λ

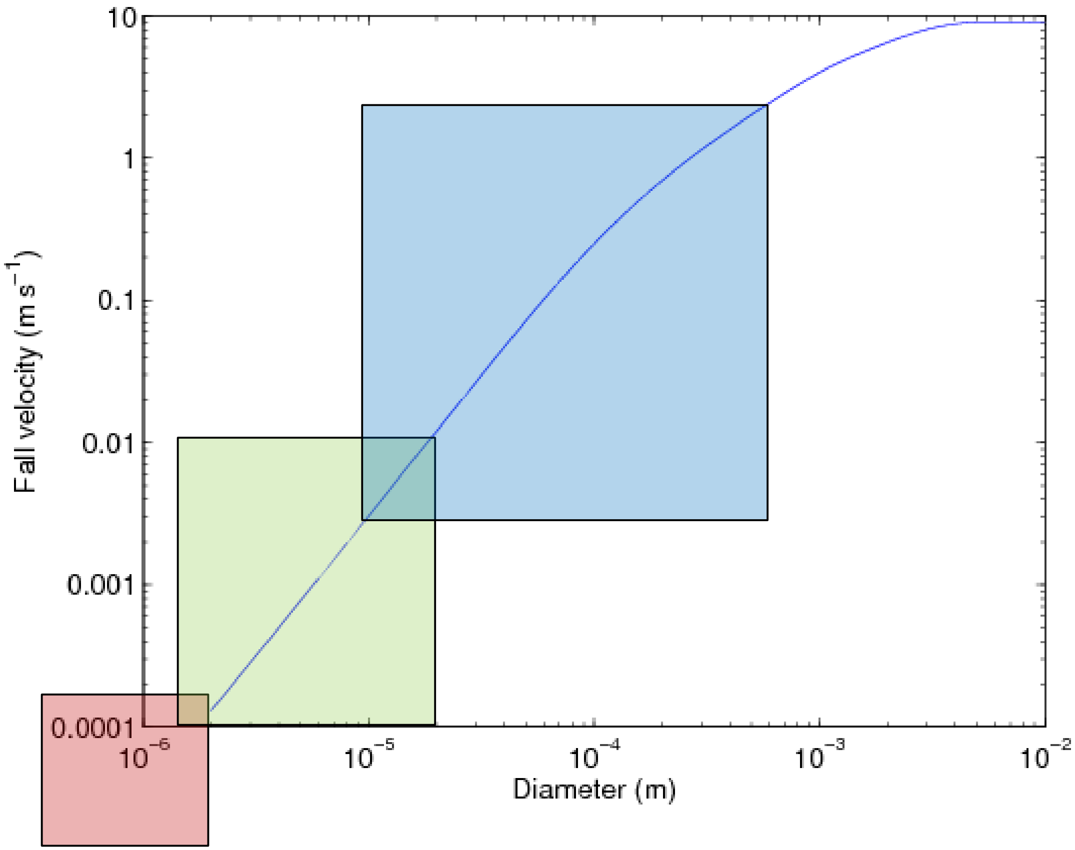
Lidar: λ=1e-6 m

Aerosol: r~5e-7 m

Cloud: r~5e-6 m

Ice : r~2e-4 m

Terminal Fall Velocity (Beard et al., 1976)



For water spheres

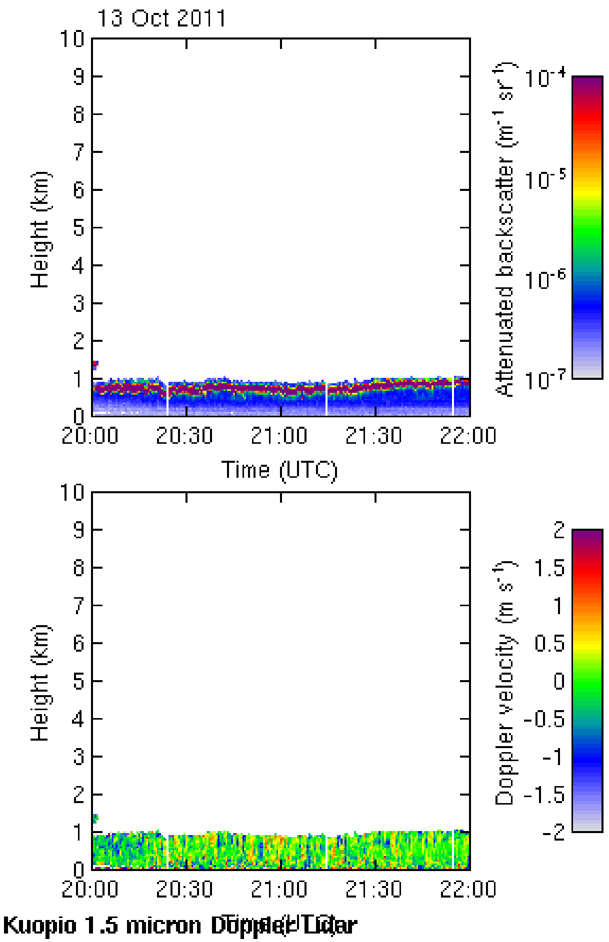
Fall speed varies slightly with pressure and temperature

Aerosol: r~5e-7 m

Cloud: r~5e-6 m

Ice : r~2e-4 m

How to interpret Doppler lidar images



Stratocumulus

- Very common cloud type, composed entirely of liquid water droplets.
- Droplets are reasonably small (around 10-20 microns in diameter), but numerous (100 per cc or more) so give a very strong lidar signal.
- Liquid layers also rapidly attenuate the lidar signal so that you cannot see through the layer.

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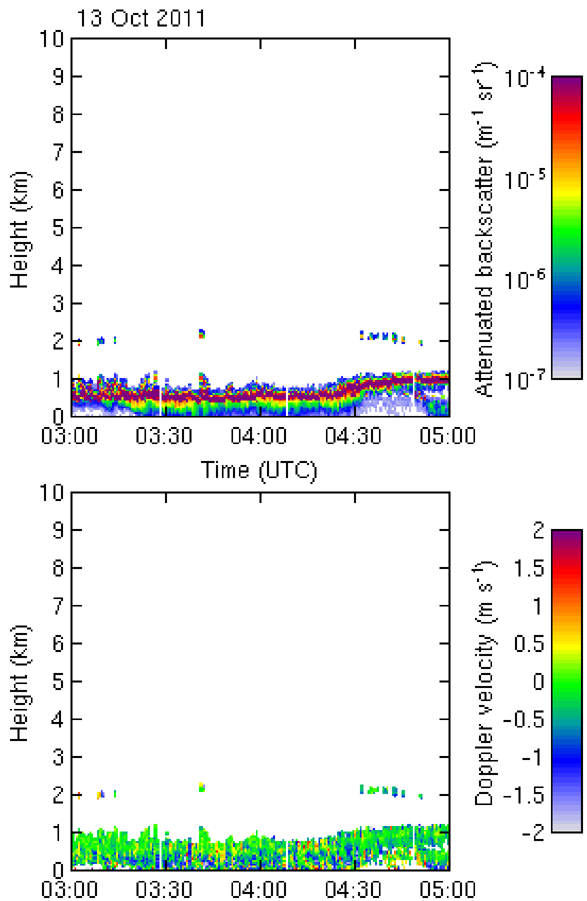
How to interpret Doppler lidar images



Kuopio 1.5 micron Doppler Lidar

Stratocumulus with drizzle

- If stratocumulus is more than a few hundred metres thick, then larger `drizzle' drops (around 100-200 microns in diameter) can grow.
- Drizzle drops are larger, but number concentration is much lower: backscatter signal is usually much lower than for the liquid layer itself.
- Drizzle often evaporates before reaching the surface.

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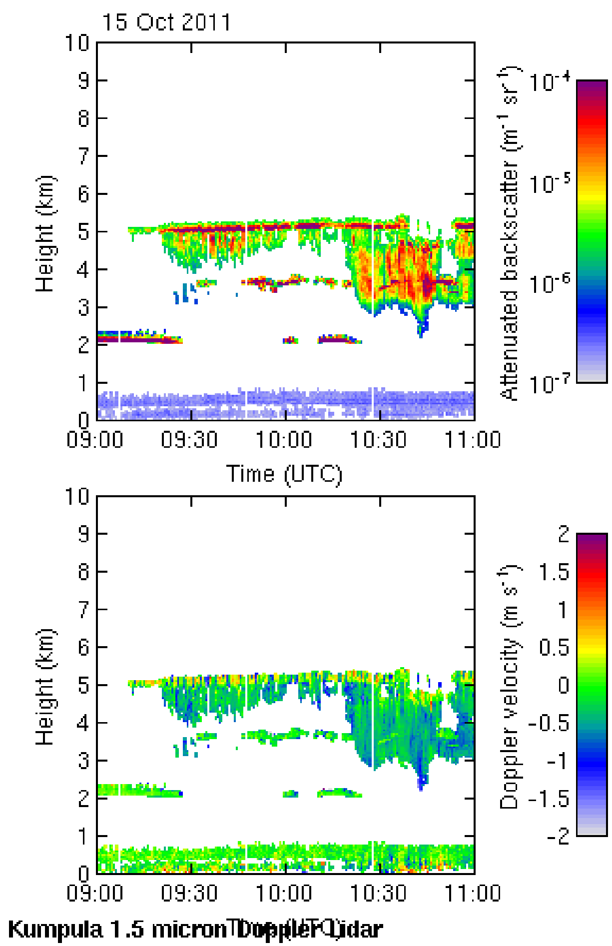
How to interpret Doppler lidar images



Altocumulus

- Mid-level cloud occurs at temperatures below freezing and above -40 C.
- Typically composed of a thin layer of supercooled liquid water droplets at the top, with ice crystals falling below in a layer that can reach a couple of km deep.
- Liquid droplets are about 10 microns in diameter.
- Larger, but less numerous, ice crystals may be several hundred microns across.

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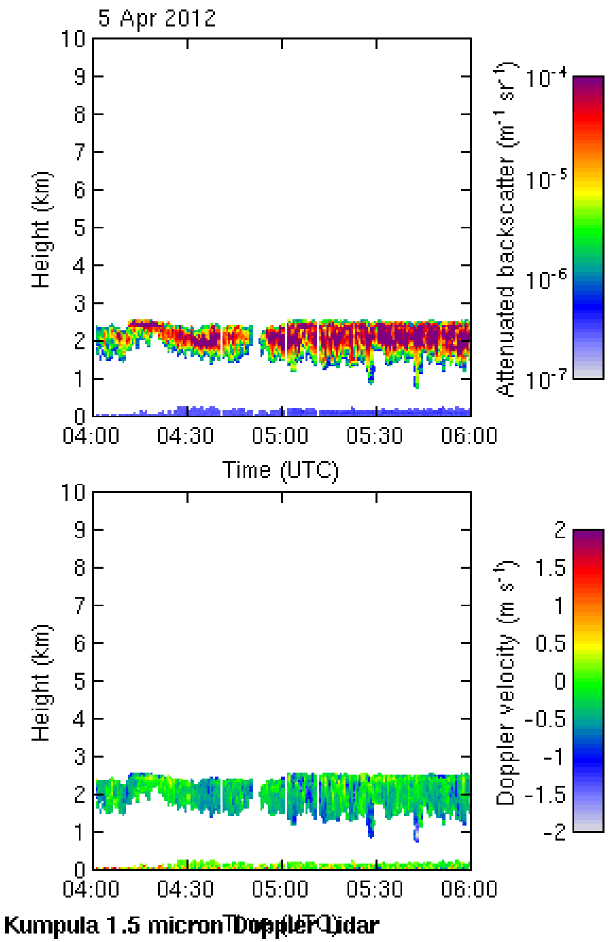
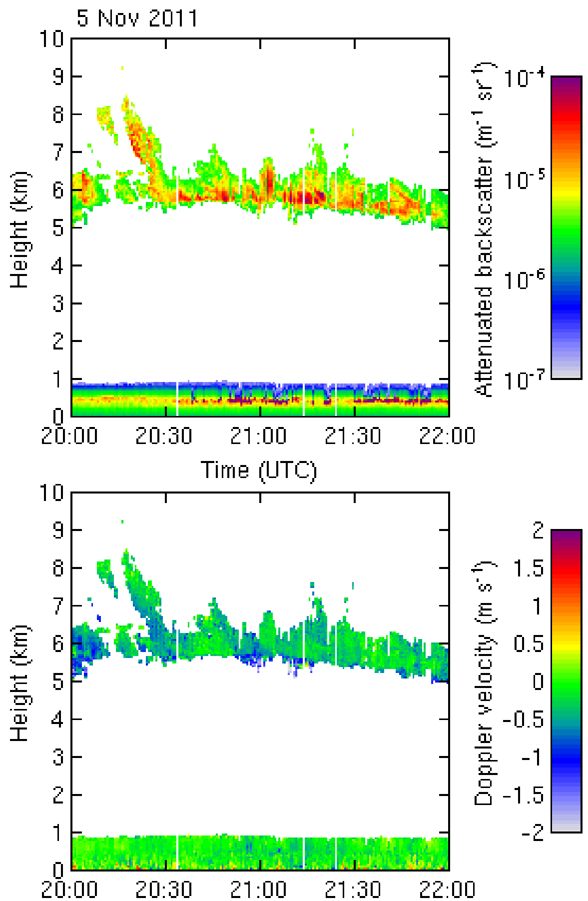
How to interpret Doppler lidar images



Altocumulus with specular reflection

- If the Doppler lidar is pointing at vertical, altocumulus may sometimes look slightly different.
- In certain conditions the pristine ice crystals falling below the liquid layer behave like mirrors.
- Causes anomalously high backscatter, termed specular reflection.
- May also impact depolarization signal, causing it to be much lower than expected.

How to interpret Doppler lidar images



Kumpula 1.5 micron Doppler Lidar

Cirrus

- Composed purely of ice crystals.
- Characterised by classic `fallstreak' structure.
- Depending on the number and size of ice crystals present, it is possible to see few km into these layers before the lidar signal is attenuated.

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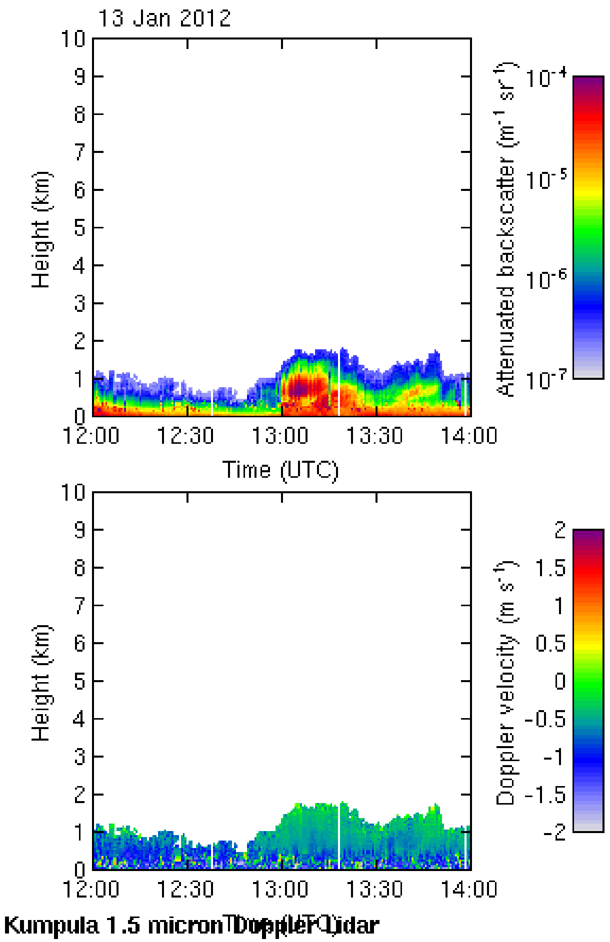
How to interpret Doppler lidar images



Snow

- Frontal or `stratiform' snow (and rain)
- Ice crystals nucleate high in the atmosphere and grow as they fall, potentially reaching sizes of a few cm.
- Fall velocities usually not much larger than 1 m s-1.
- Fall velocity increases rapidly at the melting level, if present, to greater than 4 m s-1 and the typical rain drop size is a few mm.
- Attenuation by snow/rain clearly visible - lidar backscatter decreases >10^3 within a km or two.
- Attenuation not as rapid as in liquid layers.

Doppler lidar velocity uncertainty

Directly related to SNR (Pearson et al., 2009; O'Connor et al., 2010)

$$\sigma_e = \left(\frac{\Delta v^2 \sqrt{2}}{\alpha N_p} \left(1 + 1.6\alpha + 0.4\alpha^2\right) \right)^{1/2},$$

Δv signal spectral width

B receiver bandwidth

α Ratio of detector photon count to speckle count

$$\alpha = \frac{\mathrm{SNR}}{(2\pi)^{1/2}(\Delta v / B)},$$

N_p Accumulated photon count

$$N_p = \mathrm{SNR}\; n\; M,$$

Doppler lidar velocity uncertainty

Directly related to SNR (Pearson et al., 2009; O'Connor et al., 2010)

Heterodyne detection

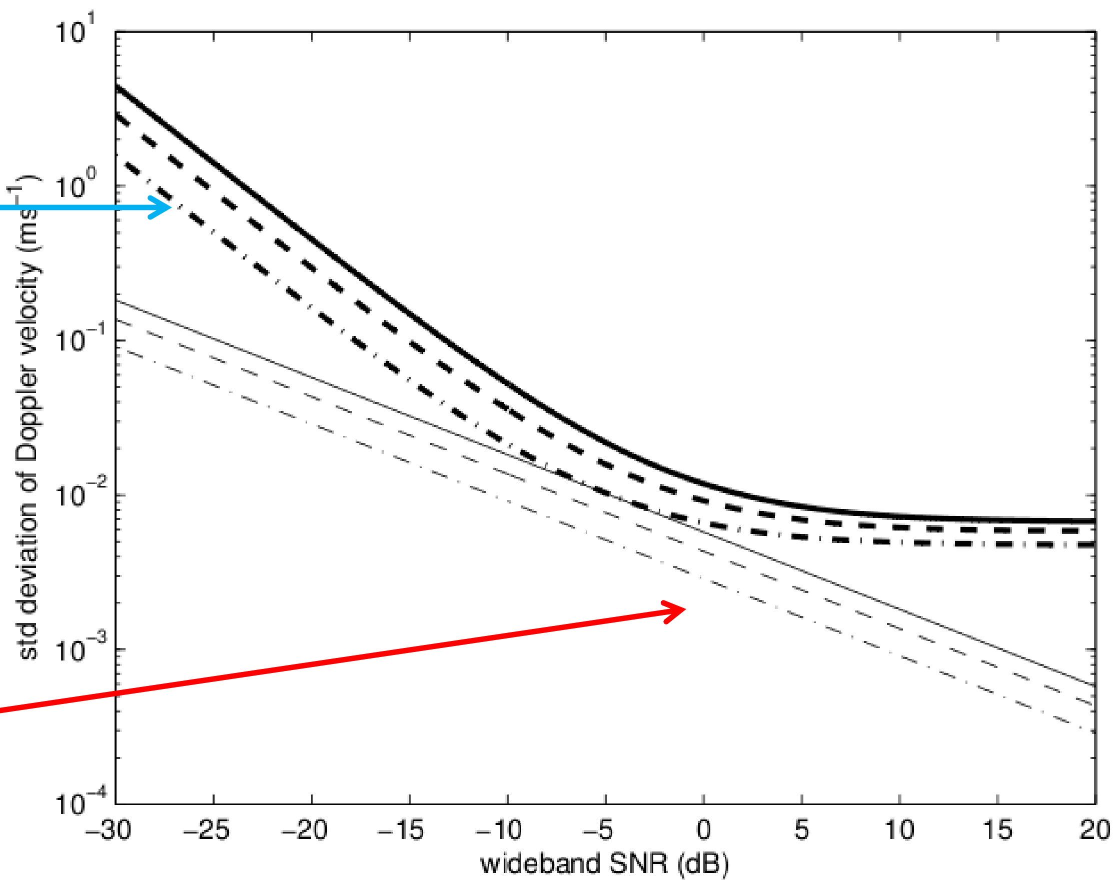
Lines indicate choice of

Δv,

(signal spectral width)

Direct detection

$$\sigma_e = \Delta v/(N_p{}^{0.5}),$$



Scan Types

- **Doppler lidar measures radial velocity**
  - Line-of-sight component only
- **Scan type**
  - Stare (usually vertical stare)
  - DBS
  - VAD
  - PPI
  - RHI
  - Scan selection based on requirements

Wind/Turbulent properties from Doppler lidar

- **Where can we retrieve these properties?**
  - Requires tracers and good sensitivity
    - Boundary layer aerosol
    - In-cloud
- **Turbulence - different methods available**
  - Which method depends on scan capability
- **Uncertainties**
  - Requires accurate determination of radial velocities

Wind

- **Doppler lidar measures radial velocity**
  - How do we get horizontal wind?
- **Scan selection**
  - VAD
  - DBS
- **Intercomparison with other measurements**
- **Optimisation through changing focus**
- **Scan close to surface**
  - PPI

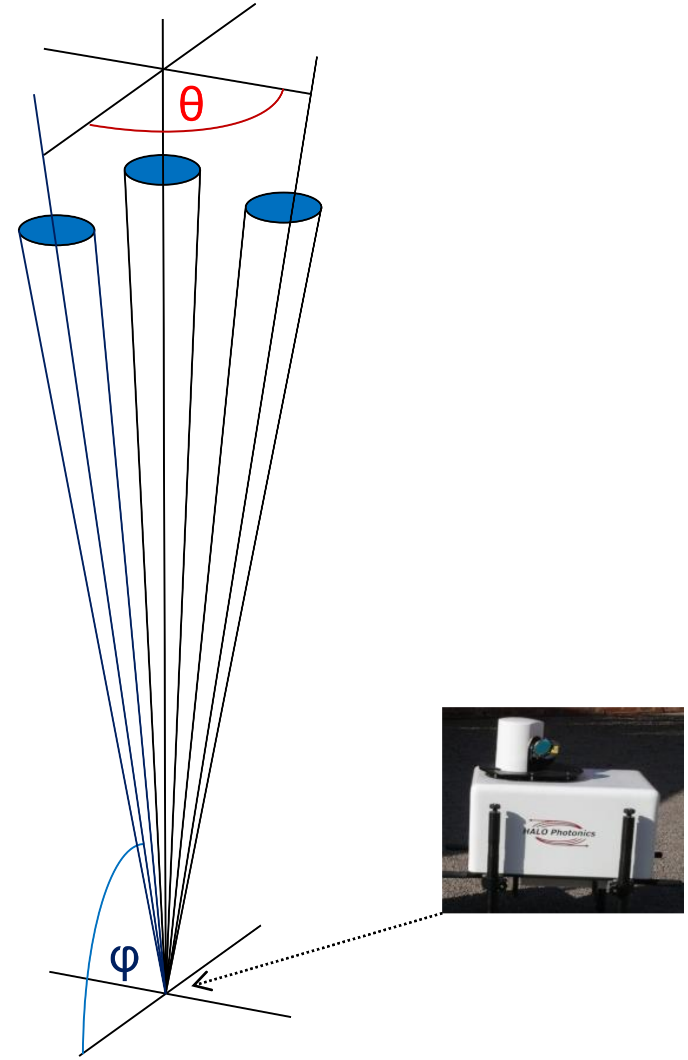
Horizontal winds from radial winds

- **To derive vector wind (u, v, w) from radial winds requires at least three independent line-of-site measurements**
- **Two main techniques**
  - VAD (Velocity Azimuth Display)
    - Conical scan at fixed elevation angle
  - DBS (Doppler Beam Swinging)
    - Three or five beams
    - One vertical, others tilted North, East (South, West)
    - Four beams (N, S, E, W, no vertical)
- **All assume homogeneity..**

Scan Types

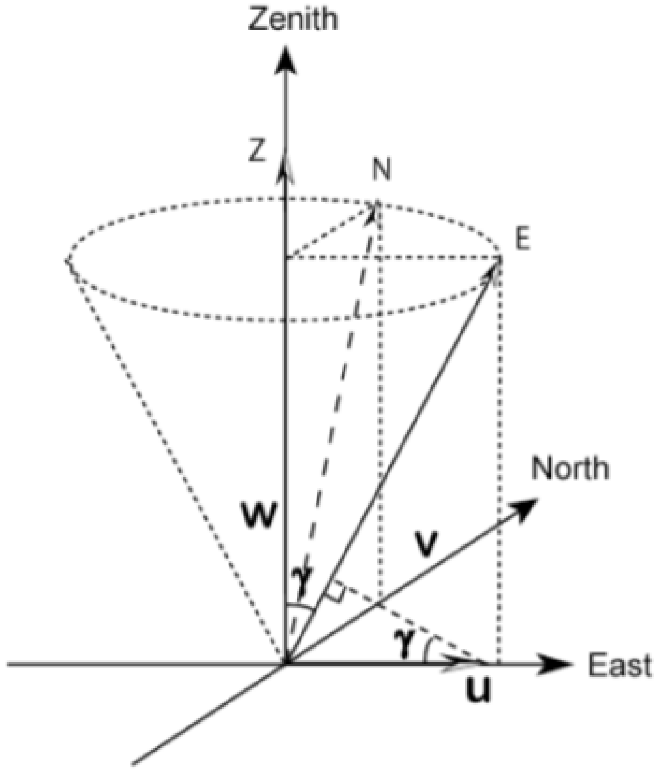
Doppler Beam Swing (DBS)

- **3-beam DBS**
  - 1 zenith (vertical) beam
  - 2 off-zenith beams
    - Orthogonal (e.g. N, E)
  - θ = 90º
  - φ = 70º (typically)



Horizontal winds from radial winds

- Doppler-Beam-Swinging (DBS) techniques: pointing lidar beam to vertical, tilted east, and tilted north.



γ is the off-zenith angle

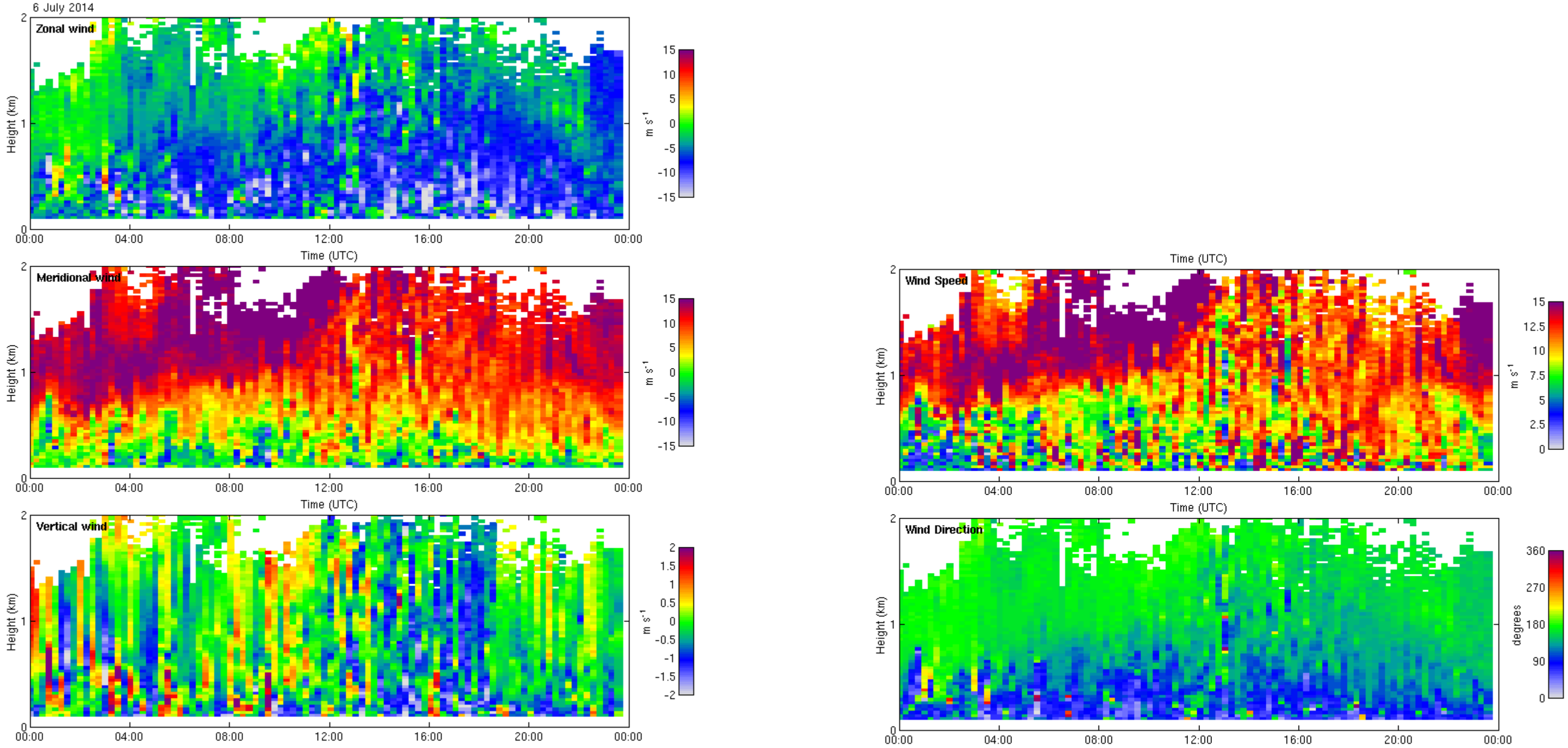
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

V_{RZ}, V_{RE}, V_{RN} are the vertical, tilted east, and tilted north radial velocities

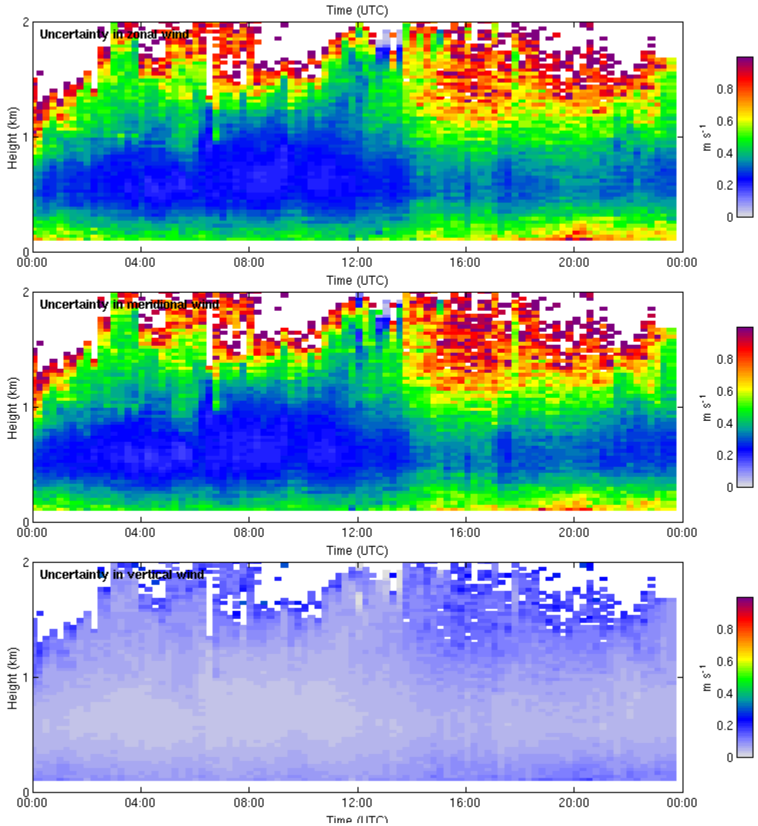
Horizontal winds from radial winds

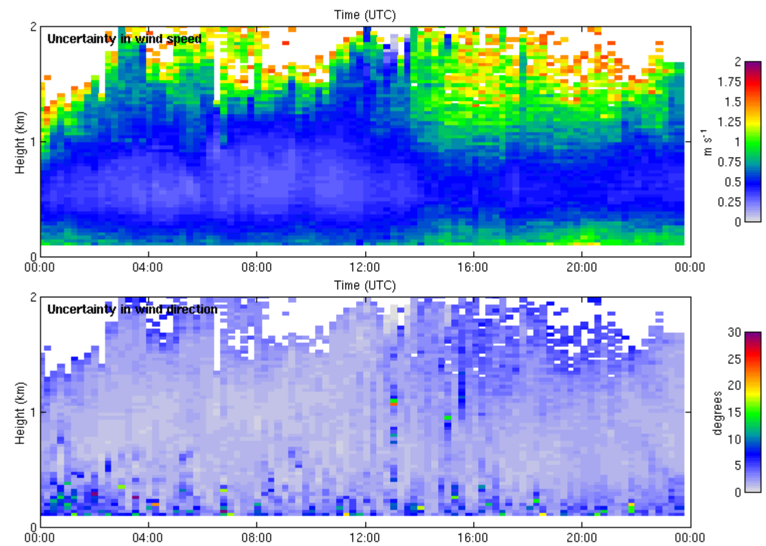
Doppler Beam Swing (DBS) Technique



Horizontal winds from radial winds

Doppler Beam Swing (DBS) Technique - Errors





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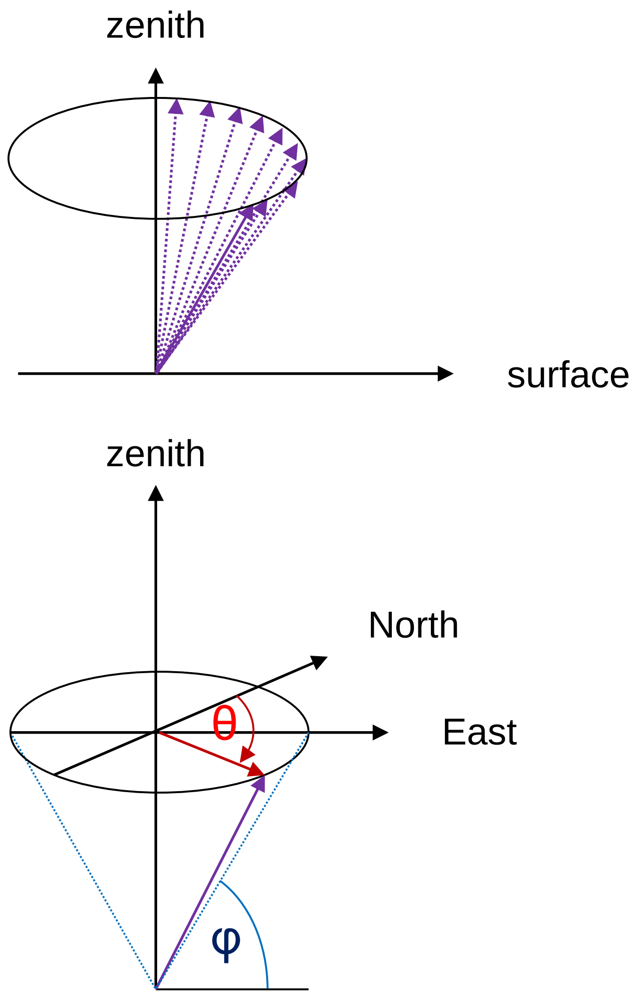
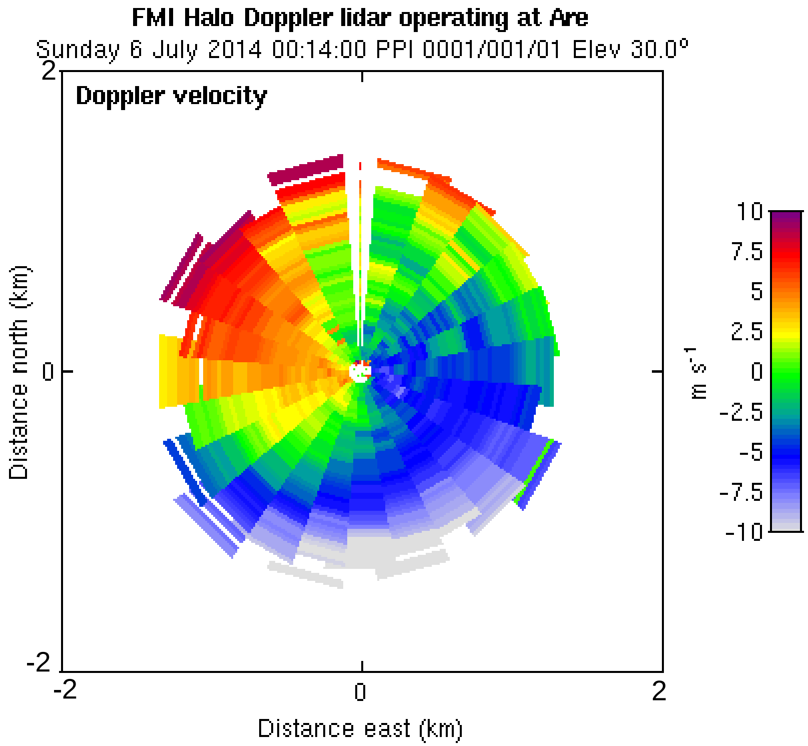
Scan Types

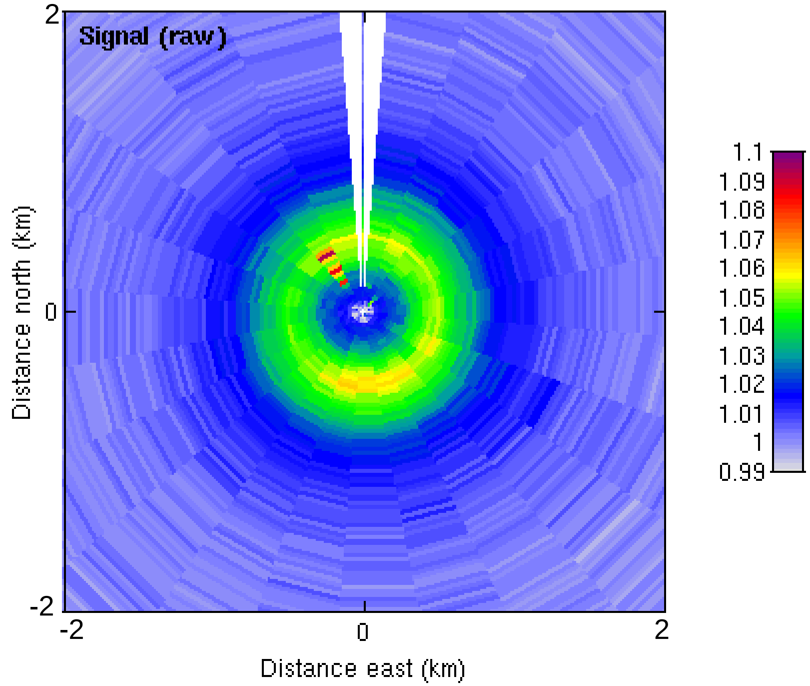
- **Velocity Azimuth Display**
  - VAD
  - Conical scan
  - N off-zenith beams
  - θ = 0:360
  - φ = constant



Horizontal winds from radial winds

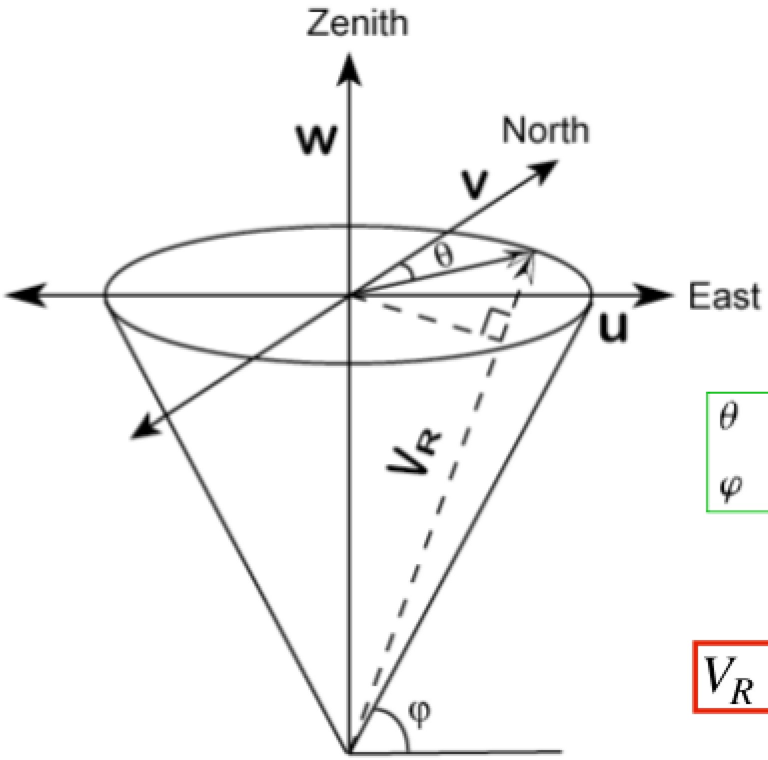
Velocity Azimuth Display (VAD) Technique





Horizontal winds from radial winds

Velocity Azimuth Display (VAD) Technique



Radial velocity V_R consists of components from u, v, and w:

Zonal wind contribution	$u\sin\theta\cos\varphi$
Meridional contribution	$v\cos\theta\cos\varphi$
Vertical contribution	$w\sin\varphi$

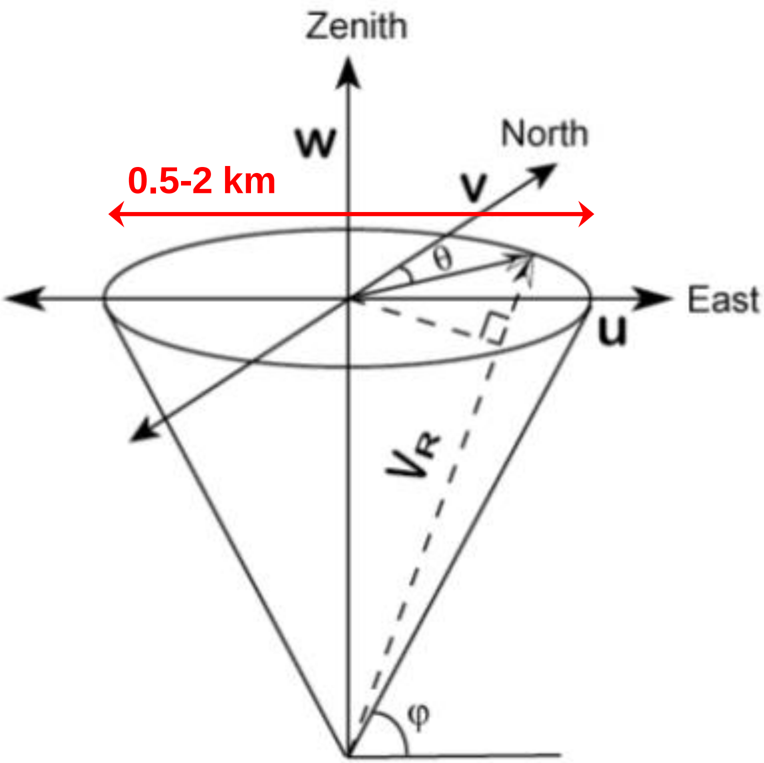
θ the azimuth angle, clockwise from North, and

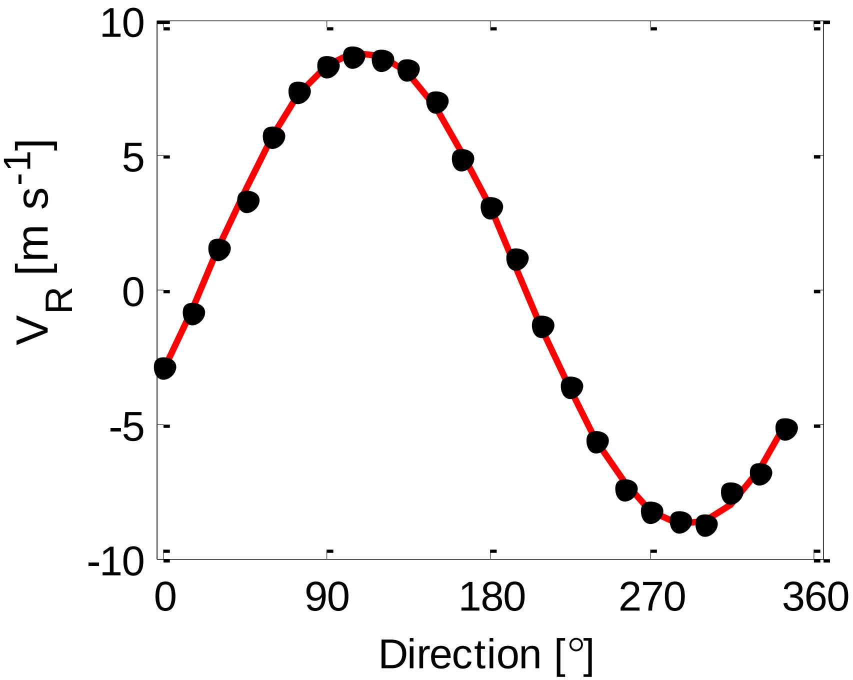
φ the elevation angle.

$$\theta_N = 0^\circ, \theta_E = 90^\circ, \theta_S = 180^\circ, \theta_W = 270^\circ$$

$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

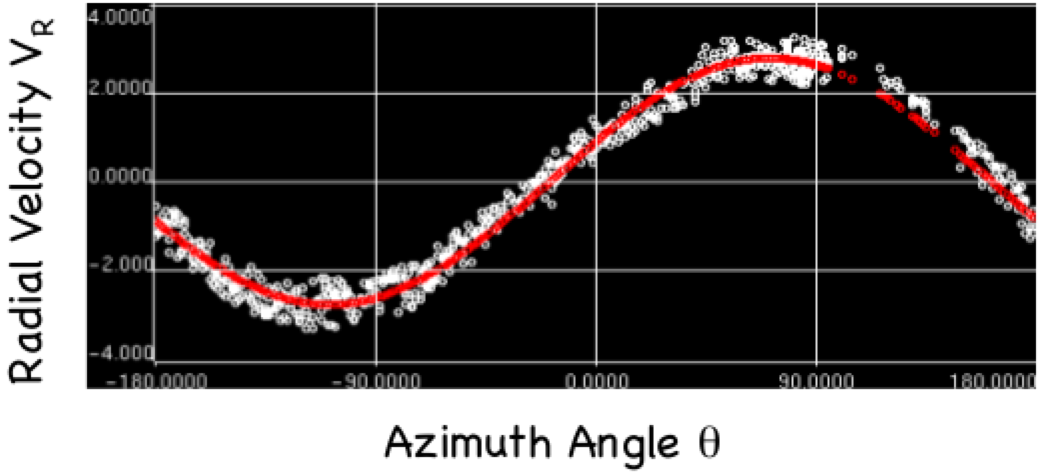
- Sinusoidal fit for horizontal wind
- Residuals from **turbulence** and **non-turbulent changes in wind**





Horizontal winds from radial winds

Velocity Azimuth Display (VAD) Technique



$$\boxed{V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi}$$

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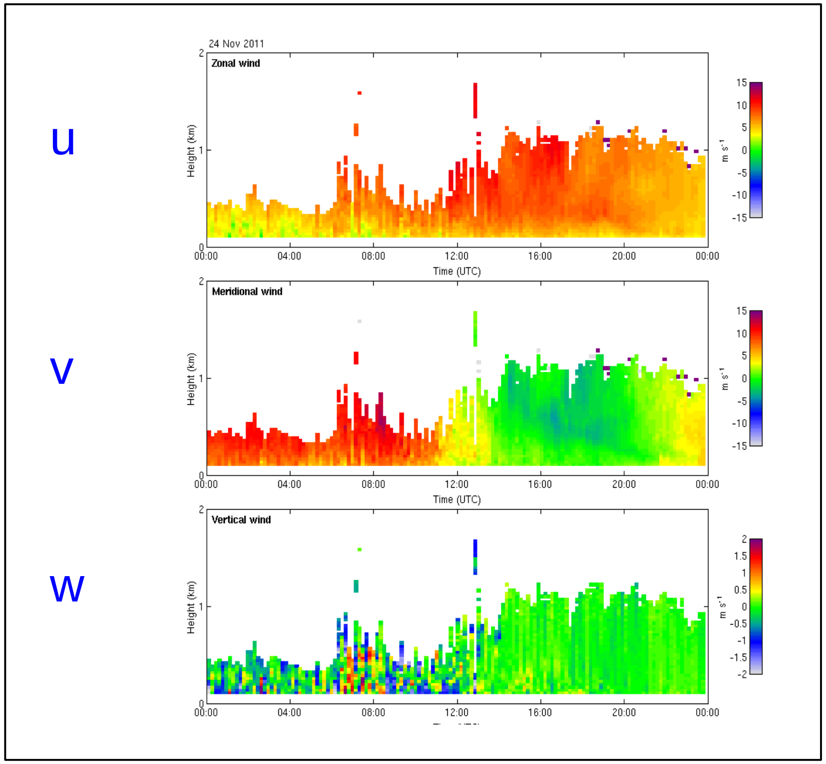
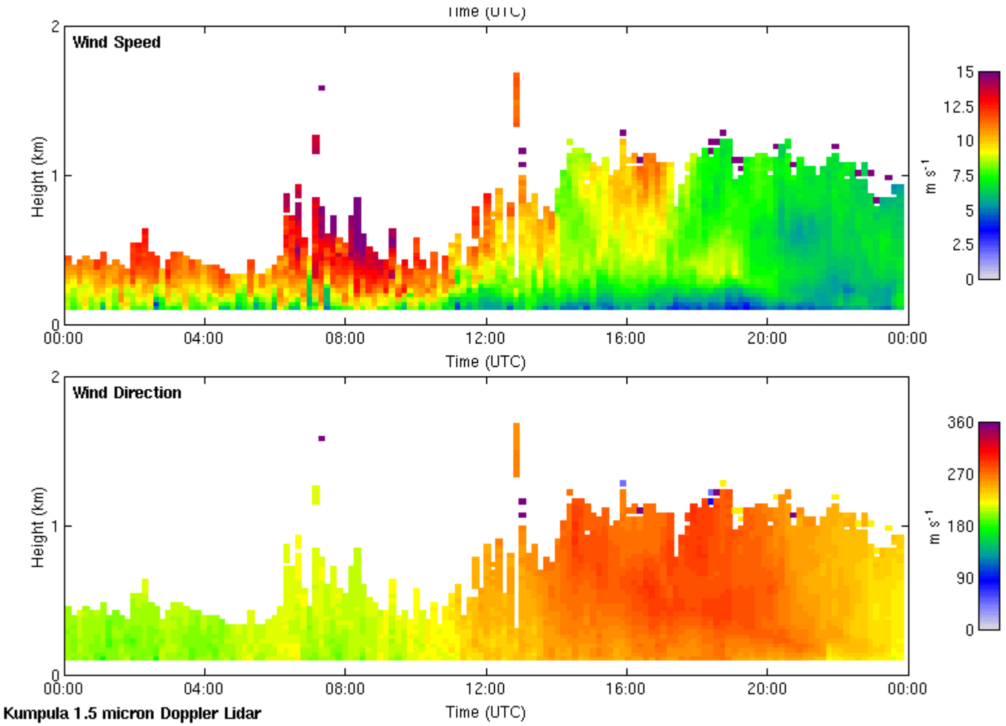
Horizontal winds from radial winds



Horizontal winds from radial winds

Wind speed

Wind direction



Horizontal winds

- **DBS**
  - Very fast – 3, 4 or 5 beams
  - Min. range determines lowest measurement
- **VAD**
  - Slower - requires more beams (12+)
  - Elevation choice determines lowest measurement
  - Can cope with missing beams (obstruction)
  - Extra information potentially available

What angle should we scan at?

- **Depends!**
  - What vertical resolution do you require?
  - How strong are the winds?
  - What is your instrument Nyquist velocity?

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What angle should we scan at?

- **Nyquist velocity is usually 20 or 40 m s^{-1}**

Elevation	0	30	60	75
Max velocity				

What angle should we scan at?

- **Nyquist velocity is usually 20 or 40 m s^{-1}**

Elevation	**0**	**30**	**60**	**75**
Max velocity	20	23	40	77

What angle should we scan at?

- **Nyquist velocity is usually 20 or 40 m s^{-1}**

Elevation	0	30	60	75
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- **What about uncertainty?**

What angle should we scan at?

- **Nyquist velocity is usually 20 or 40 m s^{-1}**

Elevation	0	30	60	75
Max velocity	20	23	40	77

- **What about uncertainty?**
  - Typical radial uncertainty < 20 cm s^{-1}

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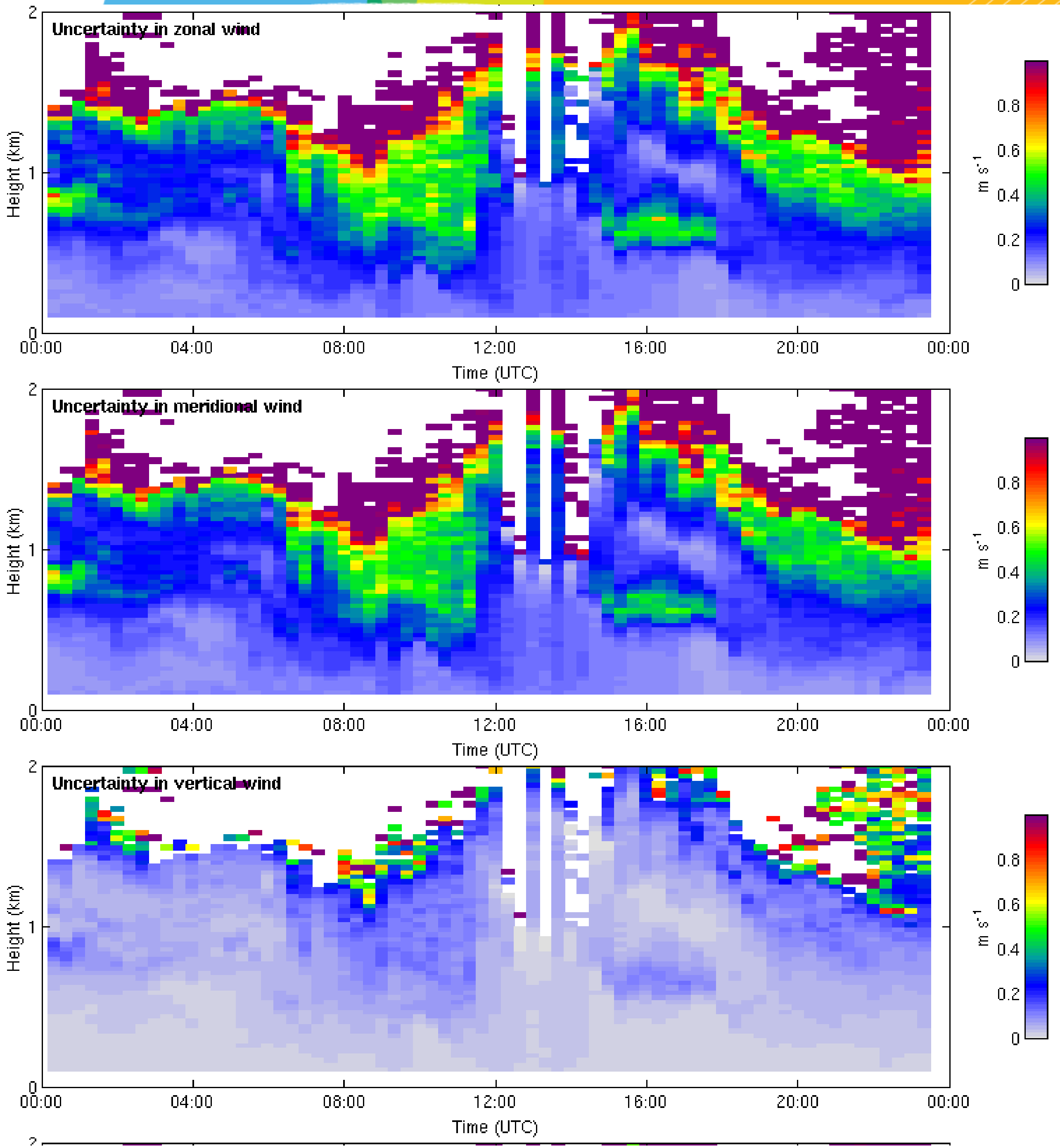

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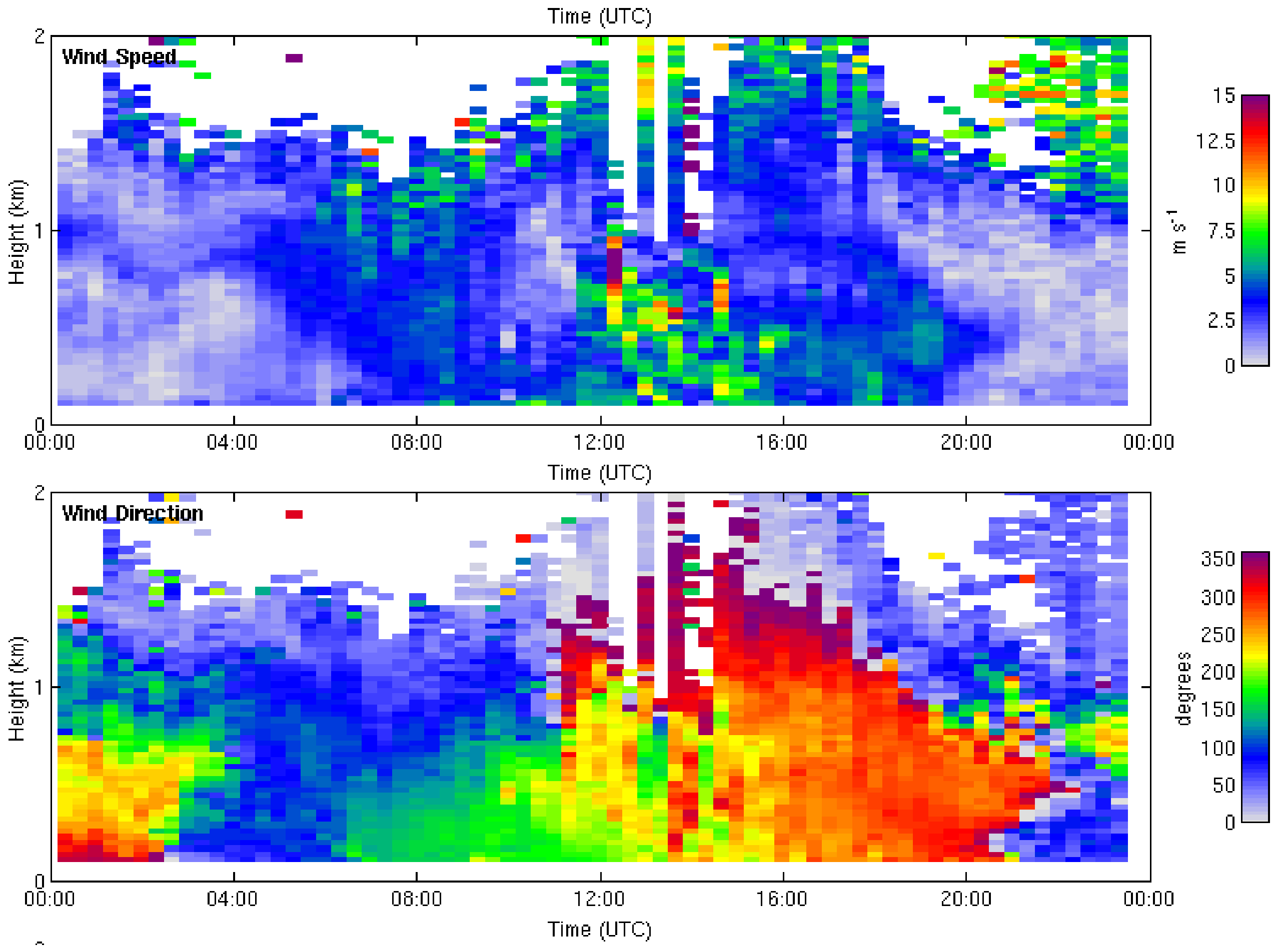

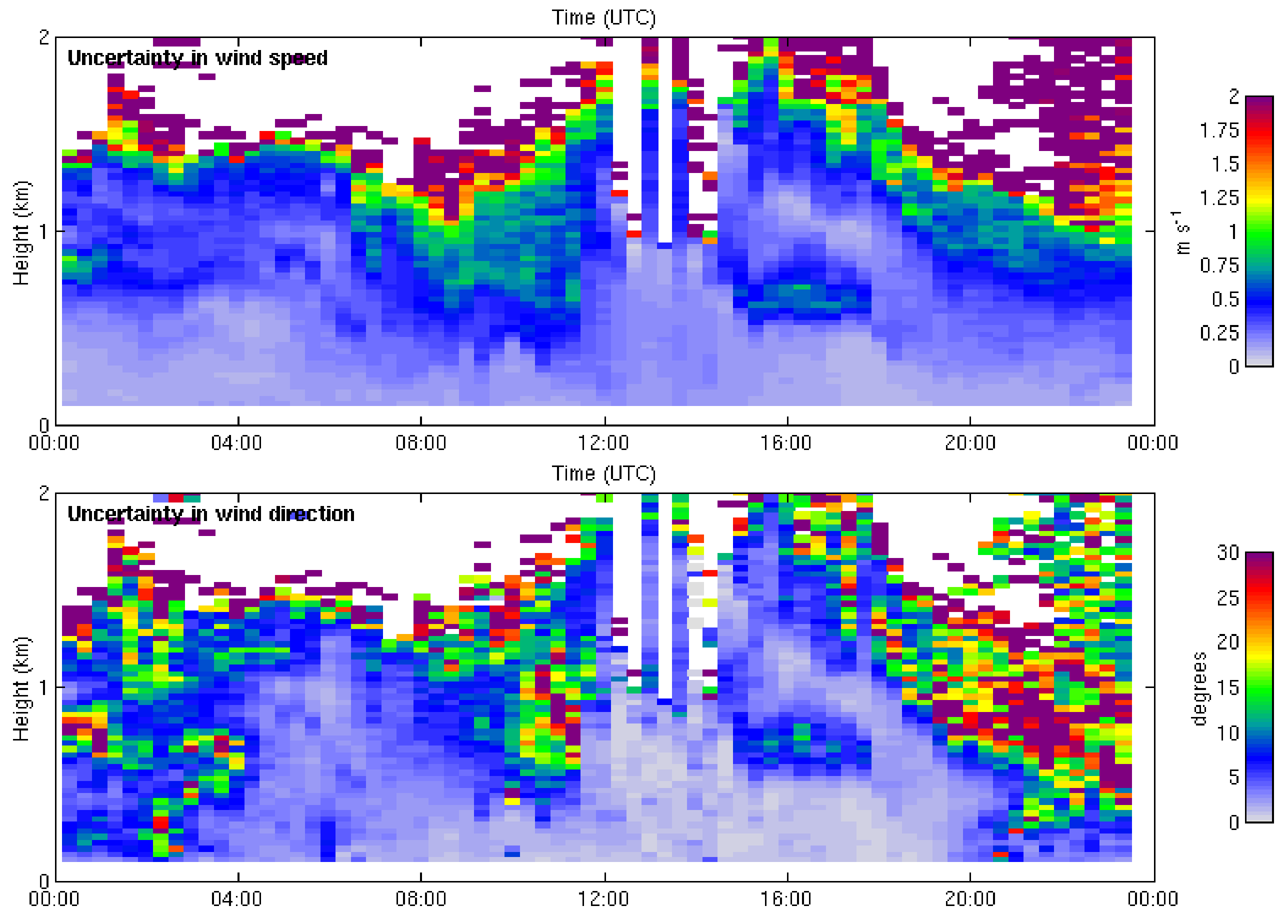

FMI 1.5 micron Doppler Lidar operating at Limassol

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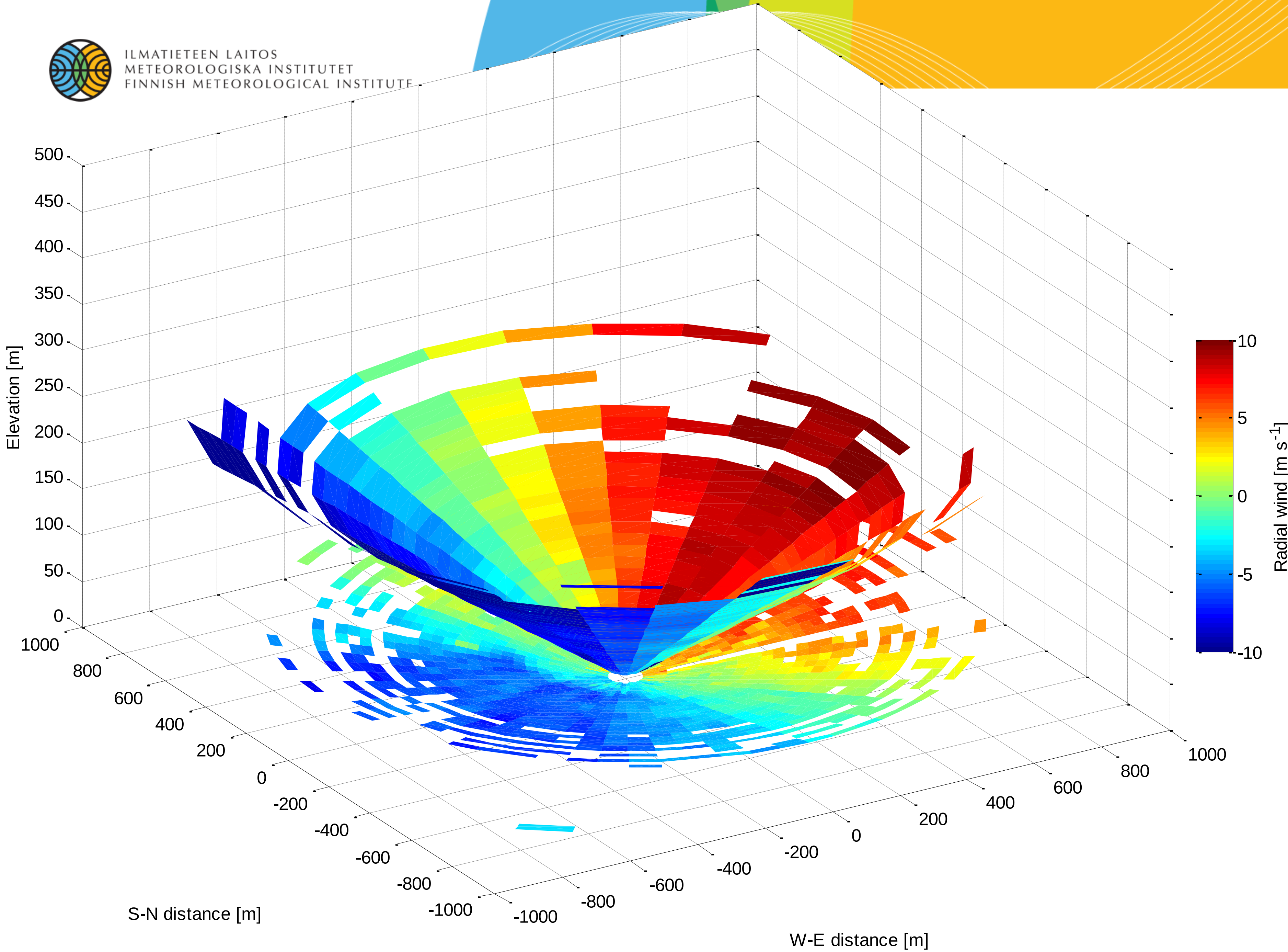
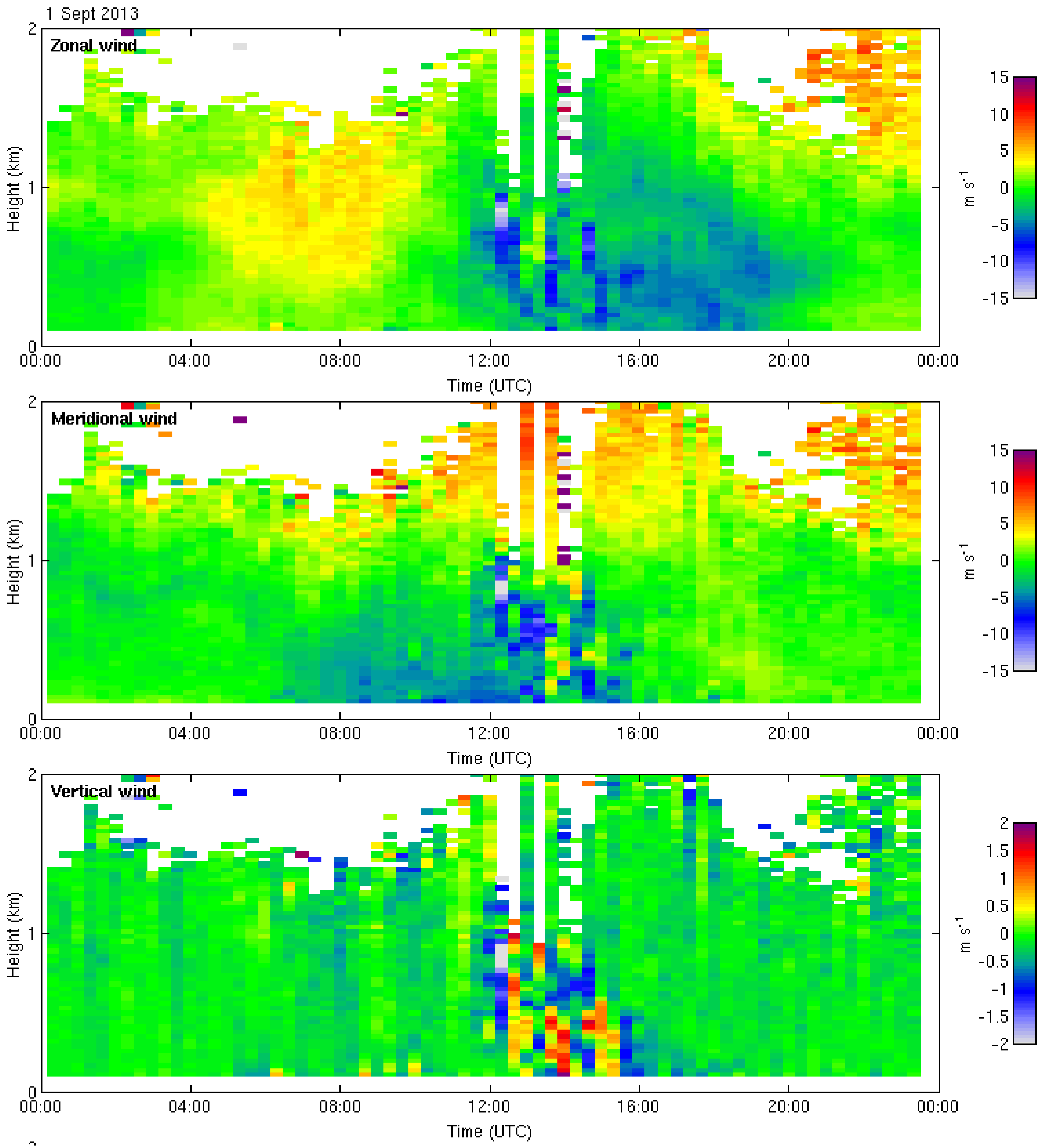


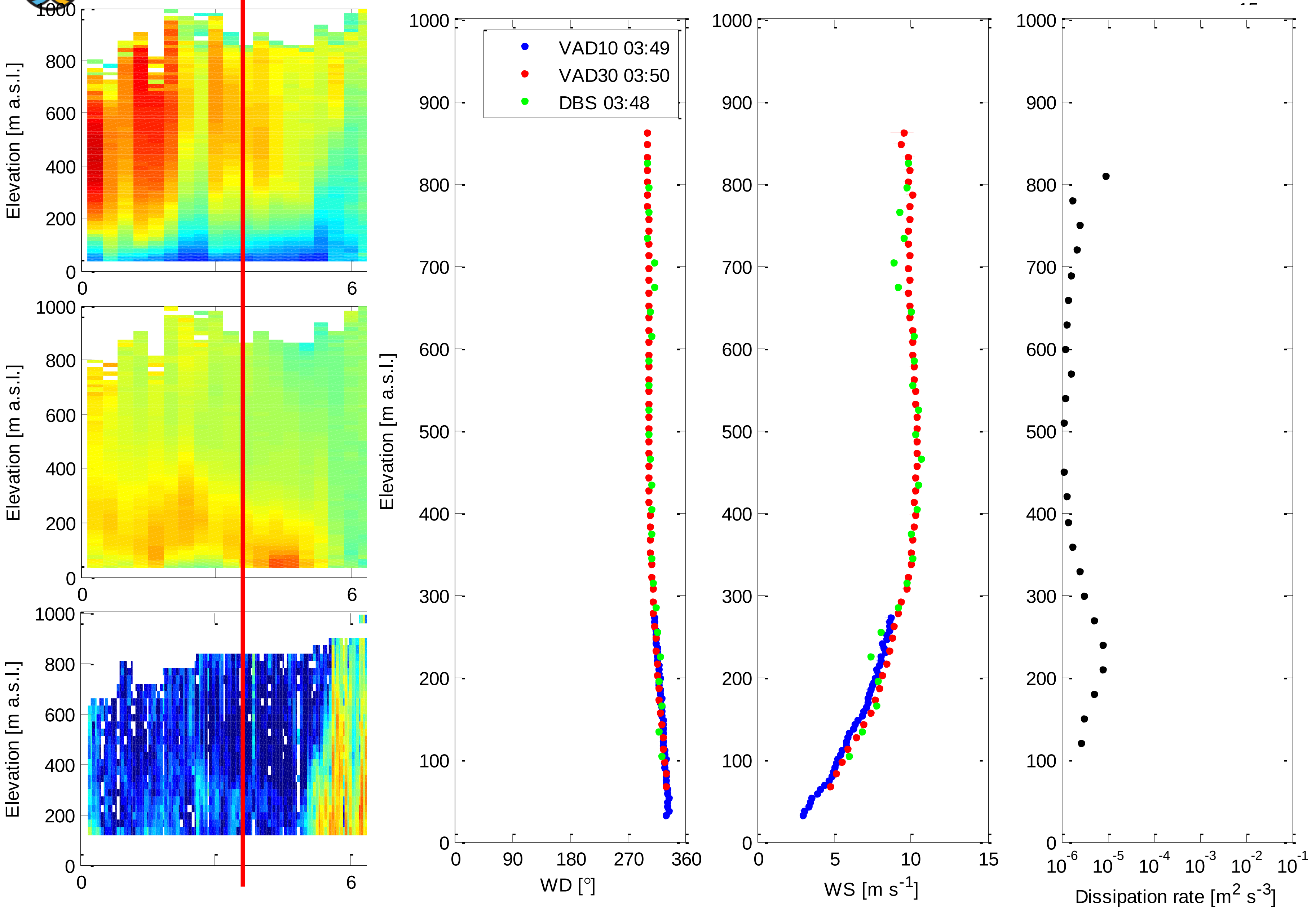
What angle should we scan at?

- **Nyquist velocity is usually 20 or 40 m s^{-1}**

Elevation	0	30	60	75
Max velocity	20	23	40	77

- **What about uncertainty?**
  - Typical radial uncertainty < 20 cm s^{-1}
- **We have neglected turbulence! See talks this week.**


1 Sept 2013
Zonal wind
Height (km)
Time (UTC)
m s-1
Meridional wind
Height (km)
Time (UTC)
m s-1
Vertical wind
Height (km)
Time (UTC)
m s-1
00:00
04:00
08:00
12:00
16:00
20:00
00:00



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17-Sep-2013
Elevation [m a.s.l.]
VAD10 03:49
VAD30 03:50
DBS 03:48
WD [°]
WS [m s-1]
Dissipation rate [m2 s-3]

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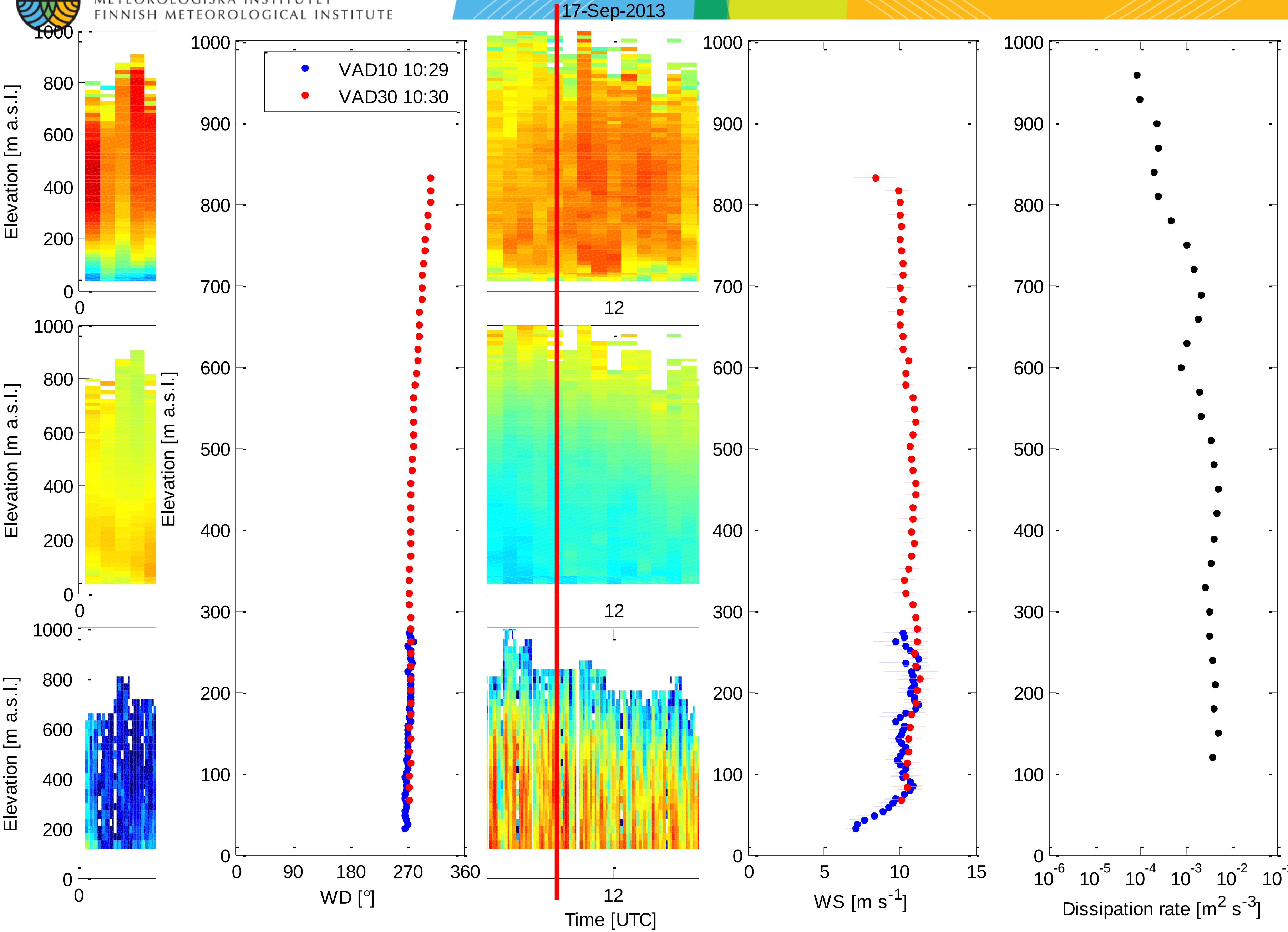

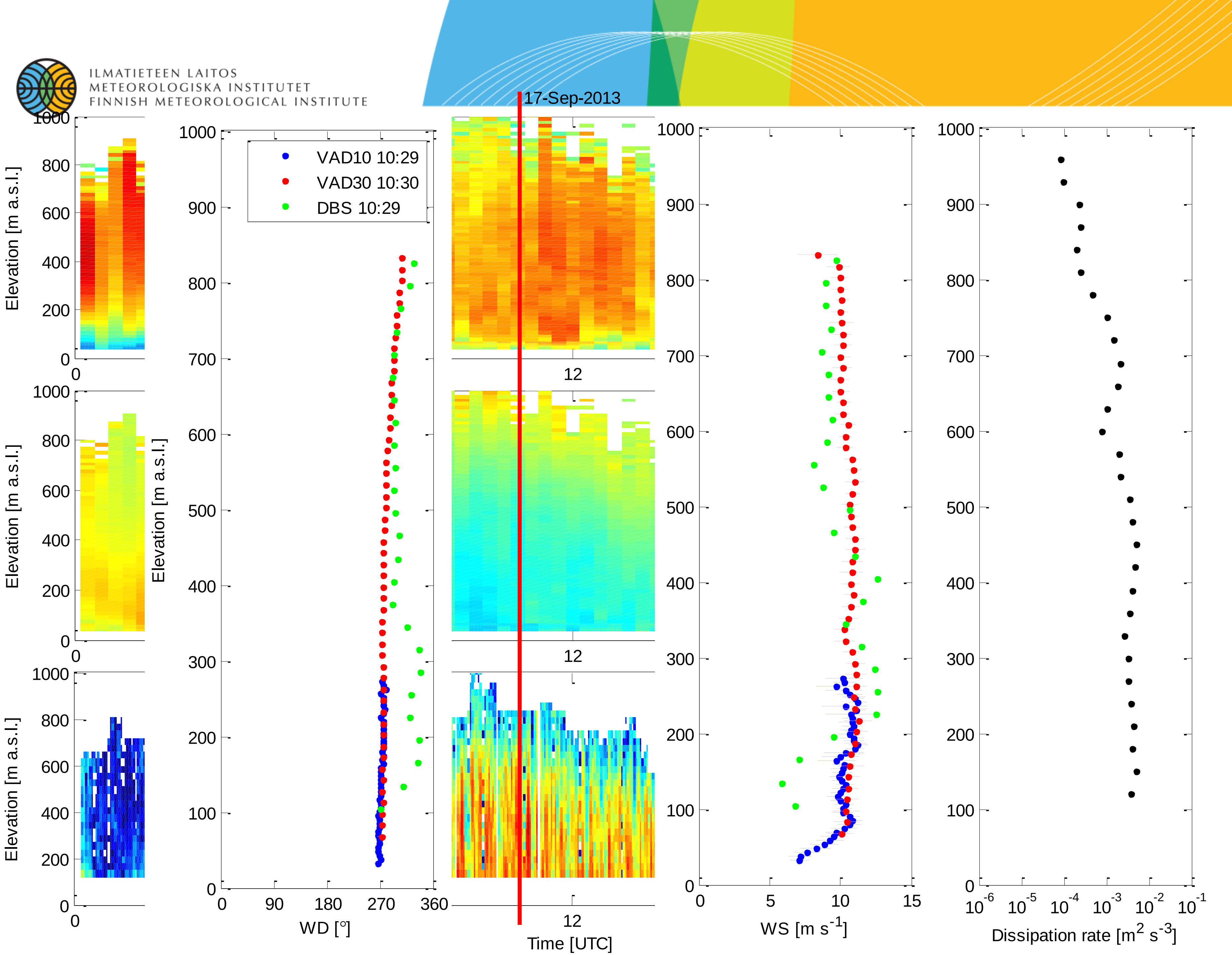

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17-Sep-2013
VAD10 10:29
VAD30 10:30
DBS 10:29
Elevation [m a.s.l.]
WD [°]
Time [UTC]
WS [m s^{-1}]
Dissipation rate [m^2 s^{-3}]

Horizontal winds

- **VAD is much more robust in turbulent conditions**
  - Some influence of averaging timescales, and spatial separation

- **Recommendation: VAD - Paeschke et al., 2015**
  - QC through Condition Number together with SNR
  - VAD at two elevation angles if possible:
    - 70-75 degrees, slow, 12 beams
      - Best retrieval – lowest uncertainty
    - 5-30 degrees, fast, 24 beams
      - High vertical resolution at near ranges
      - Representativity

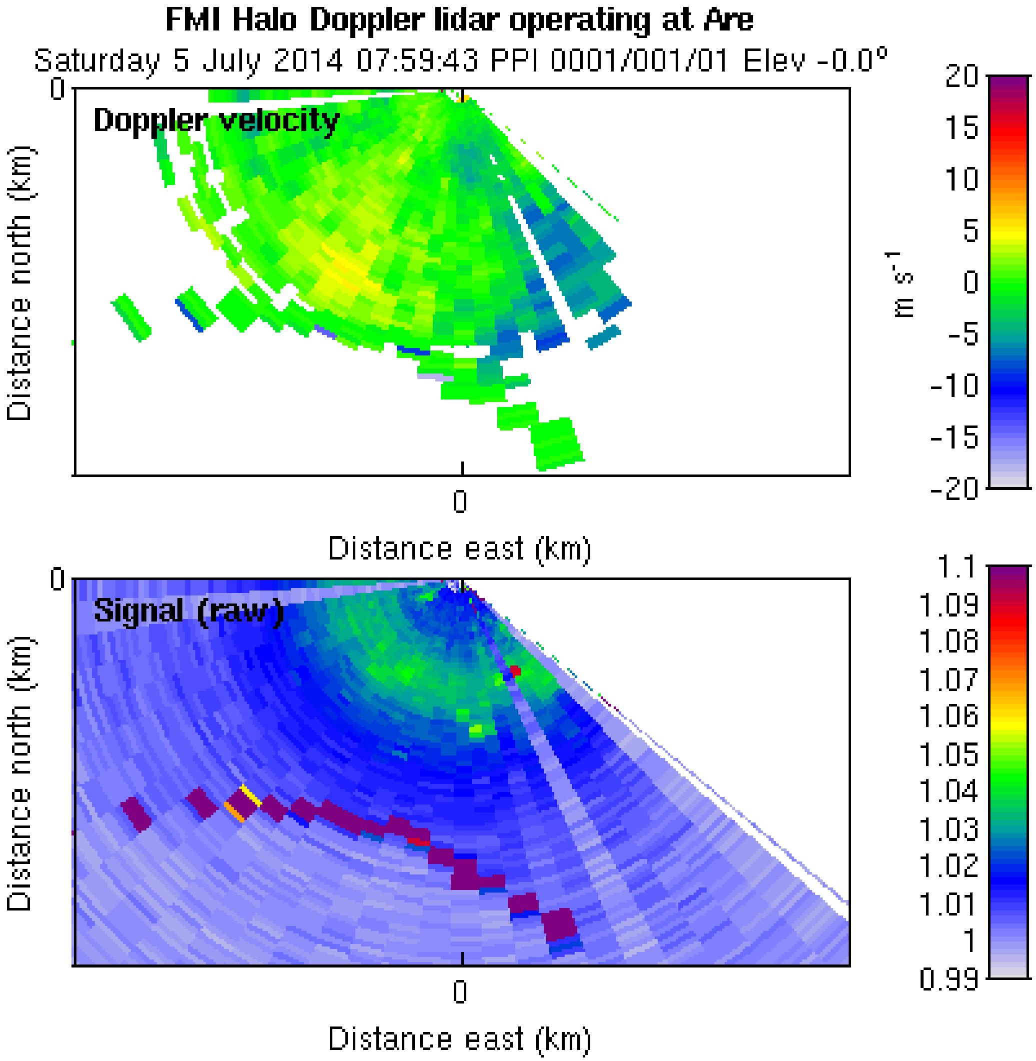
- **Uncertainties propagated from radial winds**

How to check pointing angle

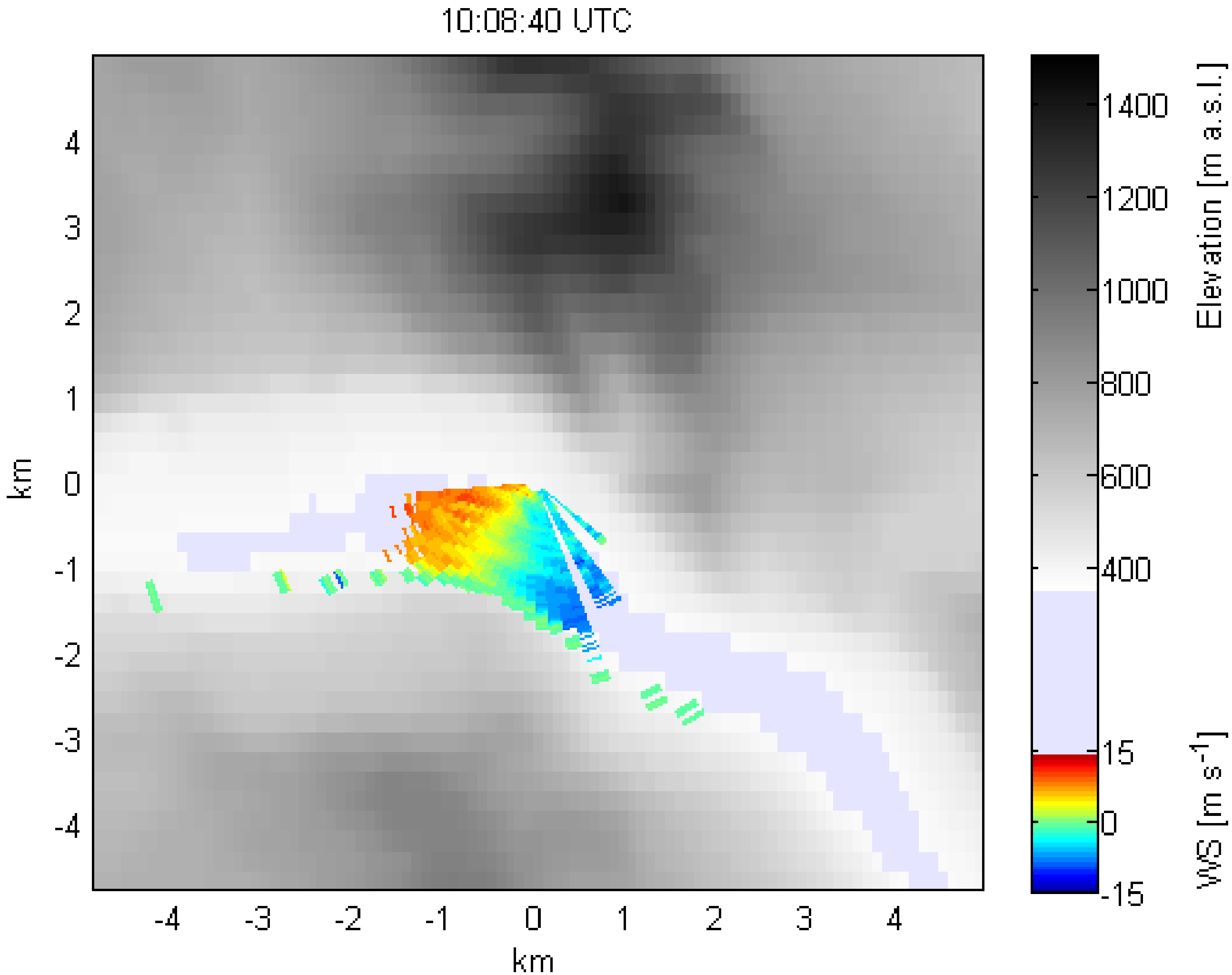
- **In-built GPS**
  - Need phone signal
  - Need accurate time

- **Scan across known target such as a mast or building**

Low-level scanning across the lake



Low-level scanning across the lake



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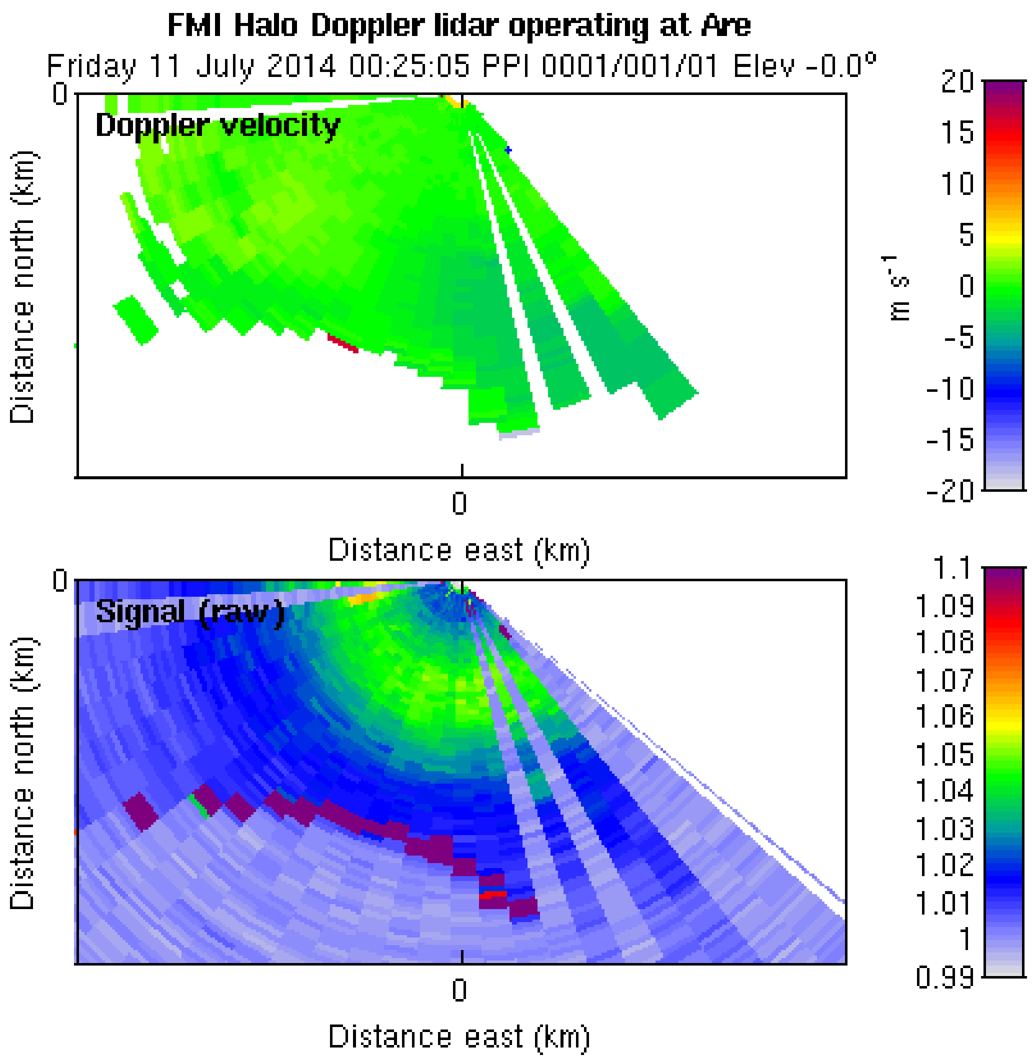
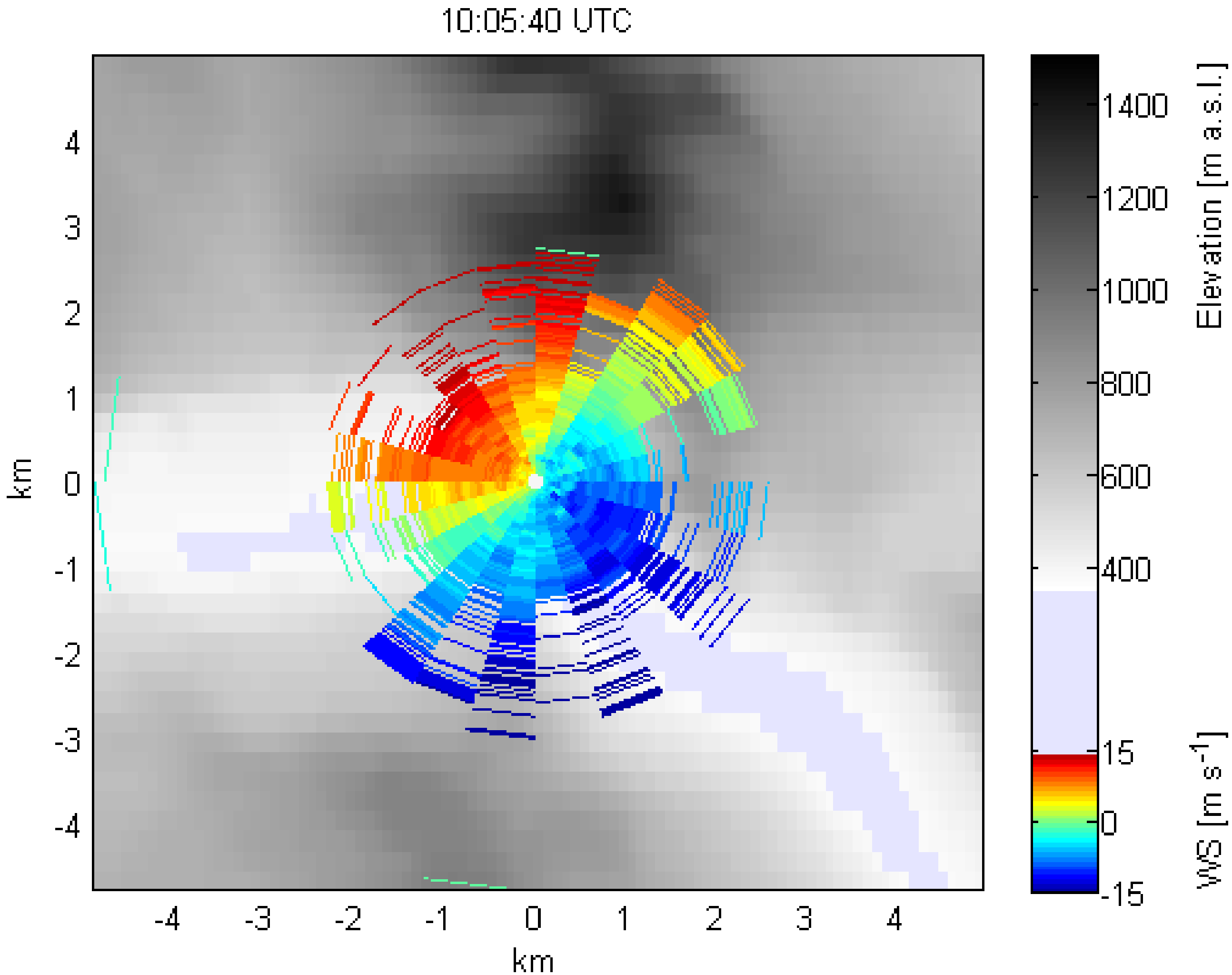
Low-level scanning across the lake



Low-level scanning across the lake



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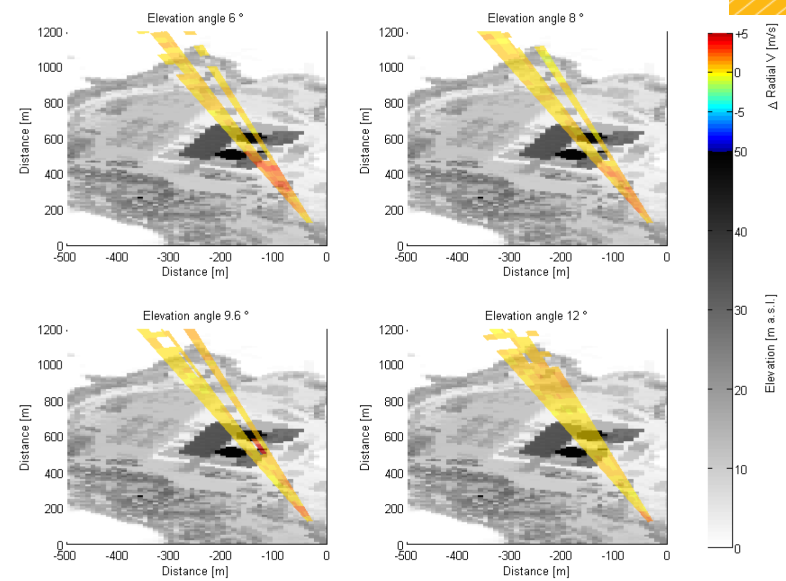
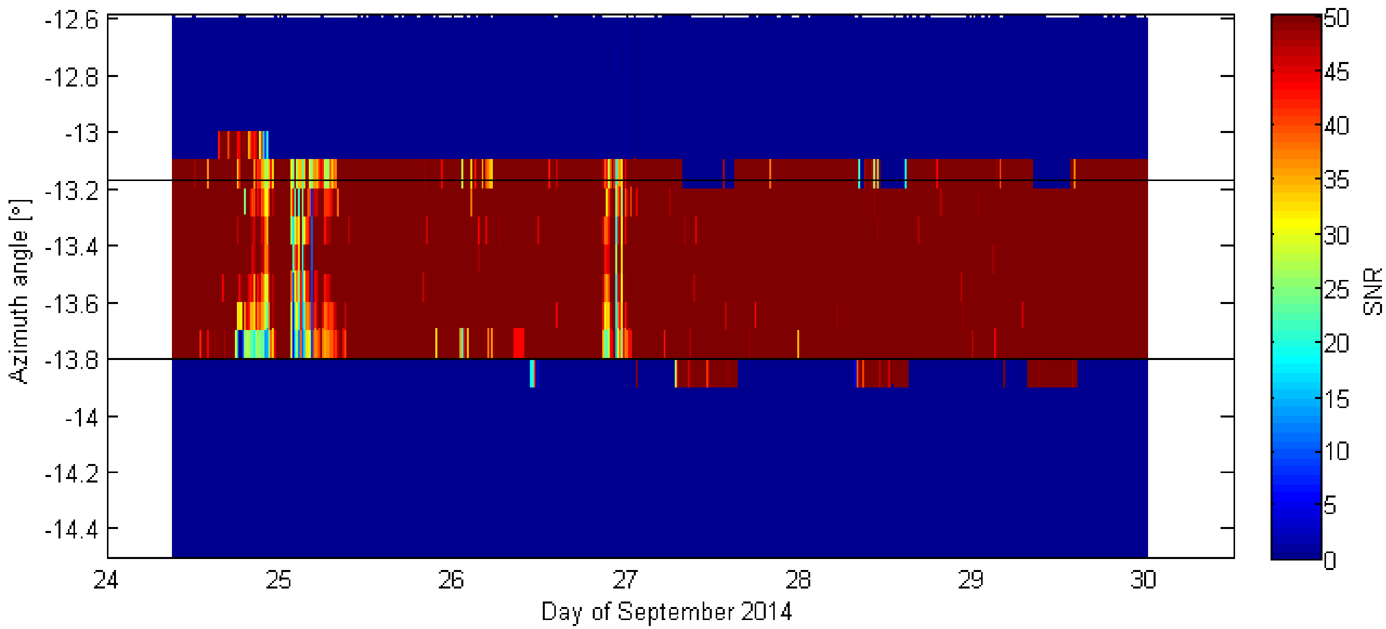
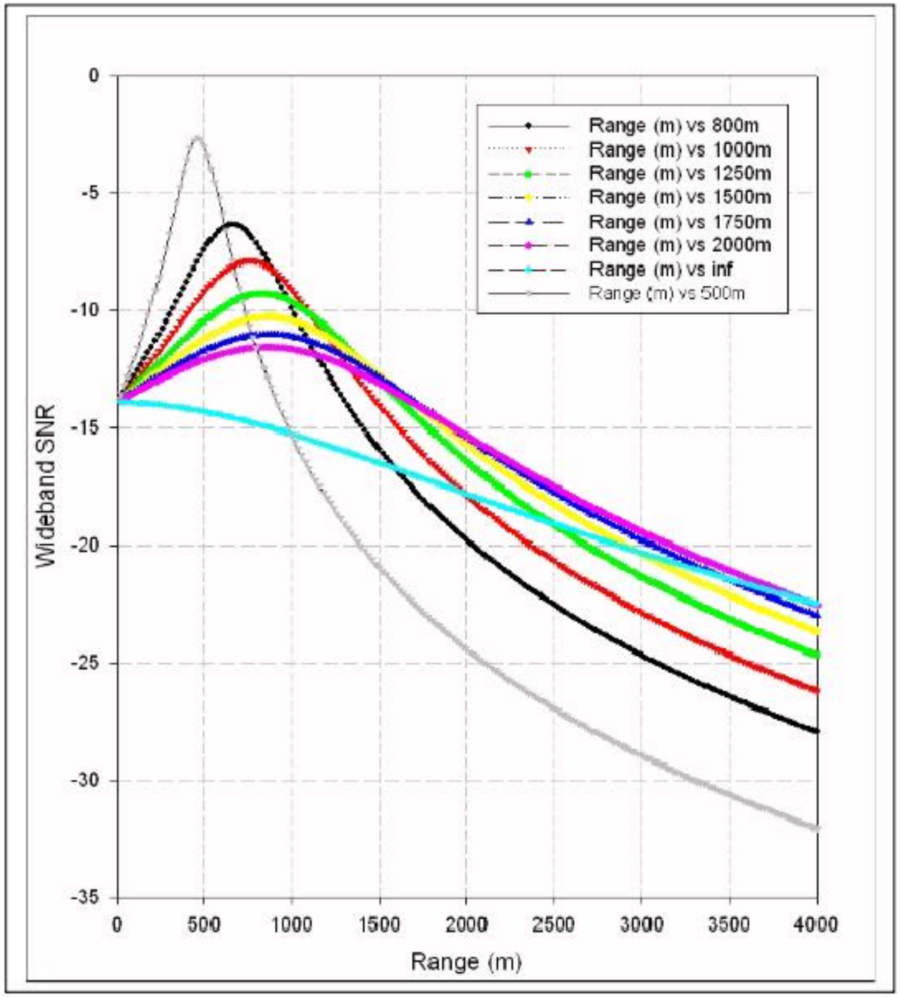
Azimuthal repeatability





Optimisation through changing focus



For a given signal (or amount of aerosol)..

Adjust focus of telescope to modify sensitivity curve depending on application

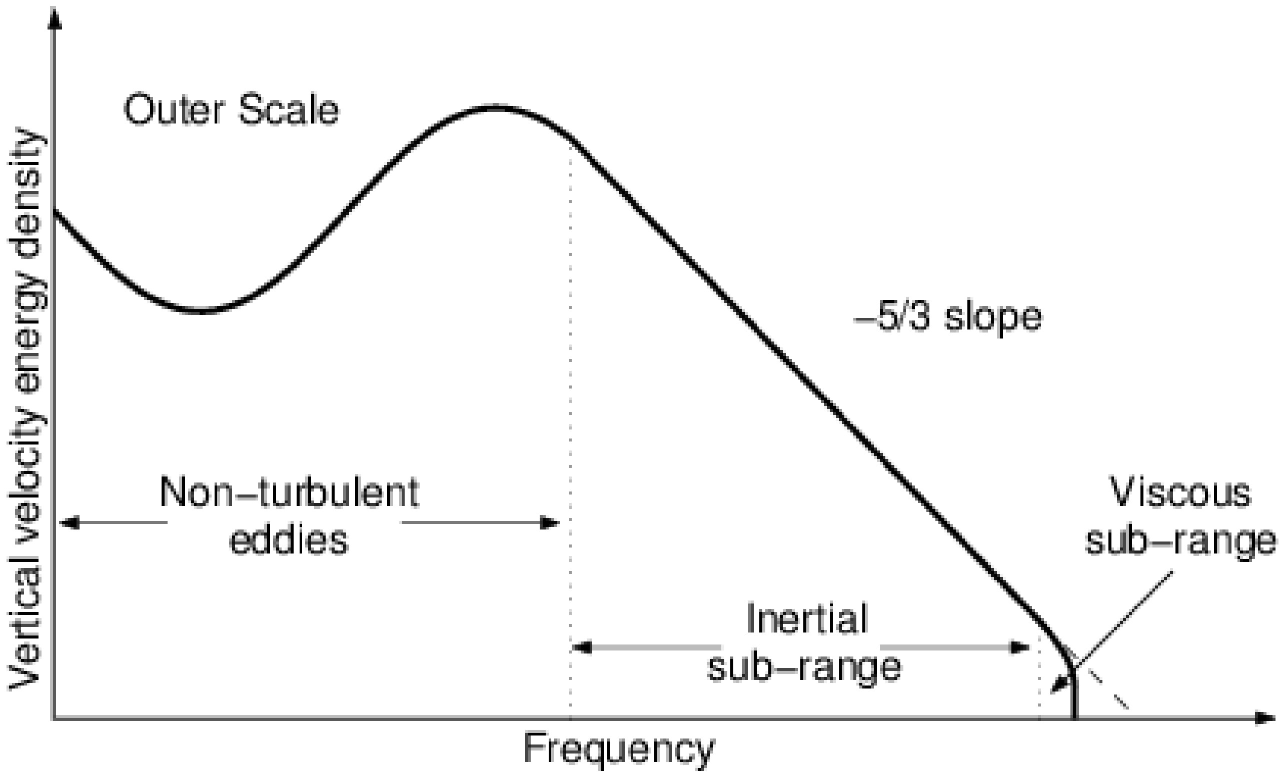
Turbulent properties from Doppler lidar

- **Where can we retrieve turbulent properties?**
  - Requires tracers and good sensitivity
    - Boundary layer aerosol
    - In-cloud
- **Different methods available**
  - Which method depends on scan capability
- **Uncertainties**
  - Requires accurate determination of radial velocities

Turbulent properties from Doppler lidar

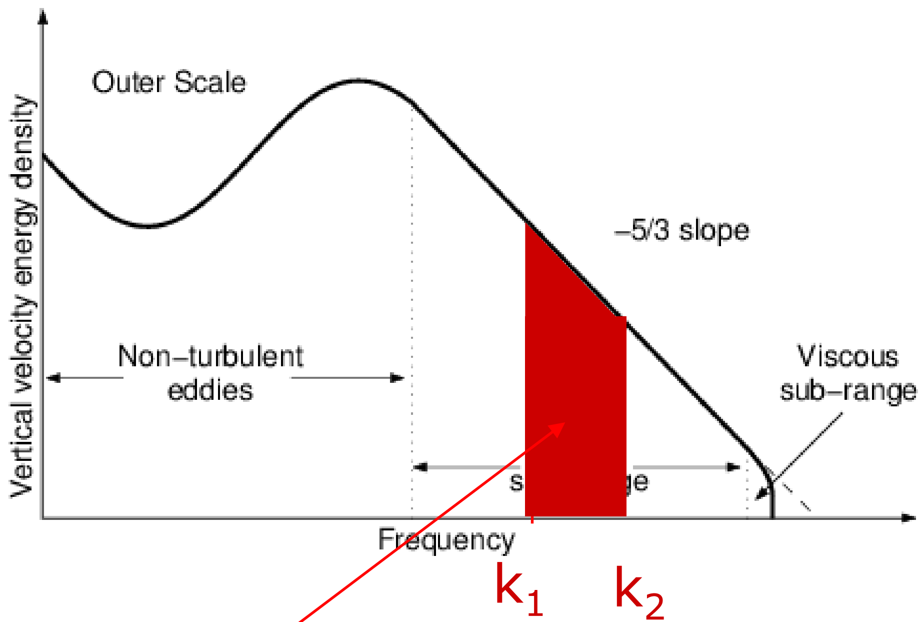
- **Methods**
  - Velocity statistics
    - Spectral width, skewness, kurtosis
  - Turbulent tensor: 4-beam DBS
  - Radial velocities
    - Incorporate within stochastic Lagrangian turbulence model
  - Kolmogorov hypothesis
    - Vertical pointing
    - VAD (conical) scanning

Turbulent properties from Doppler lidar



Vertical velocity energy density spectra versus frequency conforming to Kolmogorov's hypothesis

Turbulent properties from Doppler lidar



In the inertial sub-range (Kolmogorov)

$$S(k) = a\varepsilon^{2/3} k^{-5/3}$$

$$\sigma_v^2 = \frac{3a}{2}\varepsilon^{2/3}\left(k_2^{-2/3} - k_1^{-2/3}\right)$$

$$\boxed{\varepsilon = \left(\frac{2}{3a}\right)^{3/2} \sigma_v^3 \left(k_1^{-2/3} - k_2^{-2/3}\right)^{3/2}}$$

Turbulent properties from Doppler lidar

$$\sigma_{\bar{v}}{}^2 = \sigma_{\bar{w}}{}^2 + \sigma_e{}^2 + \sigma_d{}^2,$$

Observed variance

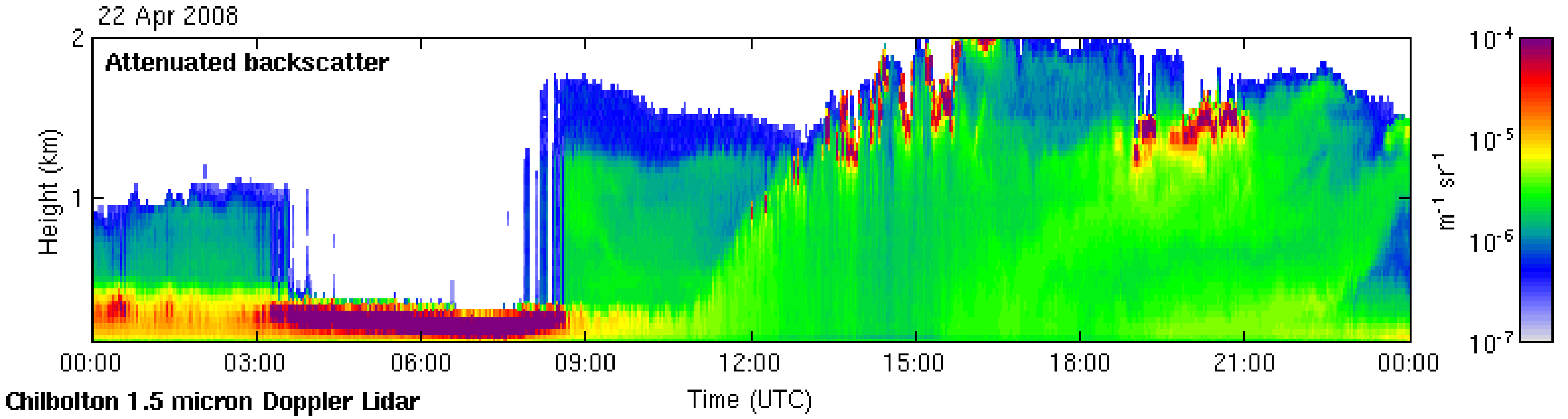
Droplet fall speed distribution

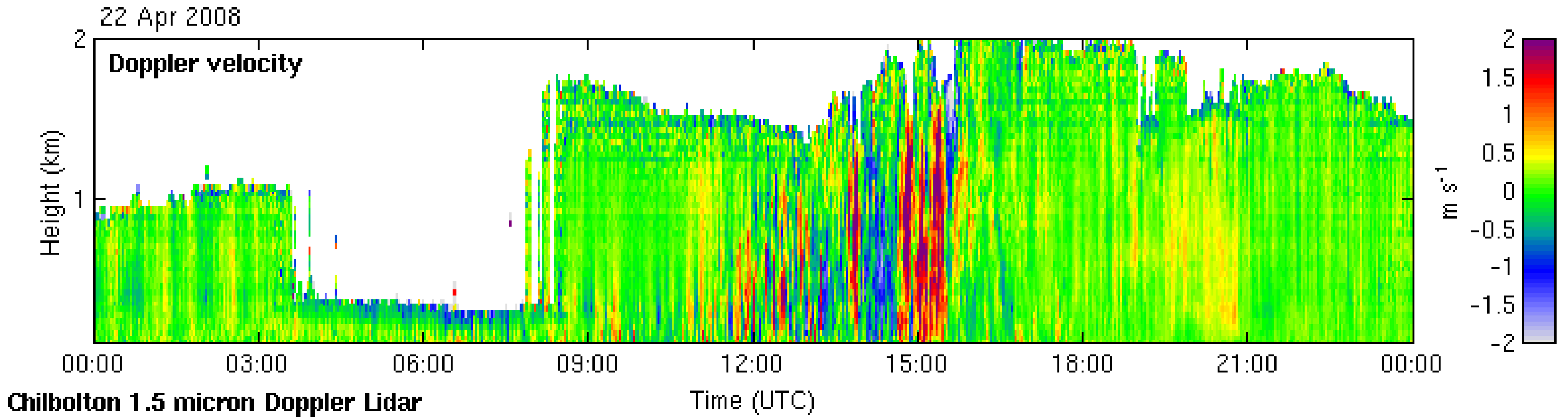
Turbulent term

Measurement uncertainty

Requires reliable uncertainties!

Turbulent properties from Doppler lidar





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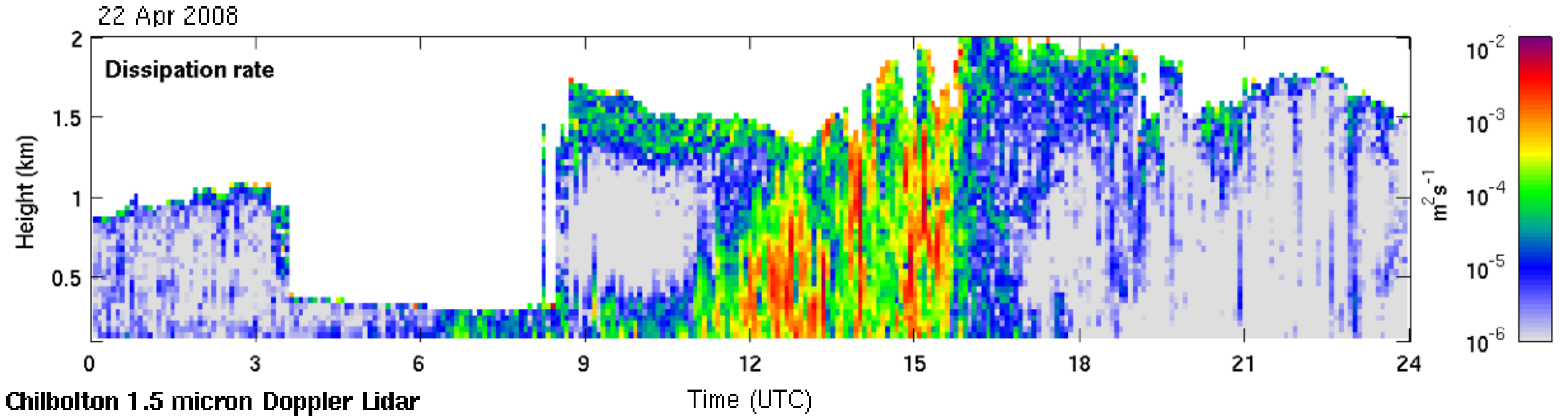
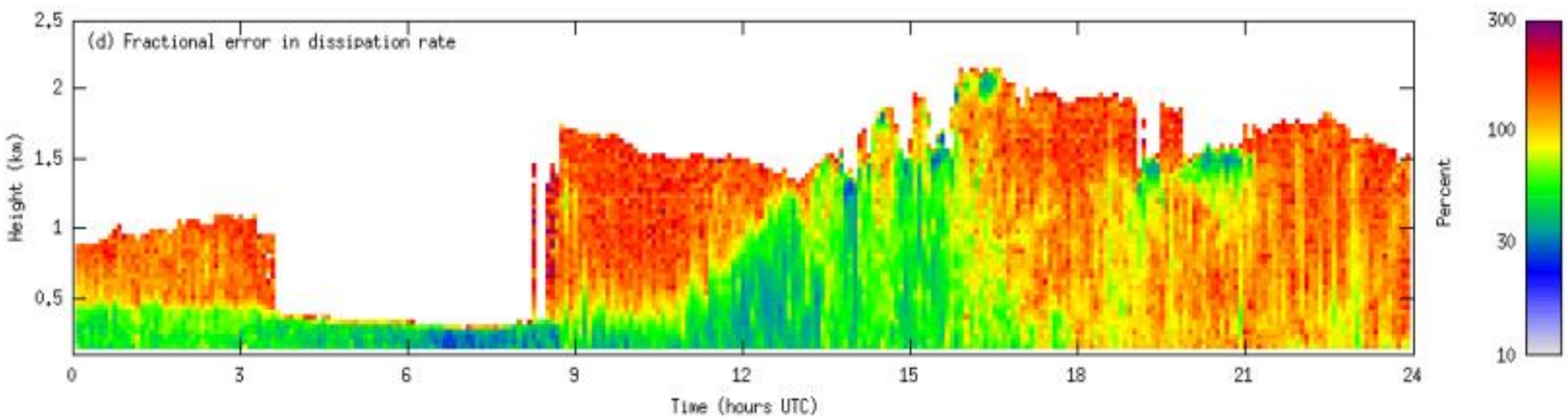
Turbulent properties from Doppler lidar





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Turbulent properties from Doppler lidar

$$\sigma_{\bar{v}}{}^2 = \sigma_{\bar{w}}{}^2 + \sigma_e{}^2 + \sigma_d{}^2,$$

Observed variance

Droplet fall speed distribution

Turbulent term

Measurement uncertainty

Requires reliable uncertainties!

- Background shape and ripple correction
  - Manninen et al. (2016, AMT)
  - Vakkari et al. (2017, ready to submit)

- Recalculate all uncertainties
  - Crucial for turbulent properties

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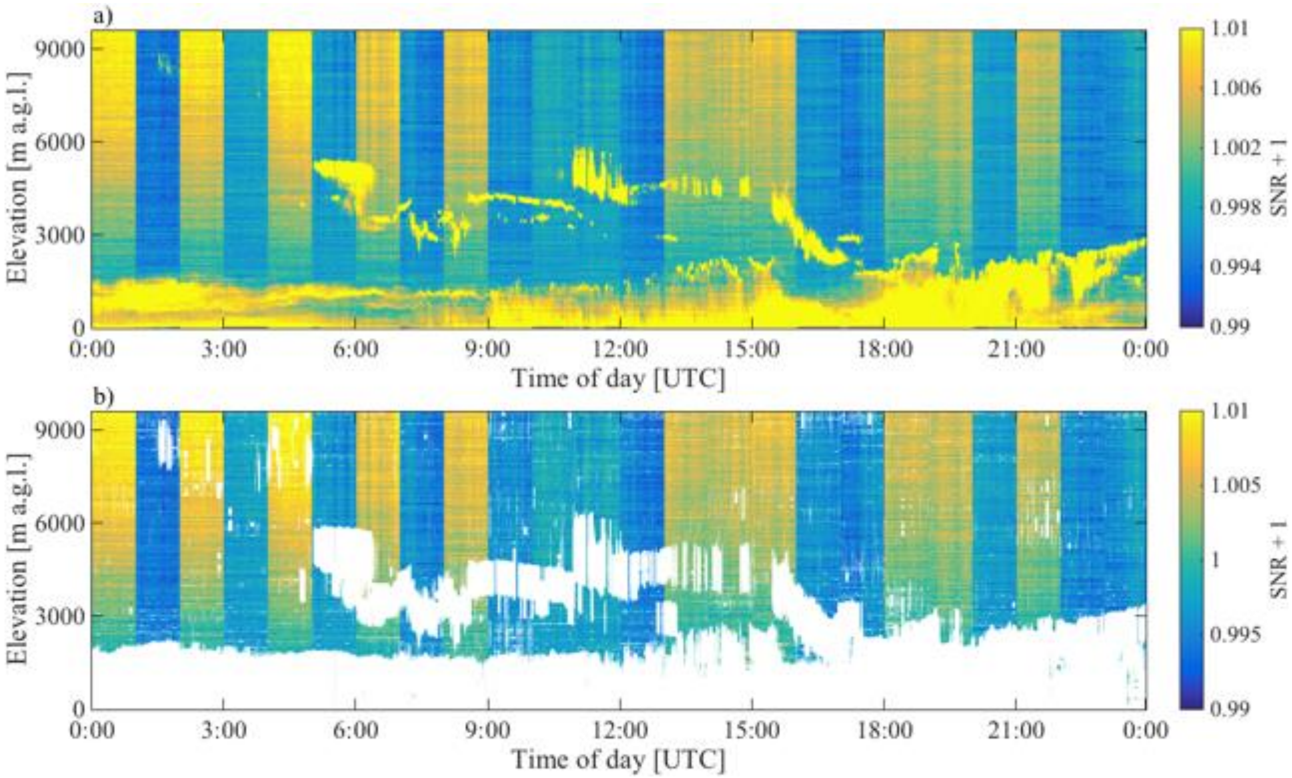
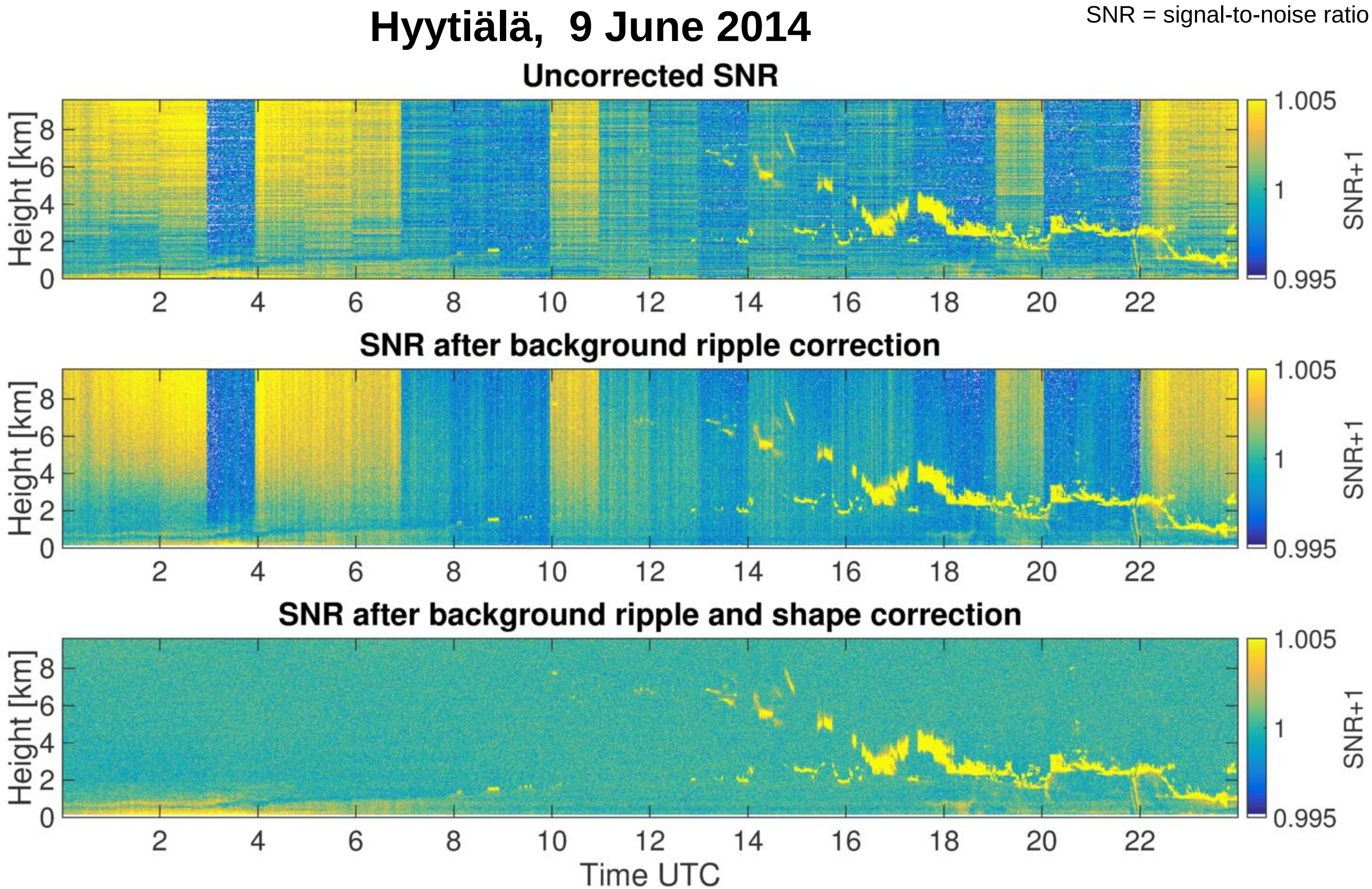
Halo data requires pre-processing



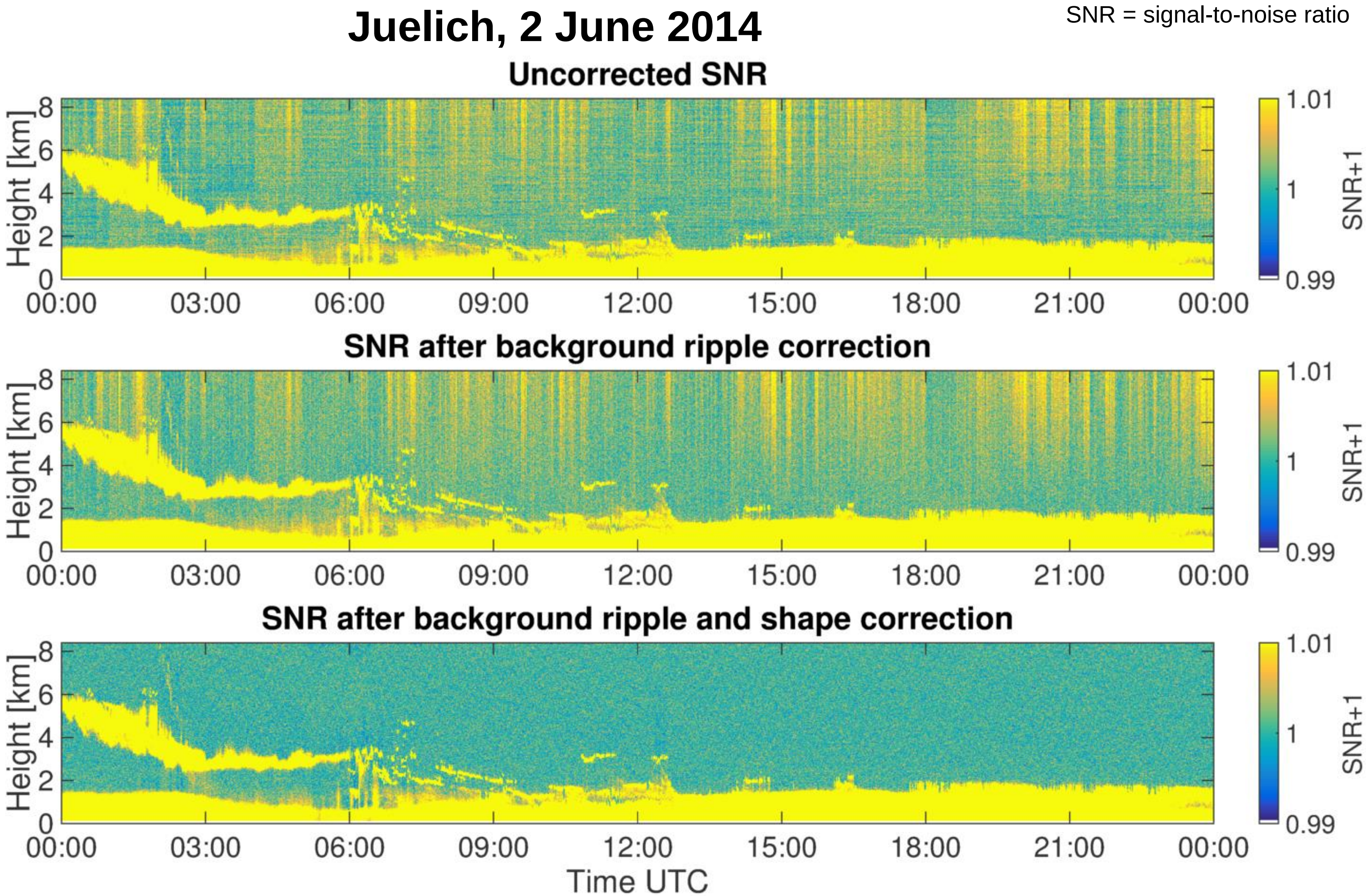
Halo data requires pre-processing

SNR = signal-to-noise ratio



Halo data requires pre-processing

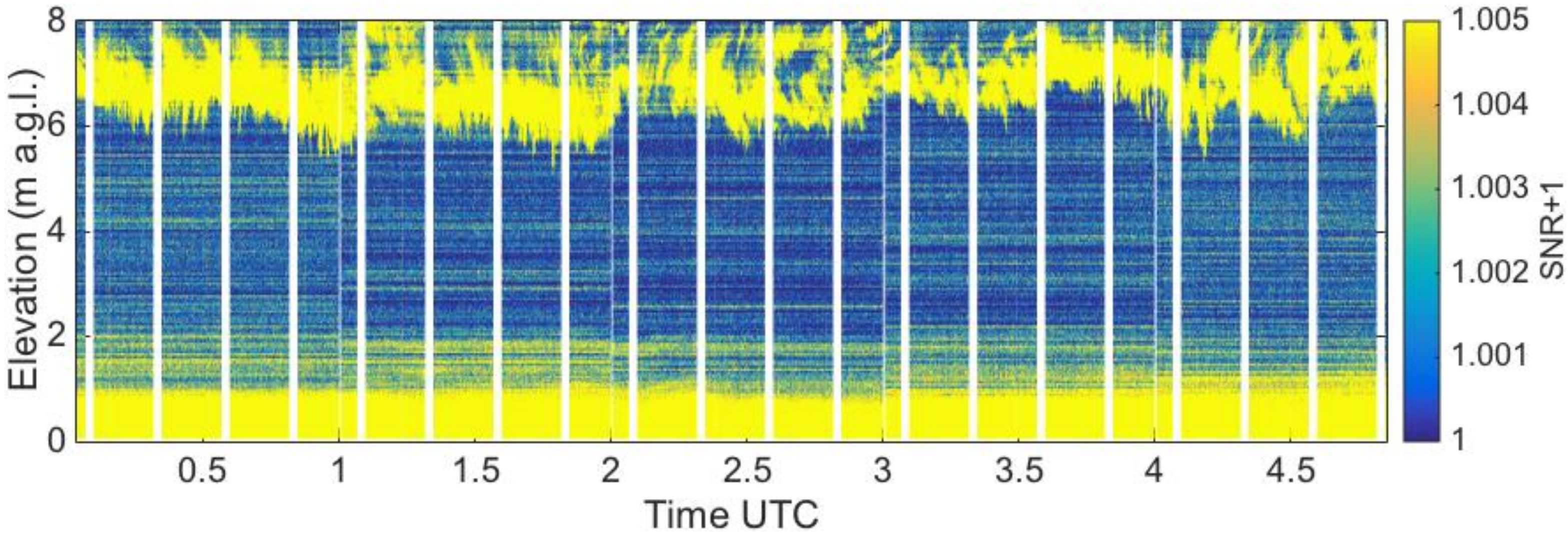
SNR = signal-to-noise ratio



Halo data requires pre-processing

Limassol, 27 March 2017

SNR = signal-to-noise ratio



Halo data requires pre-processing

Limassol, 27 March 2017

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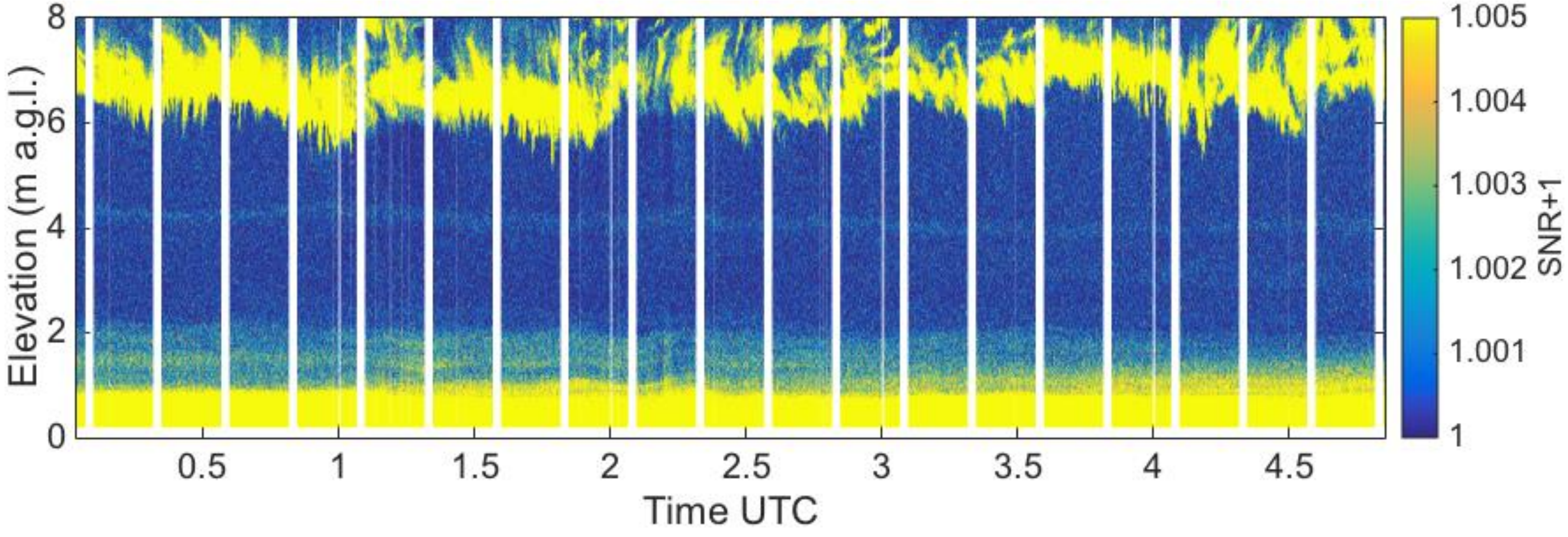
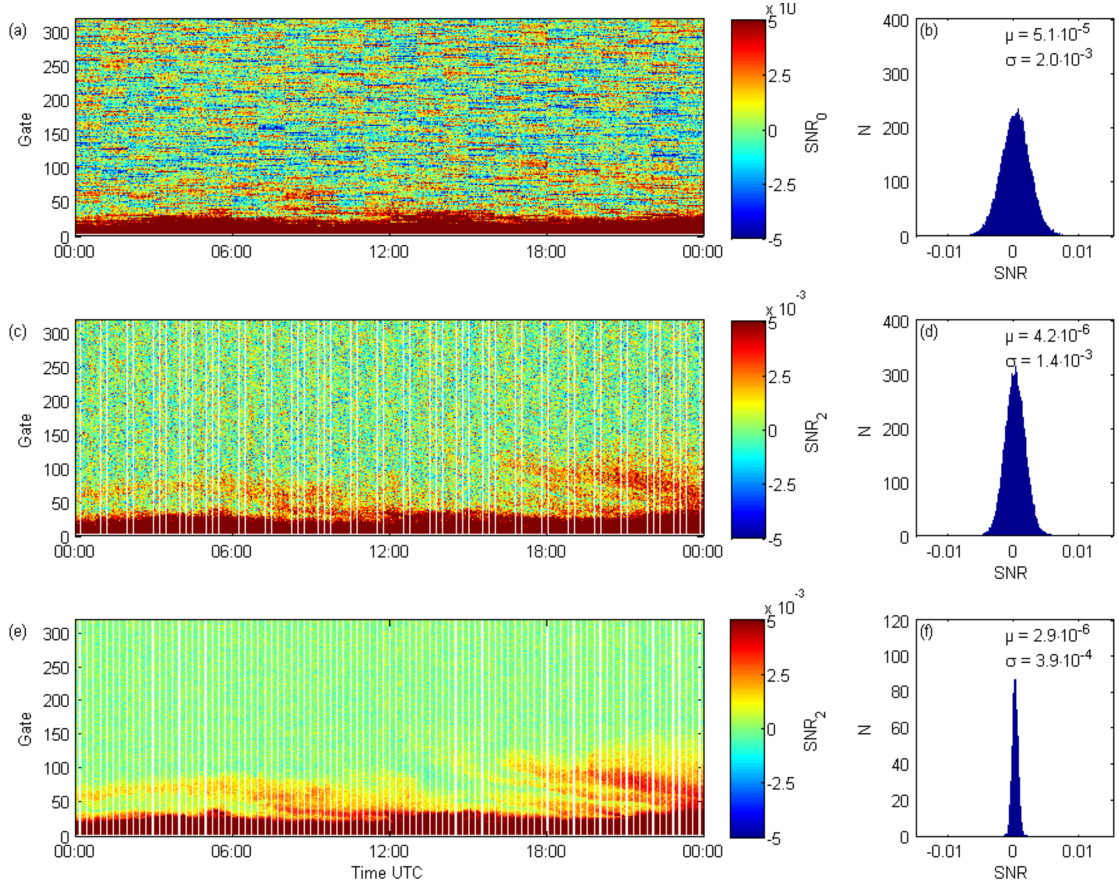


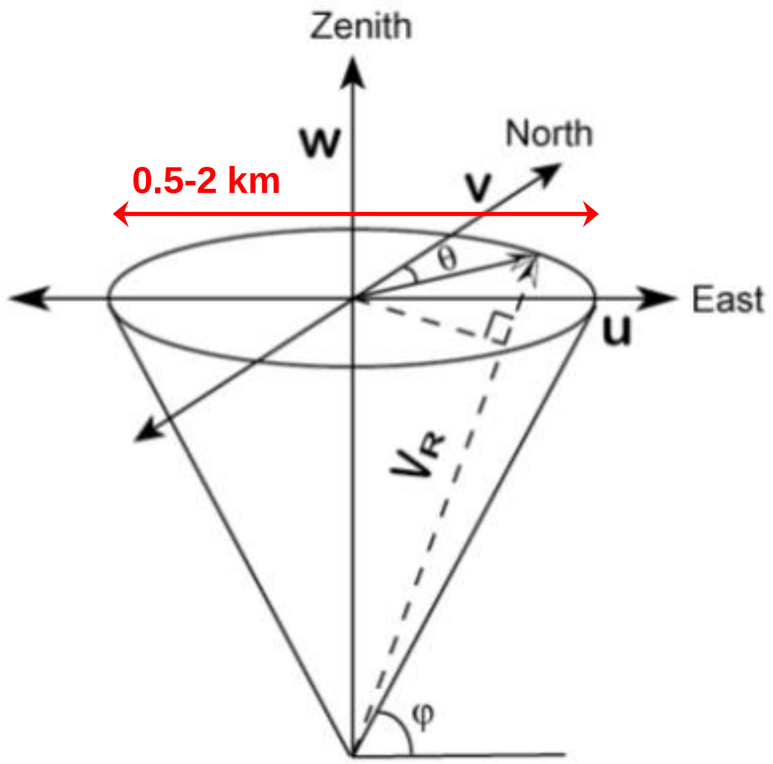
Instrument characterization – Halo systems

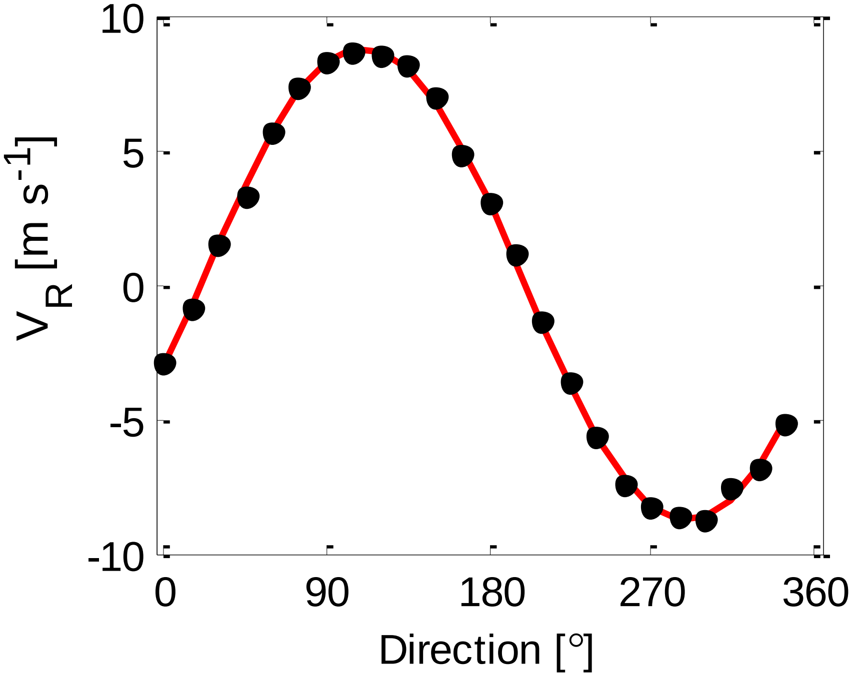
- **Background ripple determination and correction**



Turbulence from VAD scans

- Sinusoidal fit for horizontal wind
- Residuals from **turbulence** and **non-turbulent changes in wind**



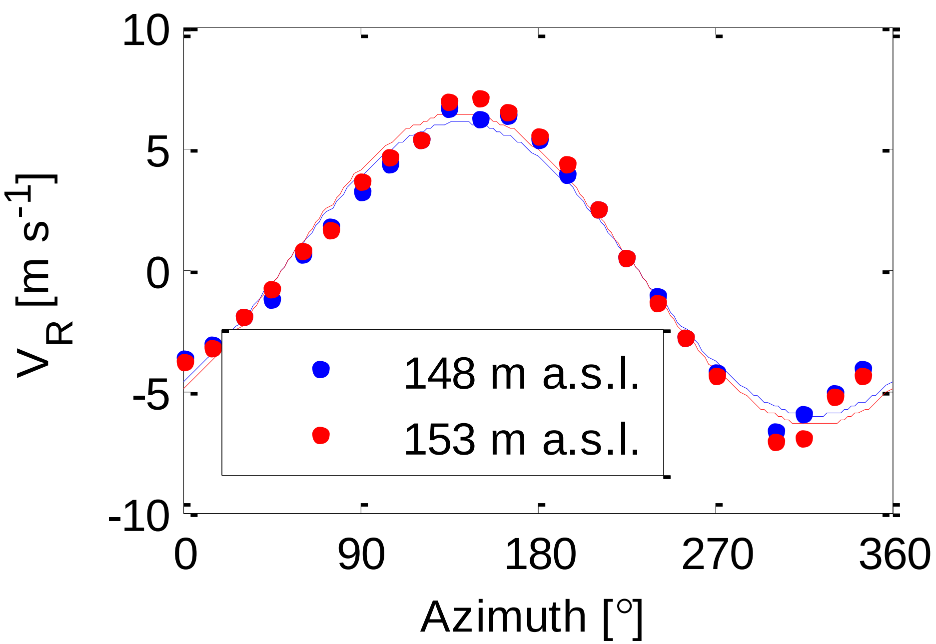


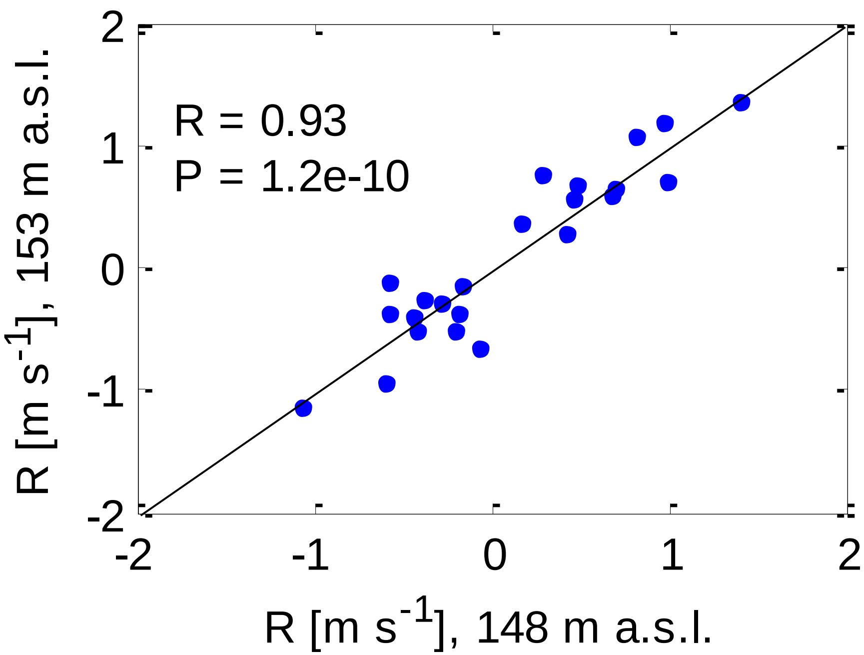
Remove non-turbulent residual

- Compare residual from one range gate to the next (same azimuth)
  - Correlated residuals indicate large-scale (>> 30 m) flow distortions
  - **Difference in residuals** leaves turbulence and instrumental noise

$$V_R = V_{wind} + R$$

$$R(r) - R(r + 30\ m) = \Delta R \approx \Delta V_{turb} + \upsilon$$

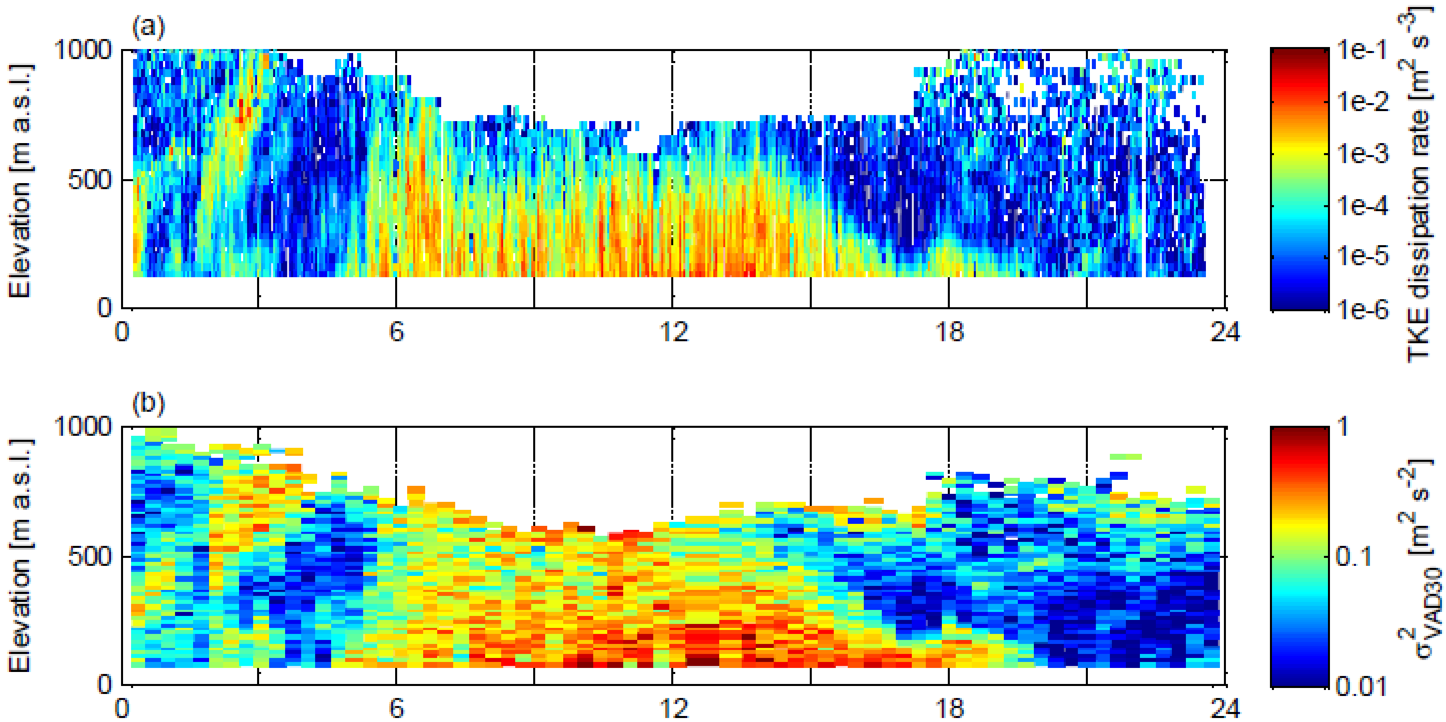




Proxy for turbulence: $\sigma^2_{VAD} = \mathrm{var}(\Delta R_i) - \sigma^2_{\upsilon}$

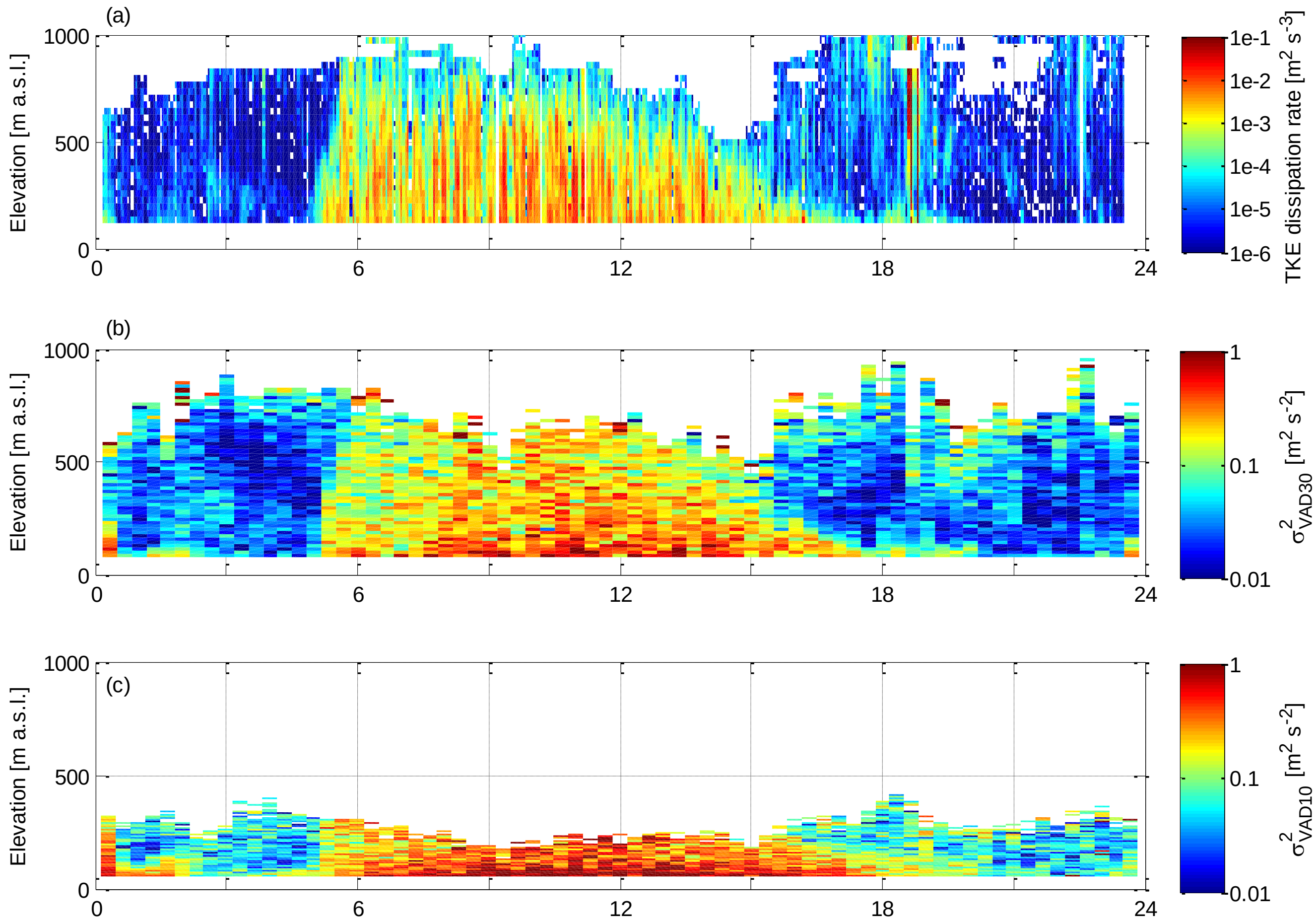
- Variance of ΔR gives a proxy for turbulence
  - Variance can be calculated over a full circle (i.e. all azimuthal angles) or over a limited sector
  - Measurement uncertainty contribution σ^2_v estimated from SNR

Summertime example (Limassol 24 Aug 2013; Vakkari et al., AMT 2015)

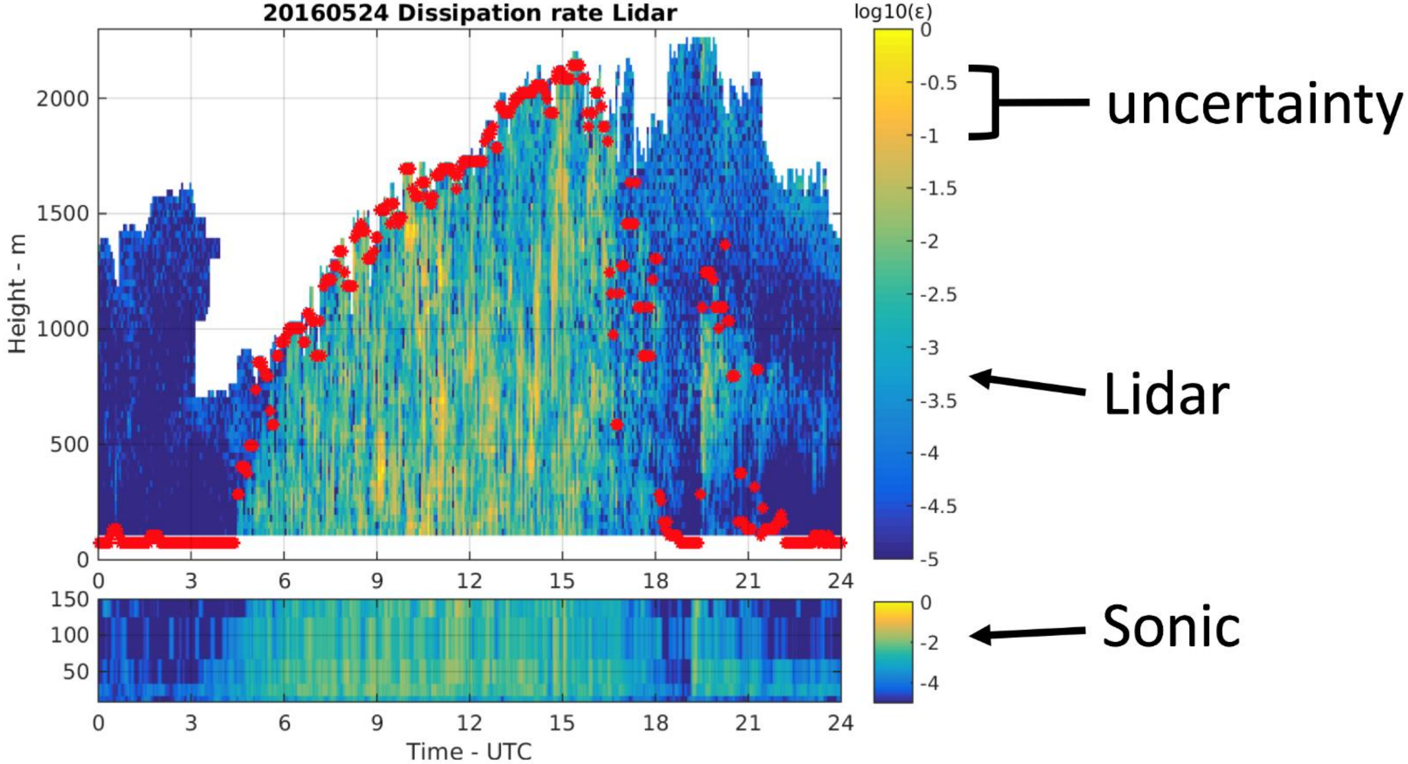


Turbulent retrieval from low-level scans

(Vakkari et al., 2015)



Comparison of TKE from lidar & sonic anemometers (mast)



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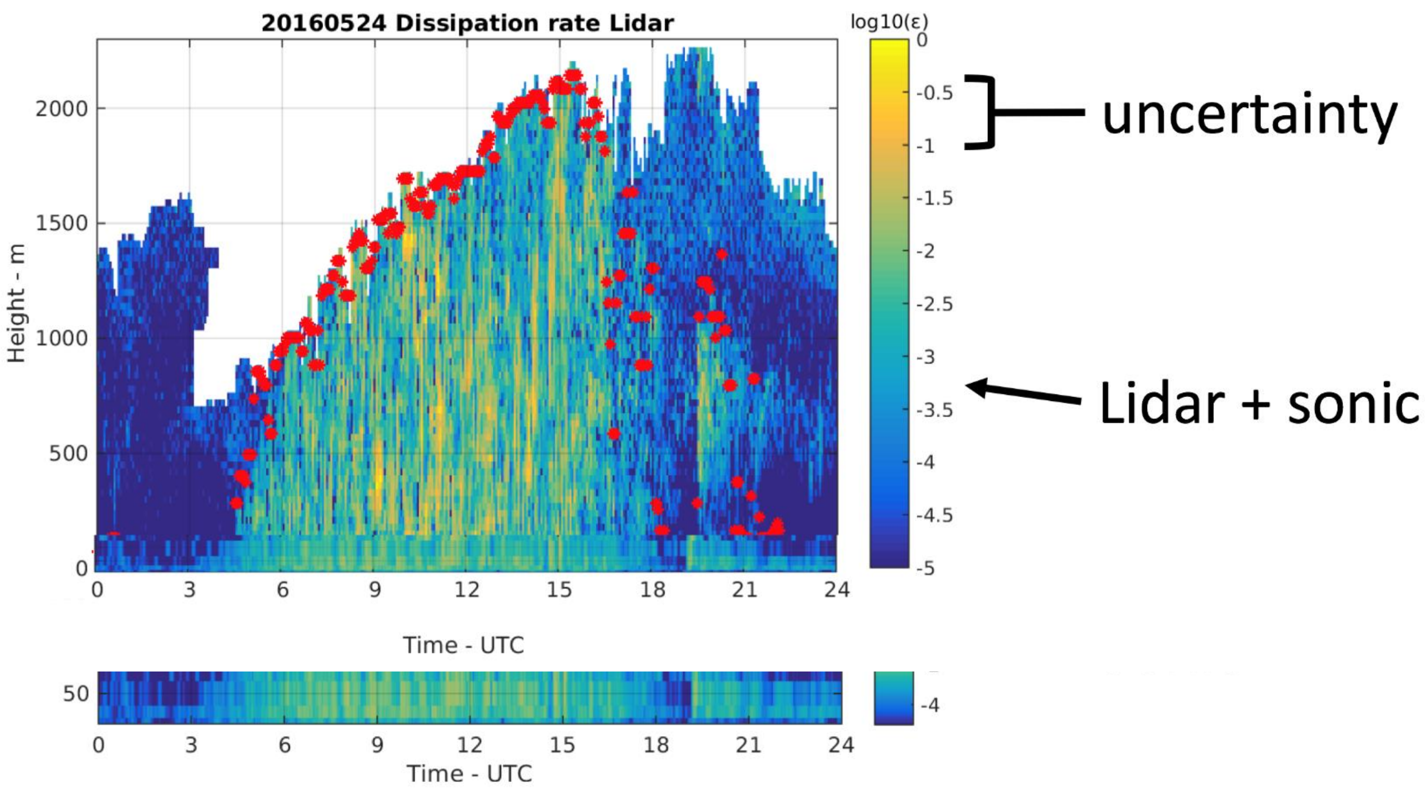
Comparison of TKE from lidar & sonic anemometers (mast)



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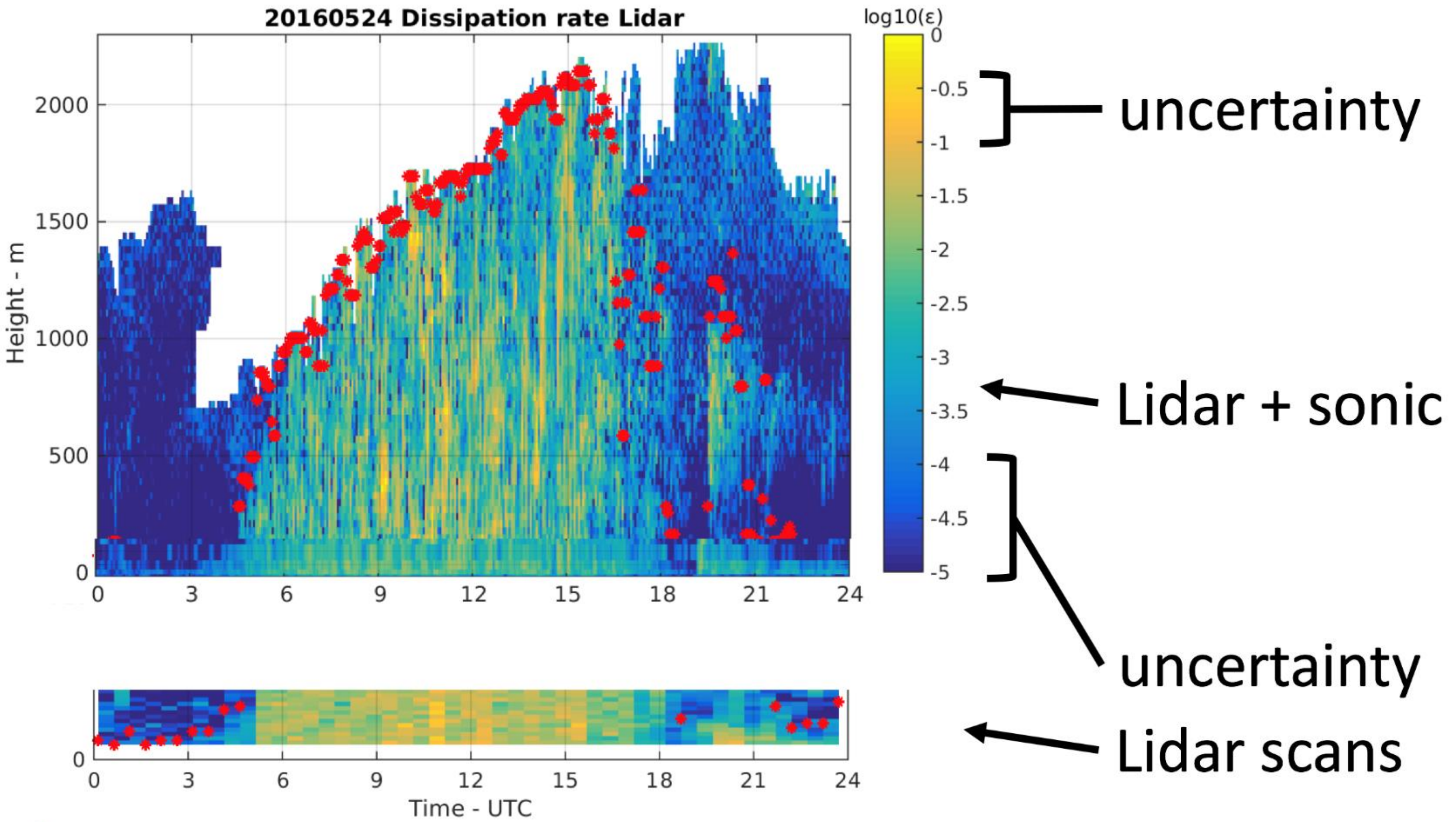
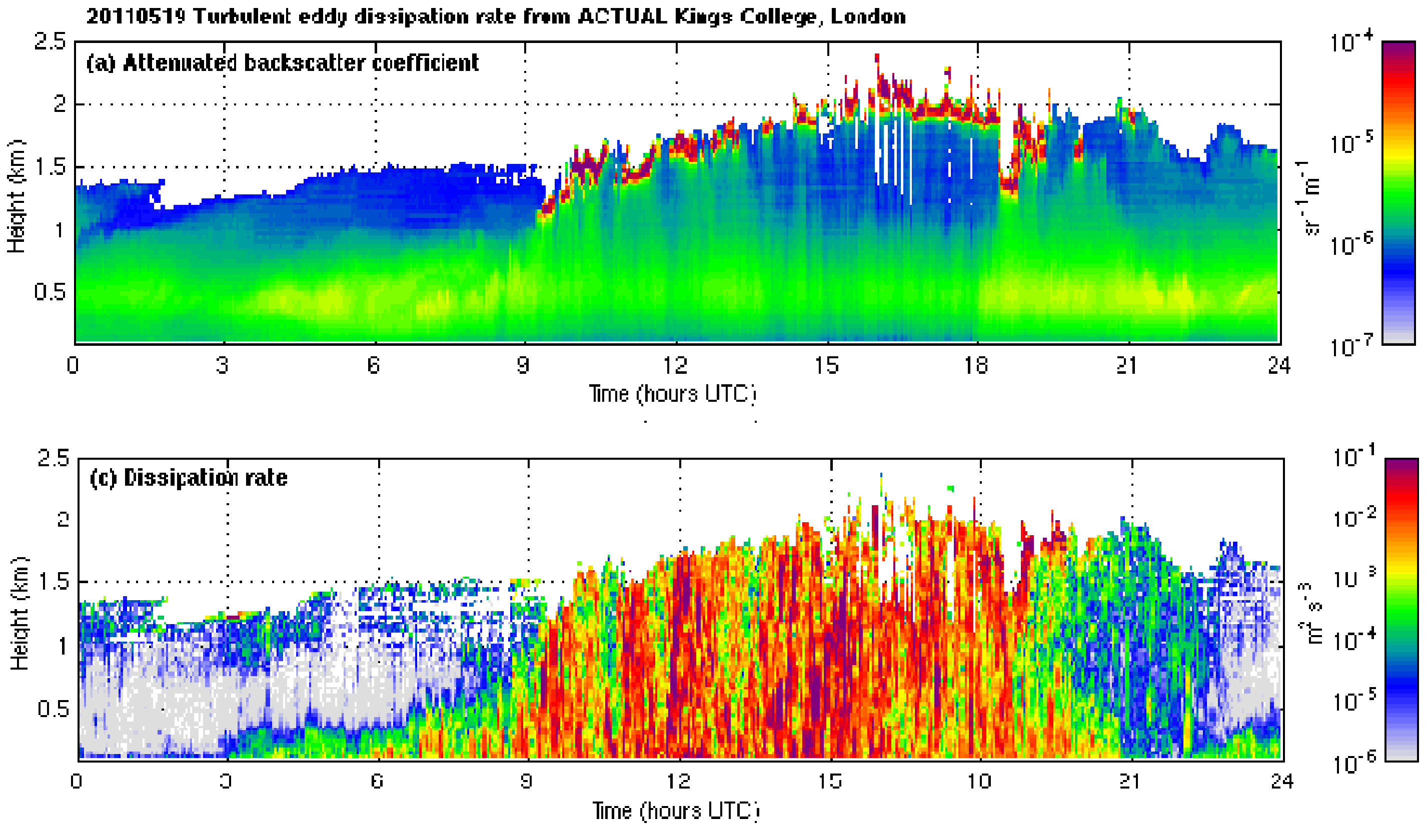
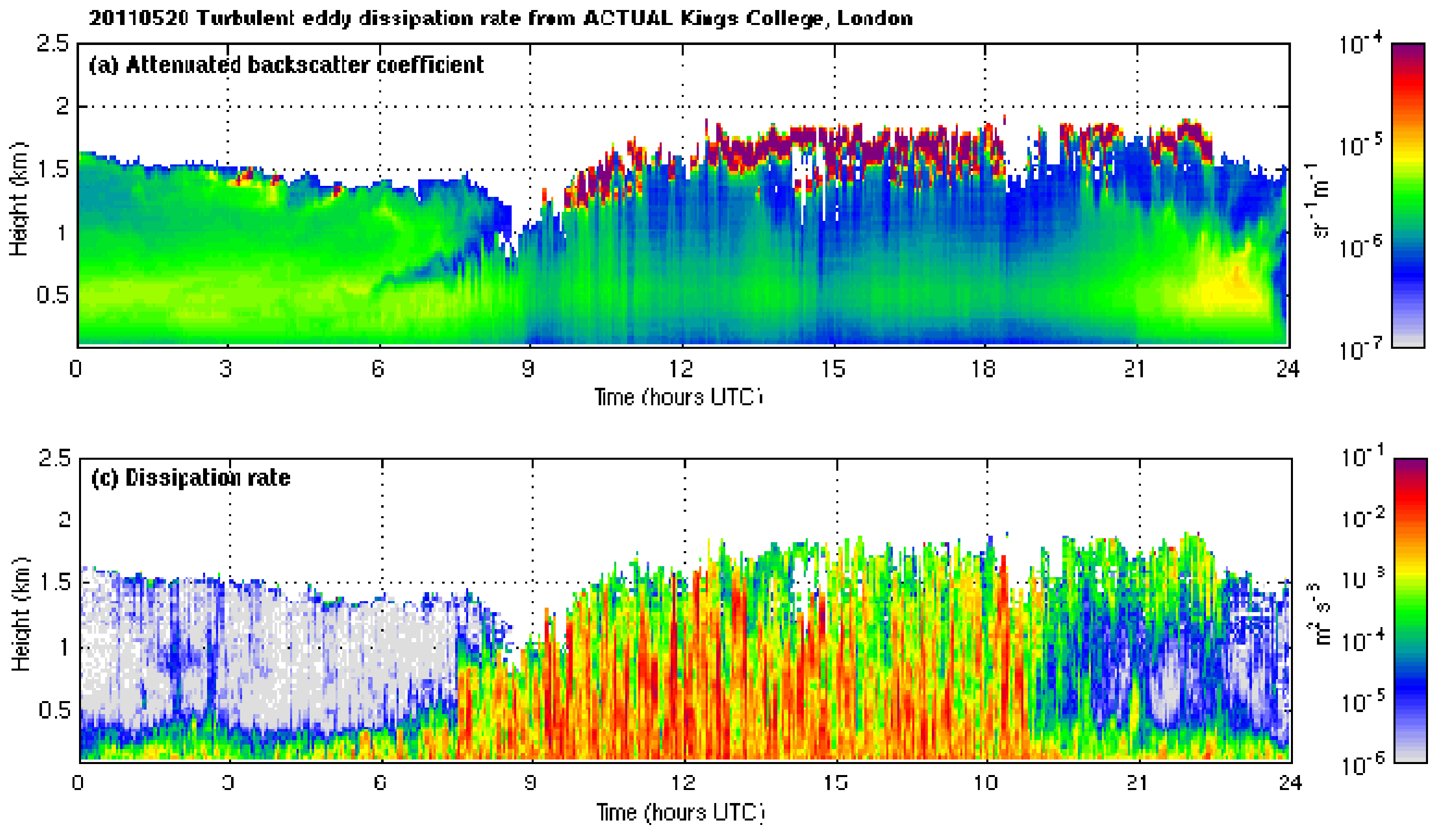
Comparison of TKE from lidar & sonic anemometers (mast)




20110519 Turbulent eddy dissipation rate from ACTUAL Kings College, London
(a) Attenuated backscatter coefficient
Height (km)
Time (hours UTC)
sr⁻¹ m⁻¹
(c) Dissipation rate
Height (km)
Time (hours UTC)
m² s⁻³


20110520 Turbulent eddy dissipation rate from ACTUAL Kings College, London
(a) Attenuated backscatter coefficient
Height (km)
Time (hours UTC)
sr^{-1} m^{-1}
(c) Dissipation rate
Height (km)
Time (hours UTC)
m^2 s^{-3}

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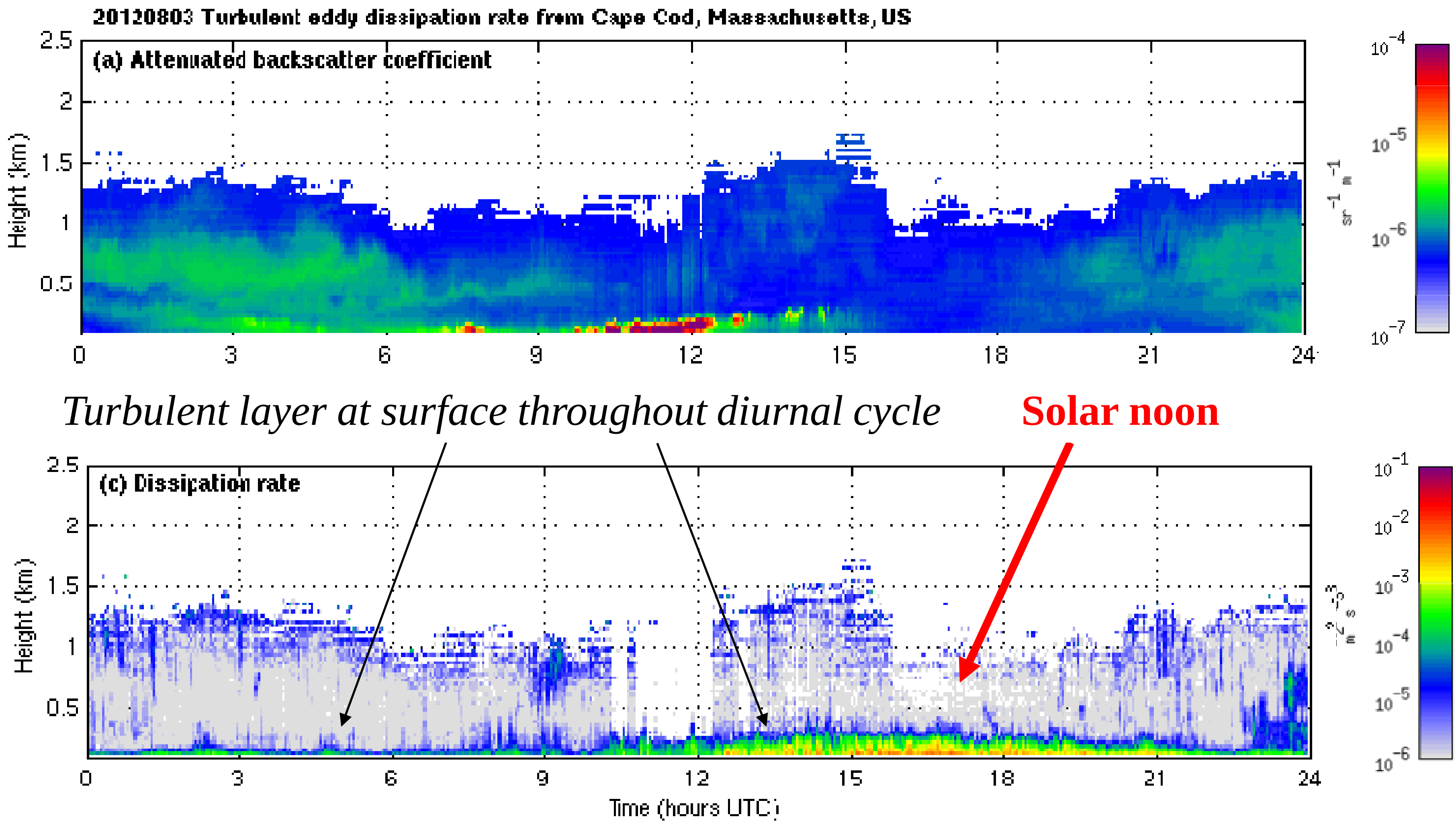
Cape Cod (Marine): 20120803



Practical applications

Wind shear

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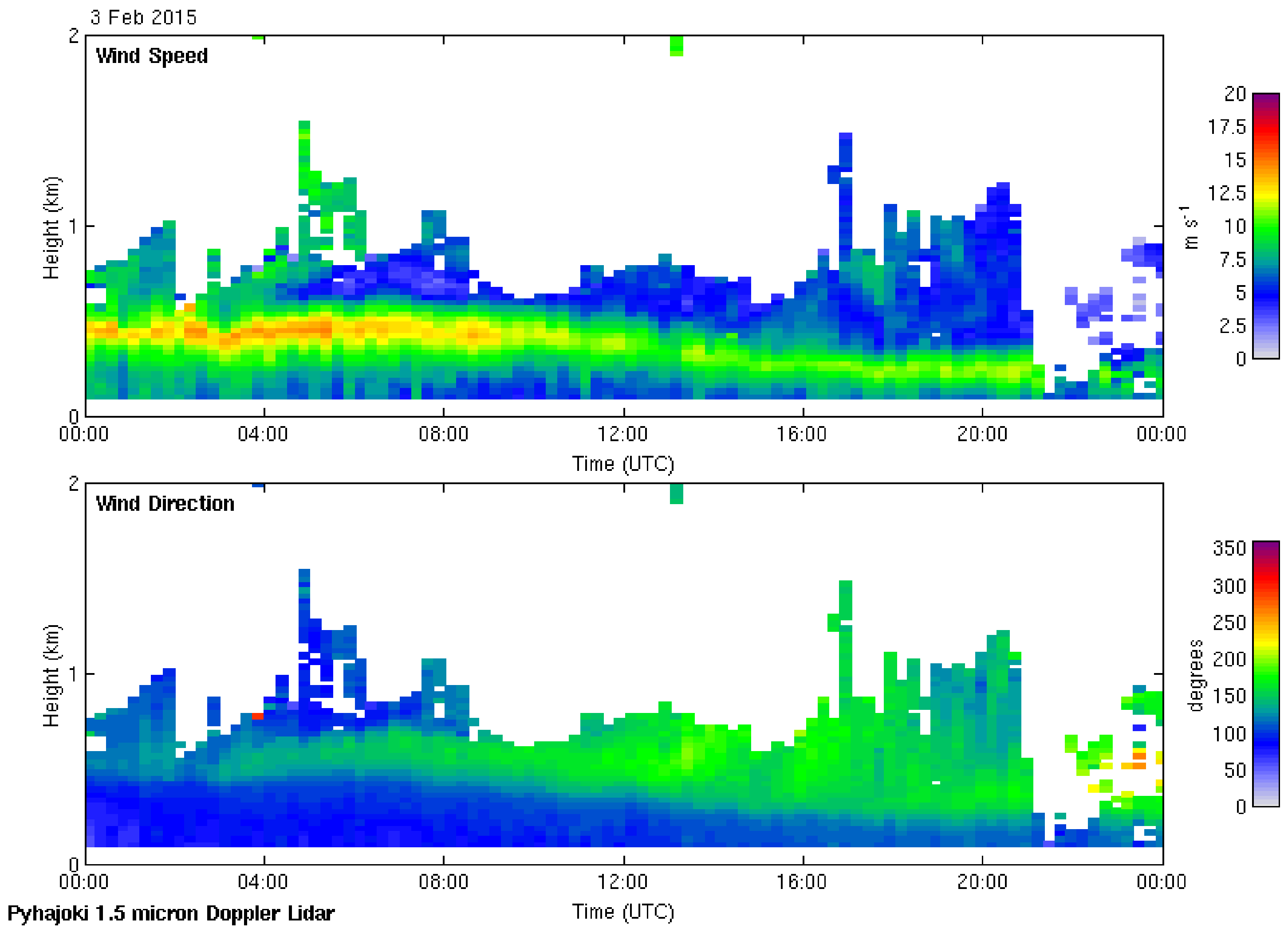
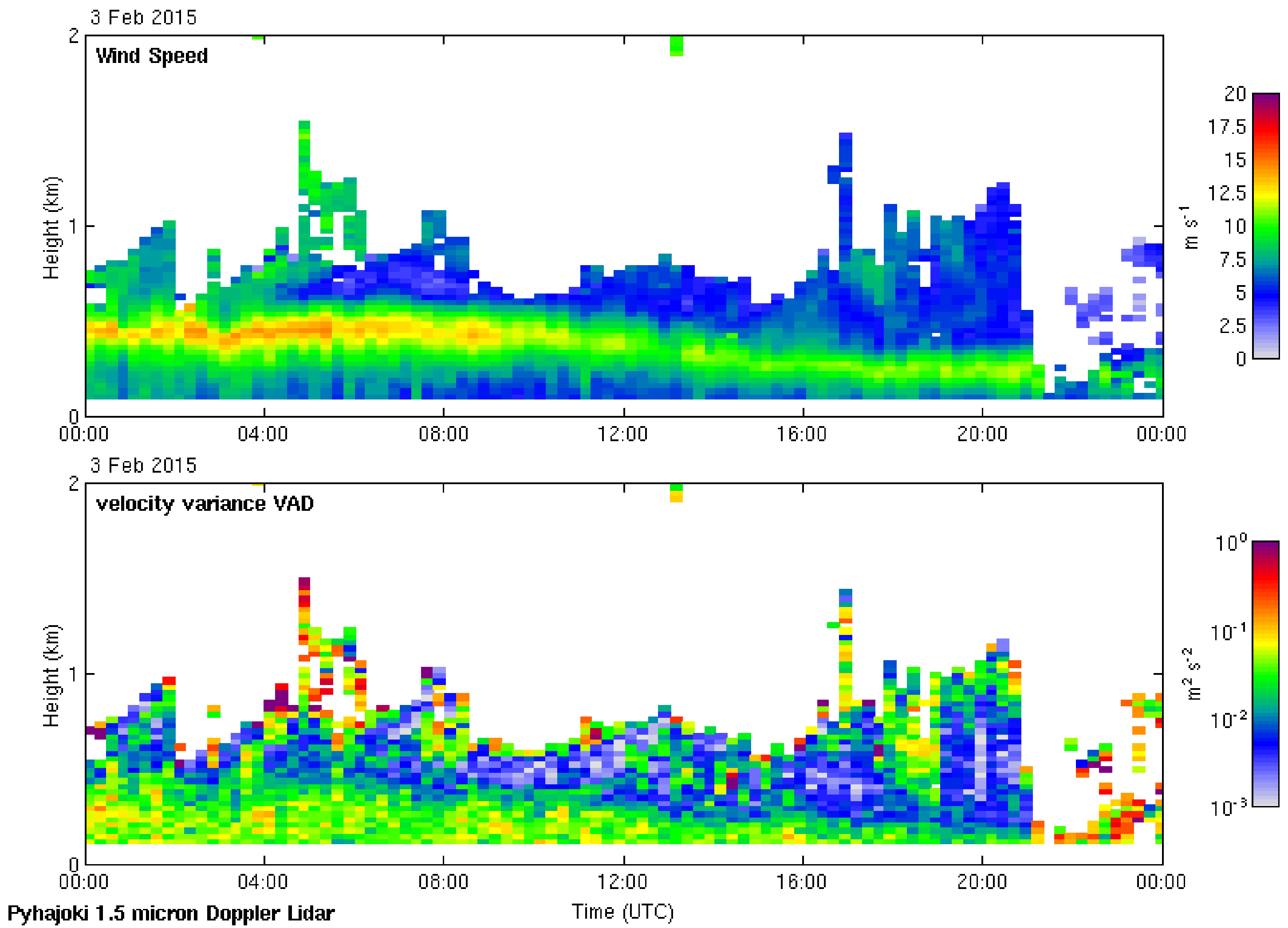
Plume observations - Kuopio

Photo: Sinclair 2015

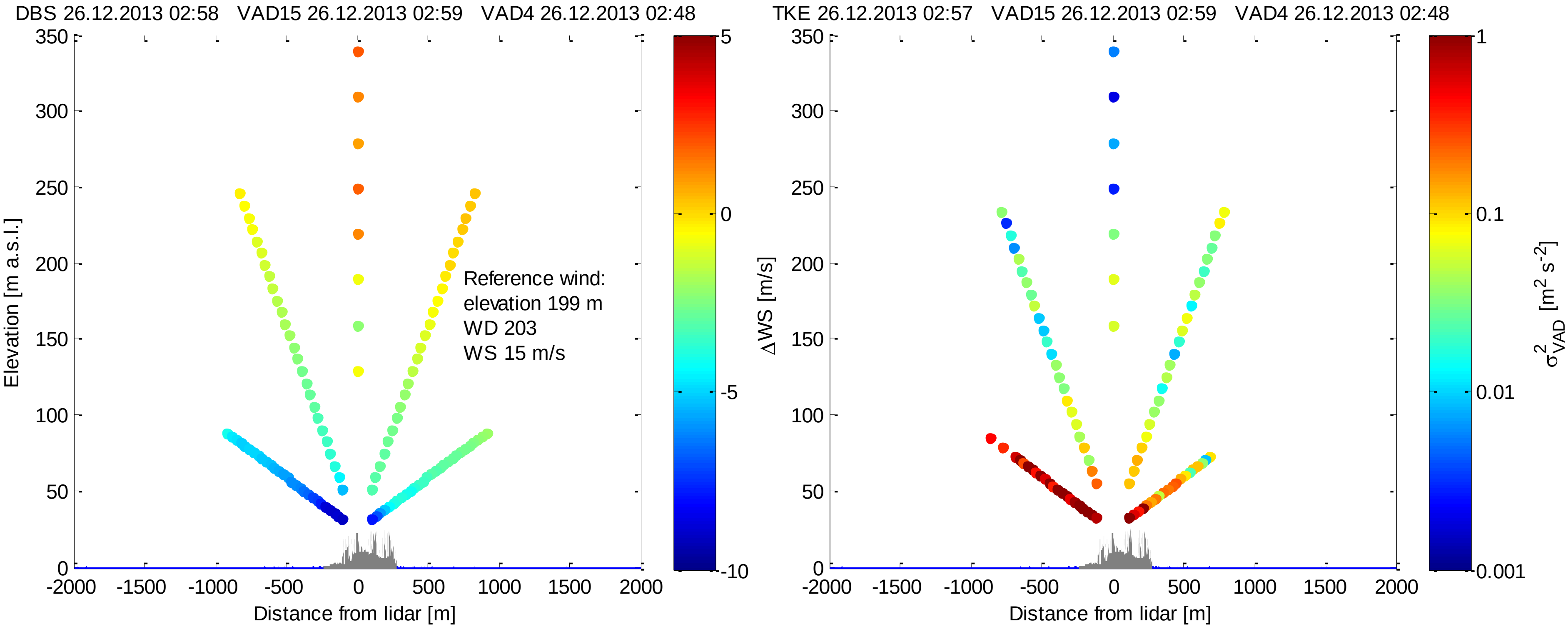
Low-level jets

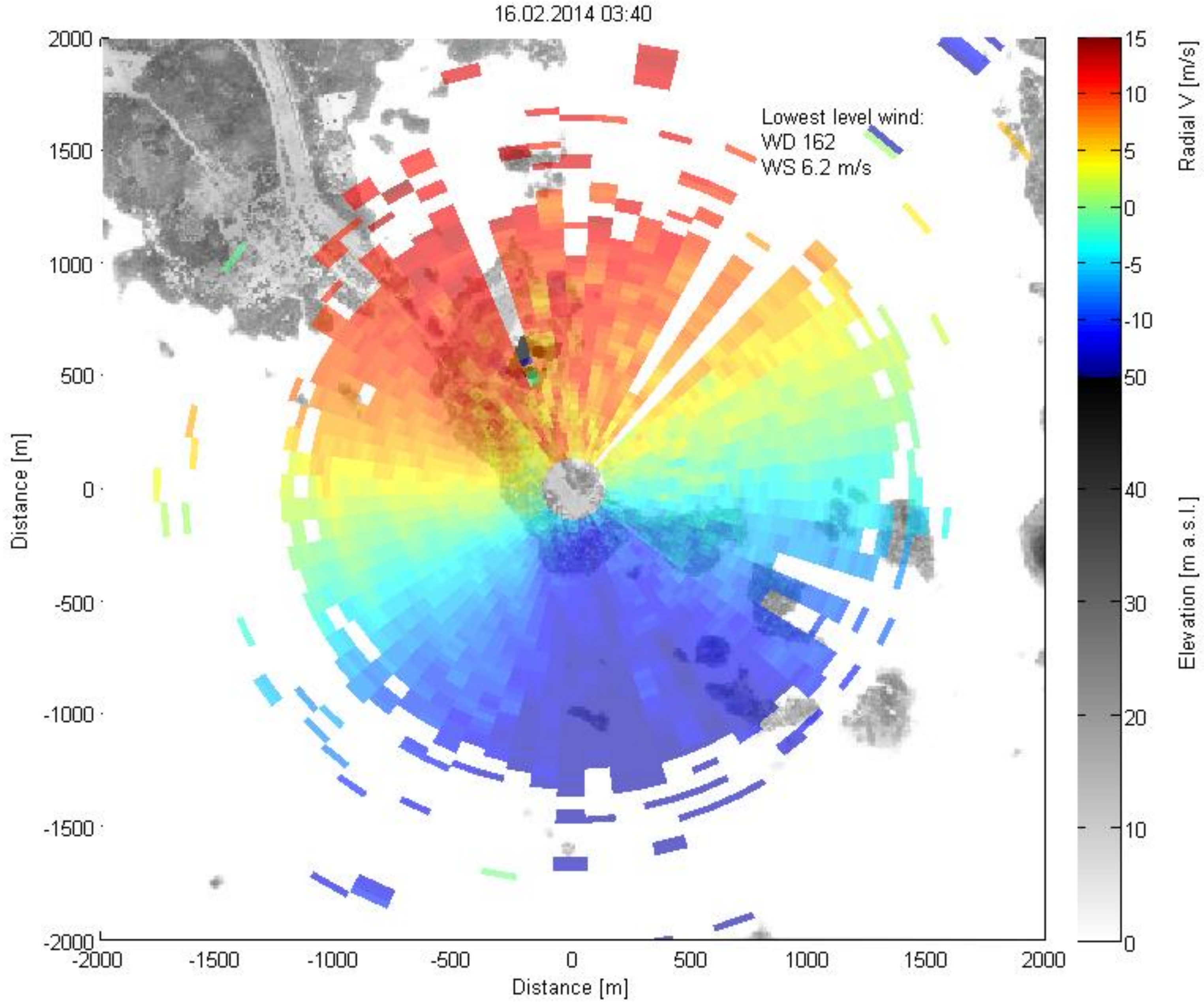


Low-level jets



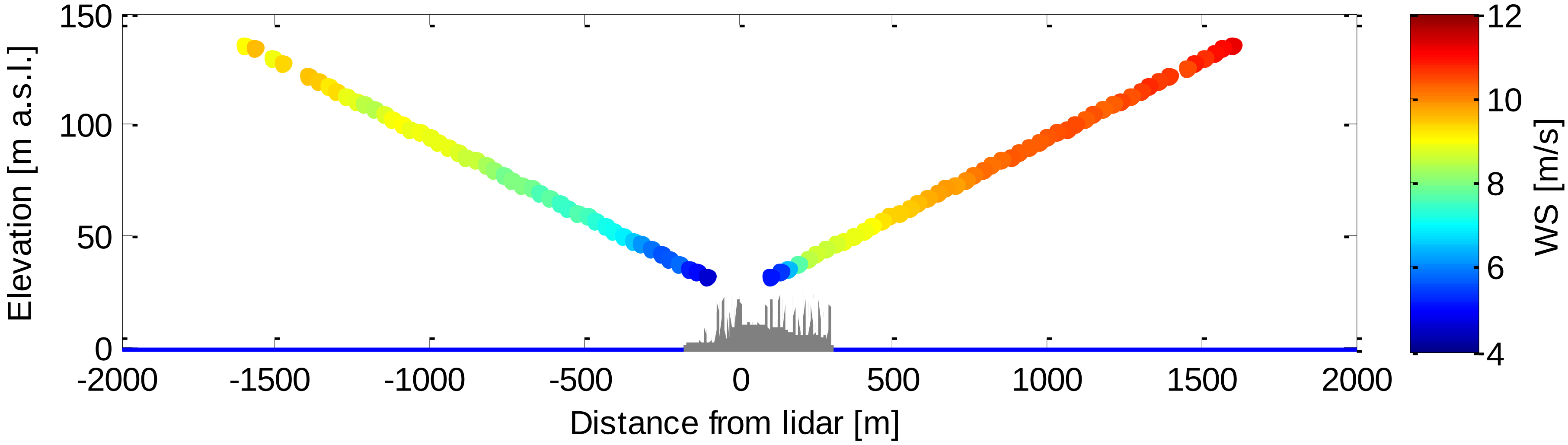
Representativity

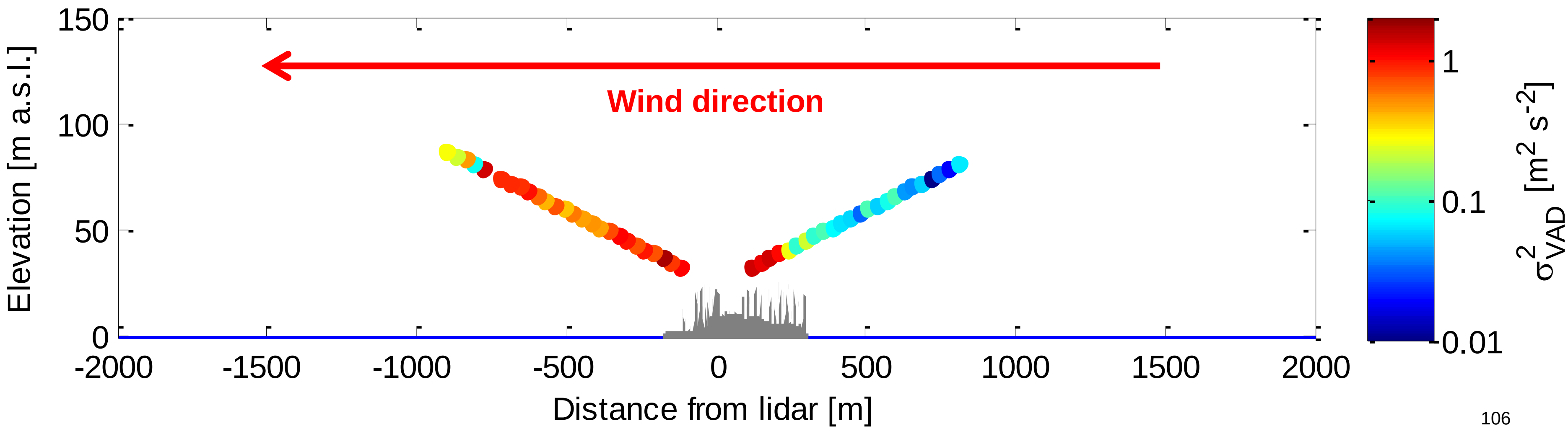


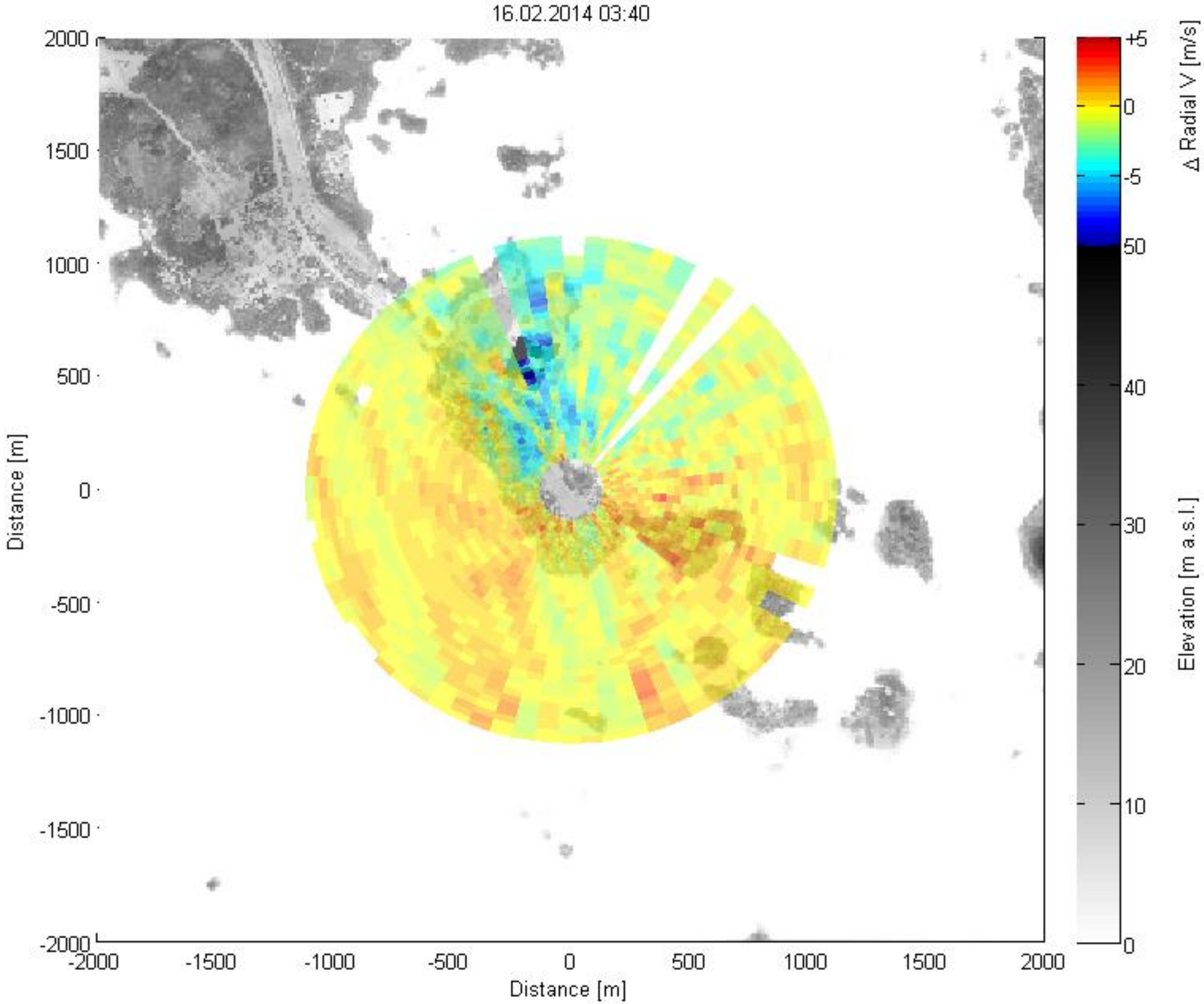

16.02.2014 03:40
Lowest level wind:
WD 162
WS 6.2 m/s
Distance [m]
Distance [m]
2000
1500
1000
500
0
-500
-1000
-1500
-2000
Radial V [m/s]
15
10
5
0
-5
-10
Elevation [m a.s.l.]
50
40
30
20
10
0

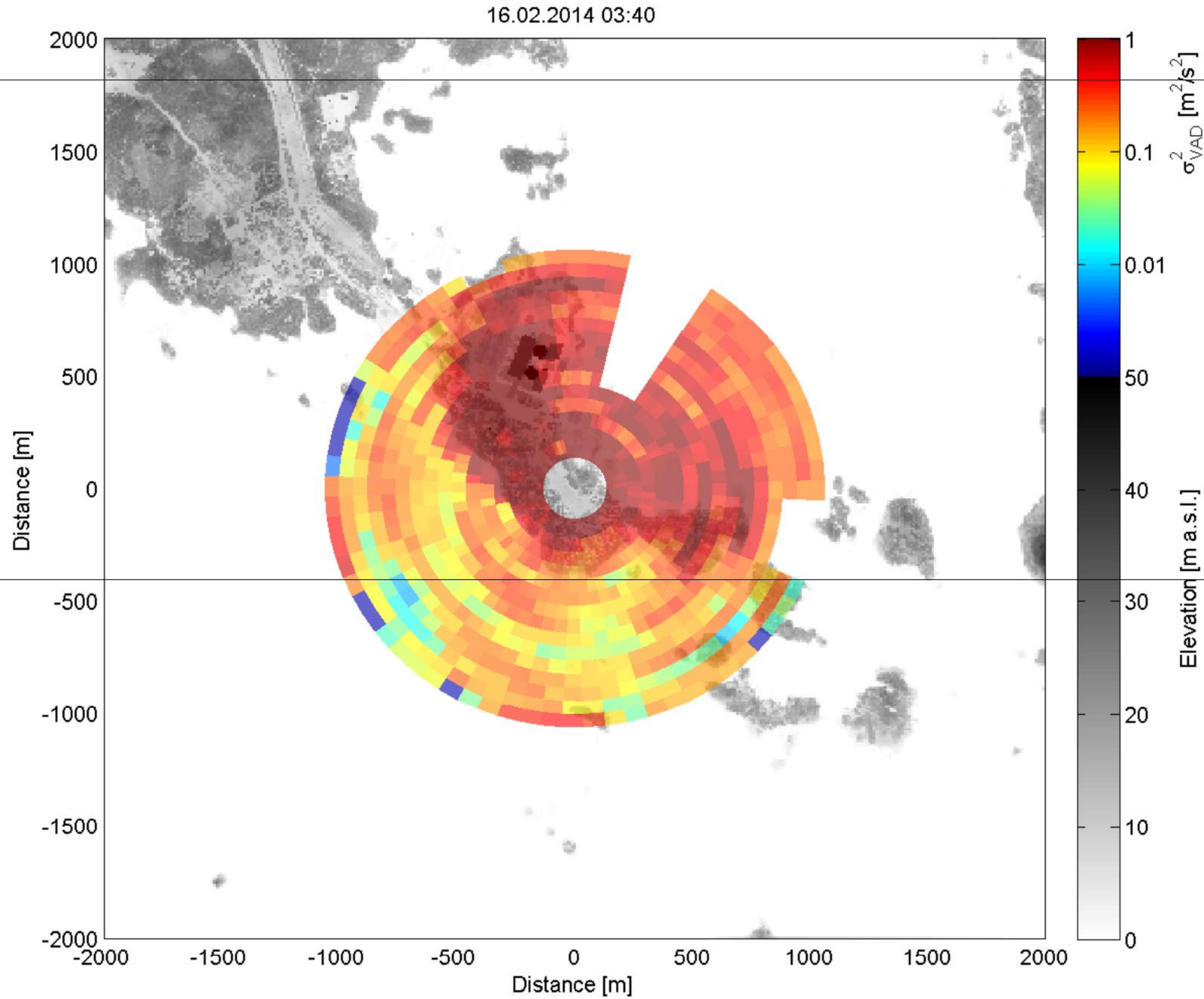
Island effect extends >1.5 km downwind

- Observations < 40 m a.s.l. are above island for both upwind and downwind profiles






16.02.2014 03:40
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Distance [m]
Distance [m]
+5
0
-5
50
40
30
20
10
0
Δ Radial V [m/s]
Elevation [m a.s.l.]



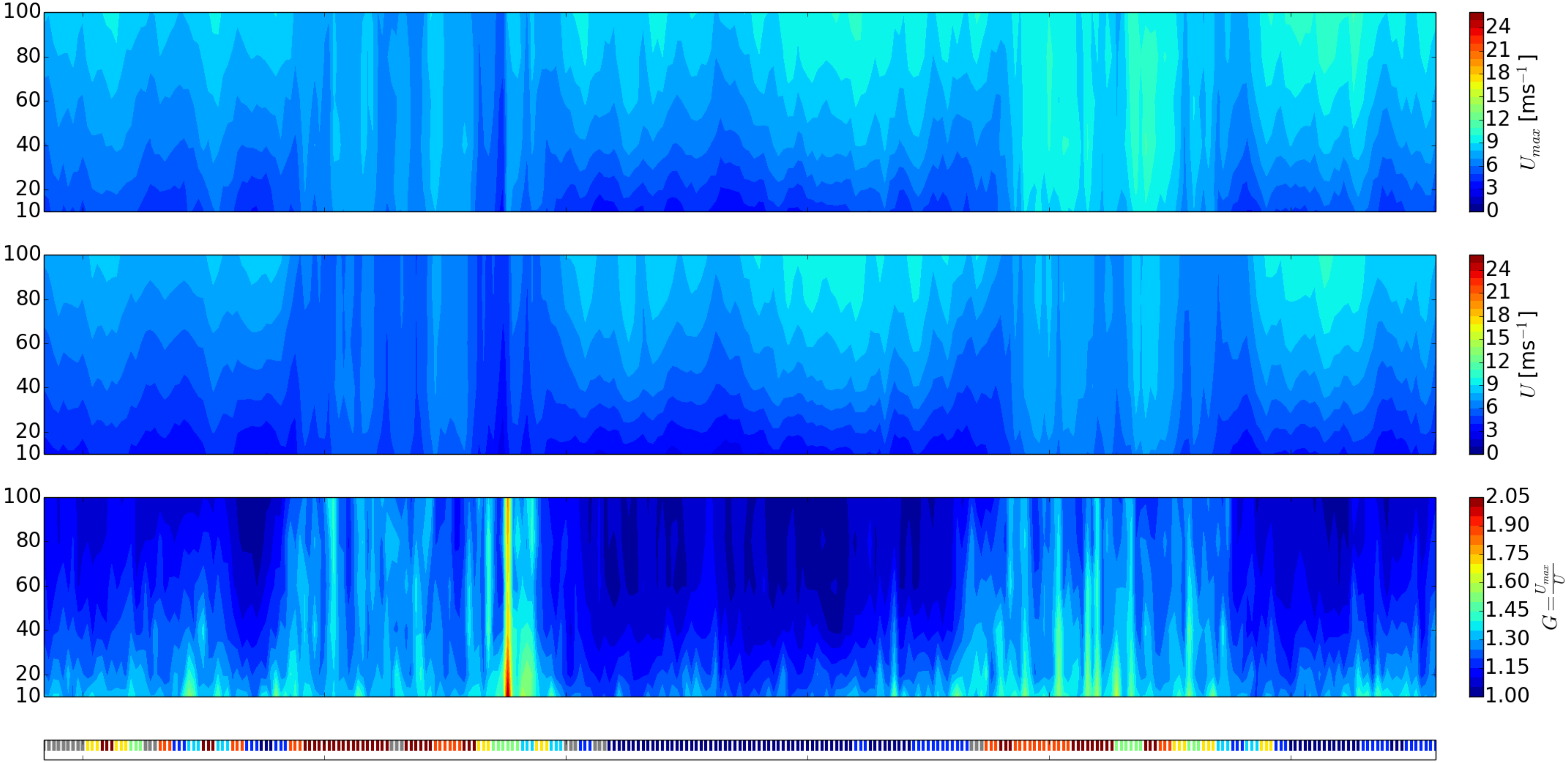
16.02.2014 03:40
2000
1500
1000
500
0
-500
-1000
-1500
-2000
Distance [m]
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Distance [m]
1
0.1
0.01
σ^2_{VAD} [m^2/s^2]
50
40
30
20
10
0
Elevation [m a.s.l.]

Wind gusts

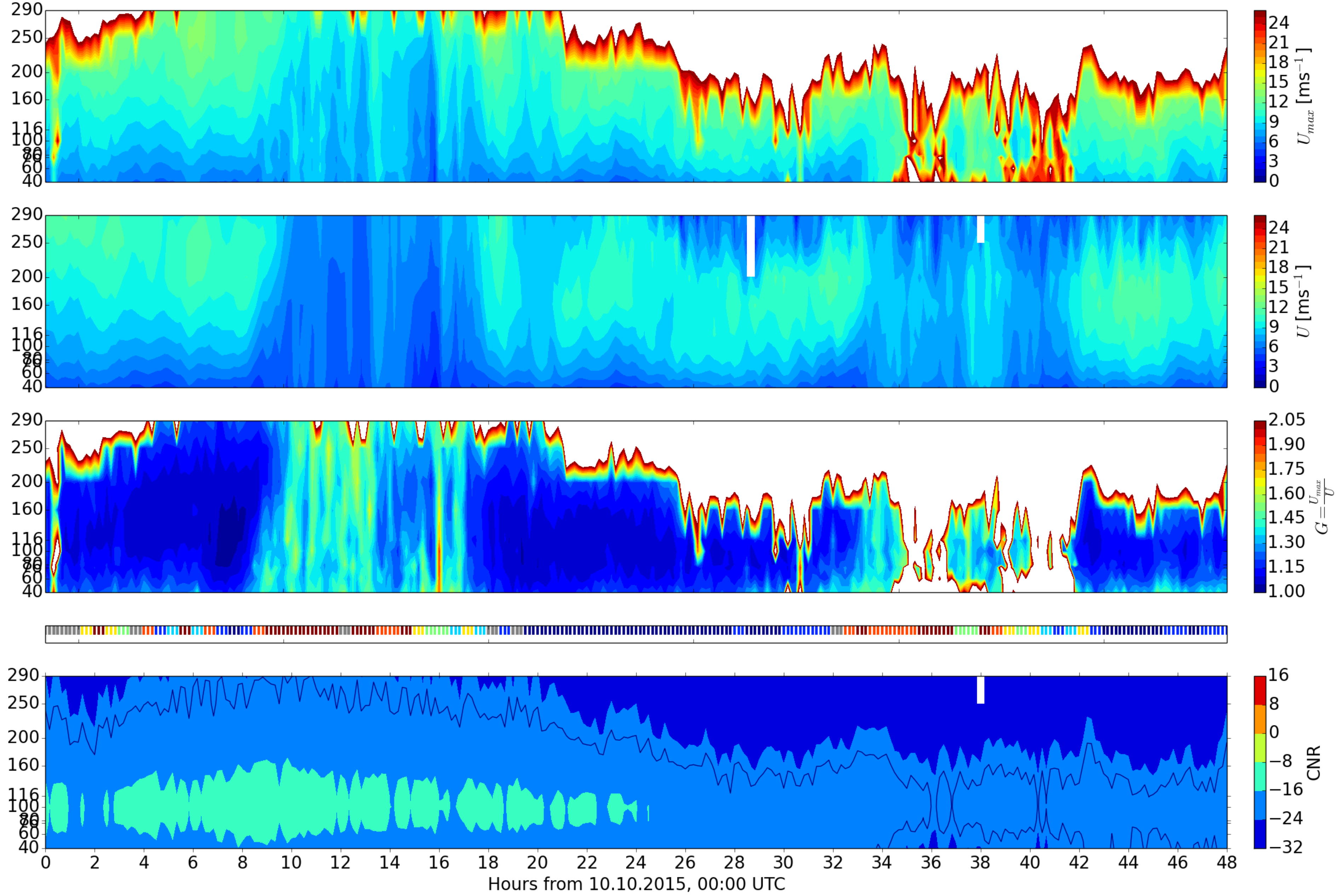
- **Standard measurement at surface or on mast**
  - 1 Hz data or better from anemometers
  - Gust factor

$$G = \frac{U_{max}}{U}$$

- **Can we do this with Doppler lidar**
  - Current instruments too slow for direct measurement
    - Typically 5 seconds minimum integration to obtain horizontal wind profile
    - Use horizontal winds plus turbulence instead

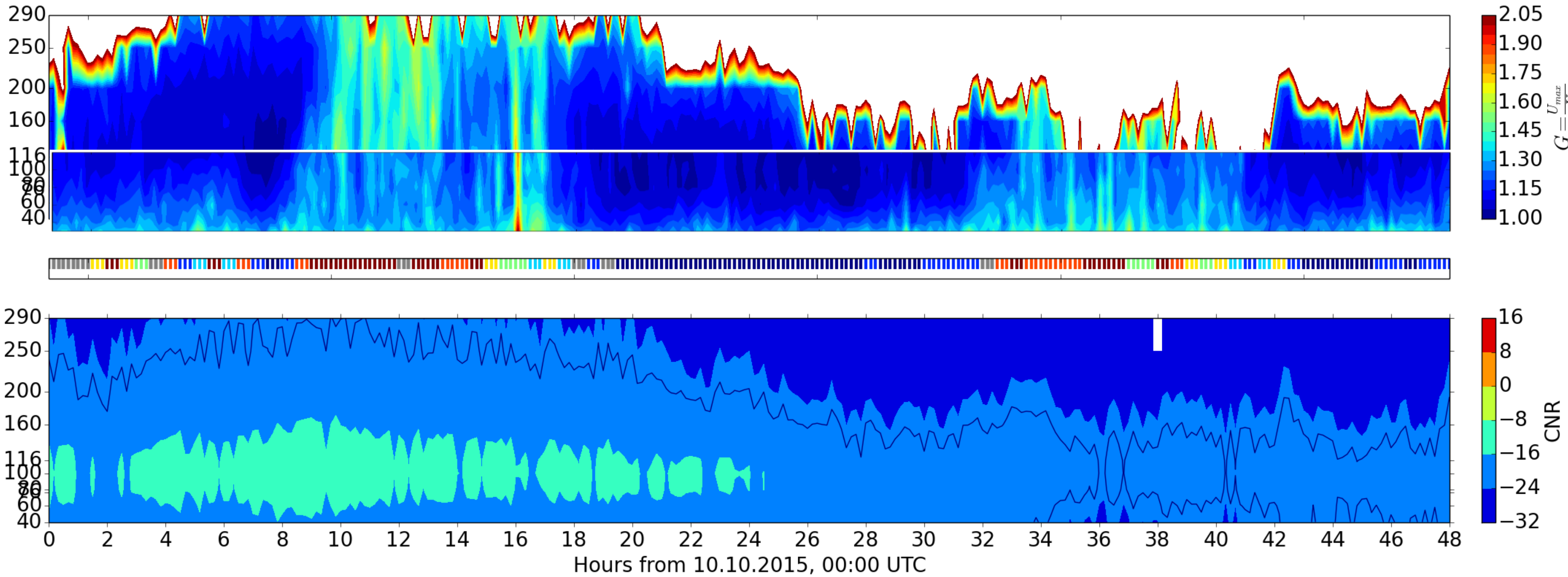


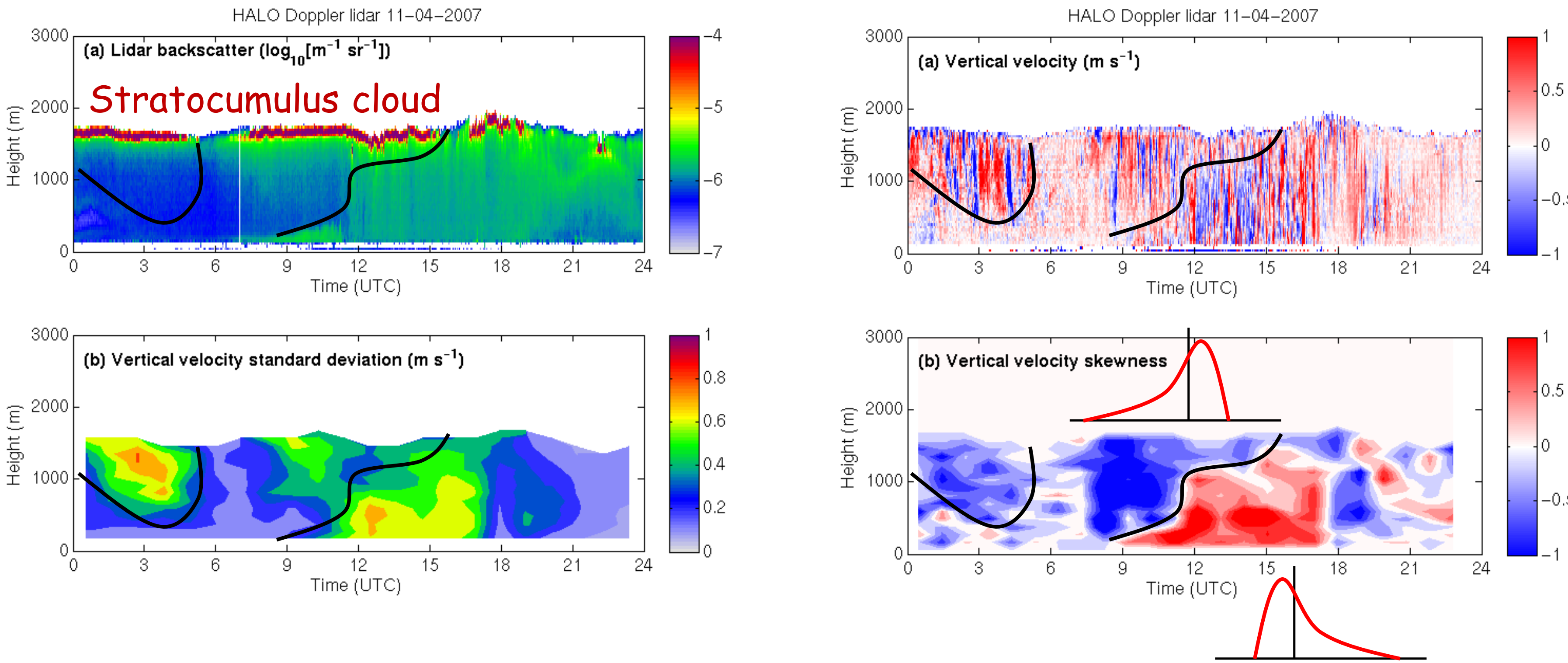
Sonic anemometers on mast at Høvsøre, Denmark



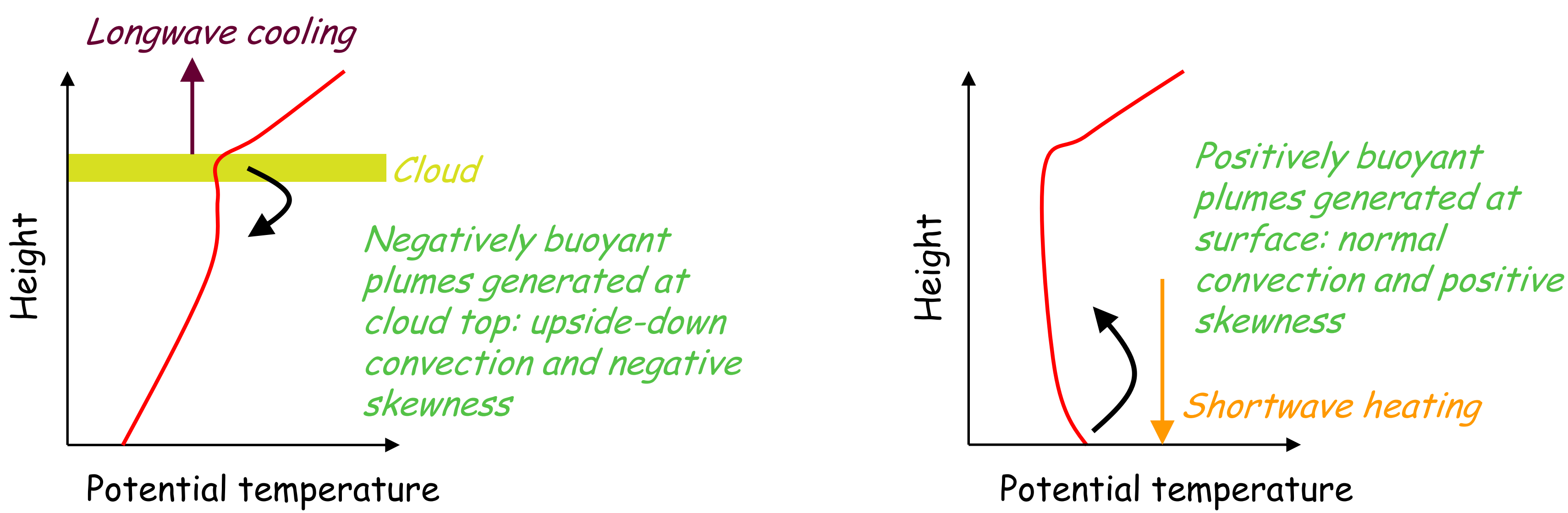
U_{max} [ms^{-1}]
U [ms^{-1}]
$G = \frac{U_{max}}{U}$
CNR
290
250
200
160
116
100
80
76
60
40
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
Hours from 10.10.2015, 00:00 UTC

Similar gust factors, including peak close to sunset





HALO Doppler lidar 11-04-2007
(a) Lidar backscatter (log_{10}[m^{-1} sr^{-1}])
Stratocumulus cloud
(b) Vertical velocity standard deviation (m s^{-1})
Height (m)
Time (UTC)
HALO Doppler lidar 11-04-2007
(a) Vertical velocity (m s^{-1})
(b) Vertical velocity skewness



Longwave cooling
Cloud
Height
Negatively buoyant plumes generated at cloud top: upside-down convection and negative skewness
Potential temperature
Height
Positively buoyant plumes generated at surface: normal convection and positive skewness
Shortwave heating
Potential temperature

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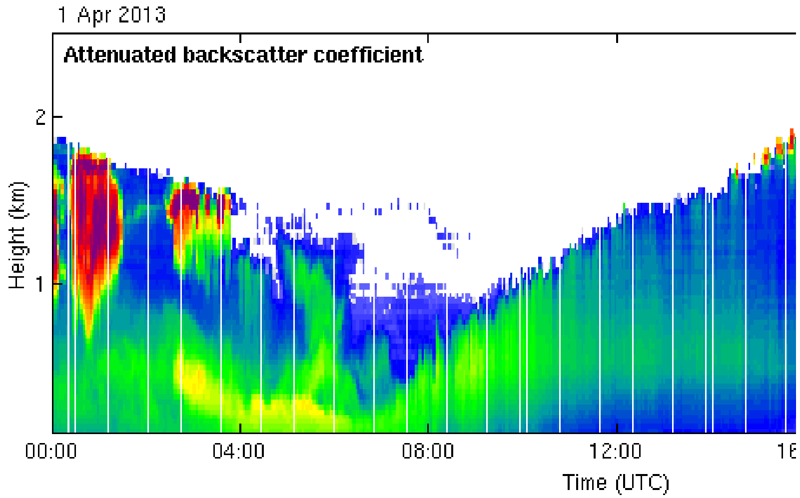

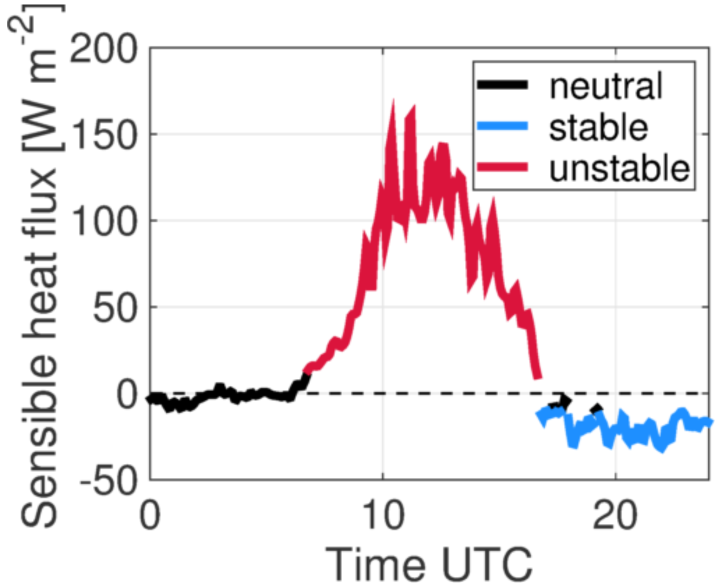

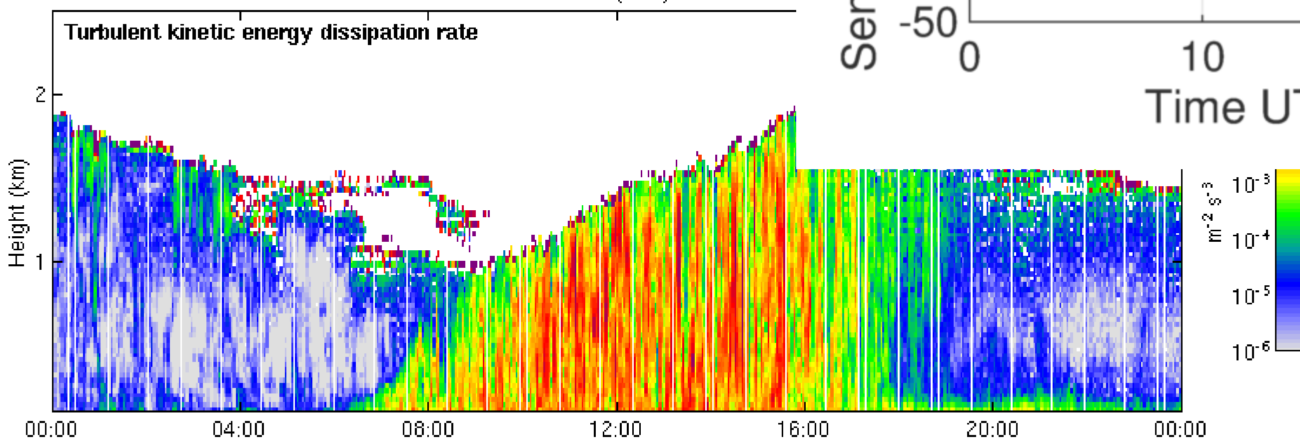

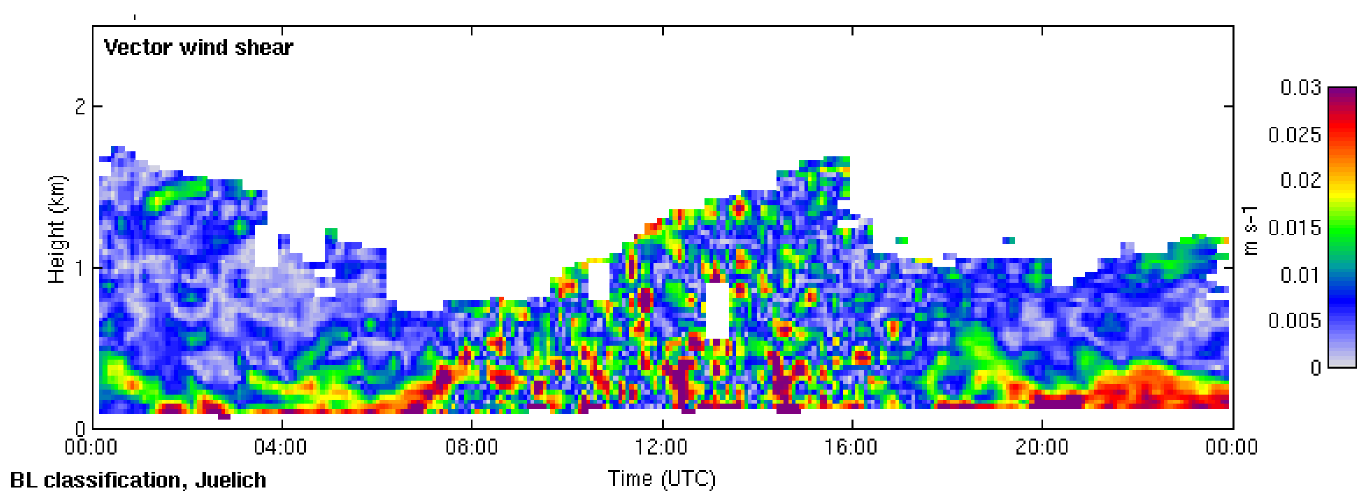

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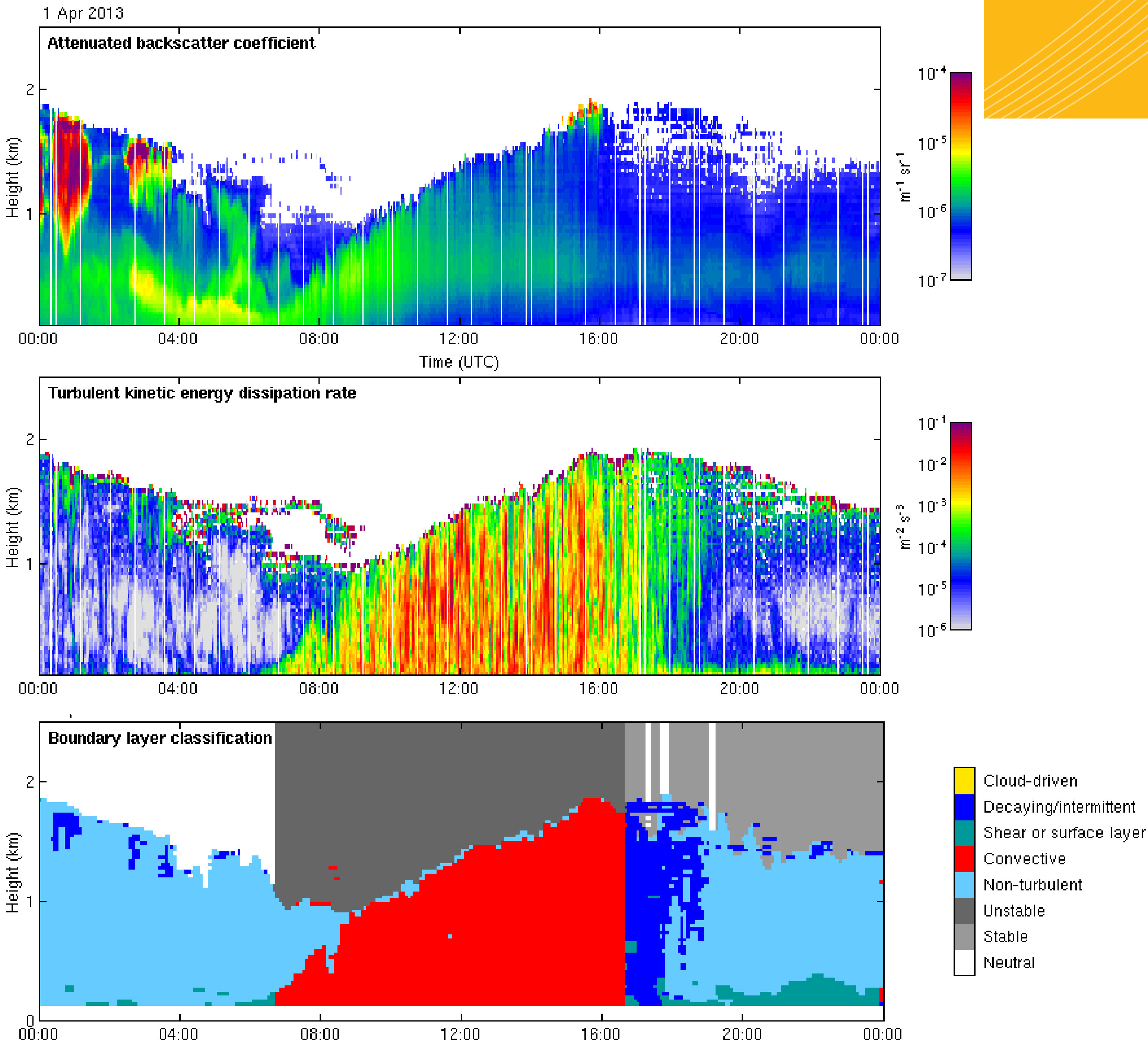
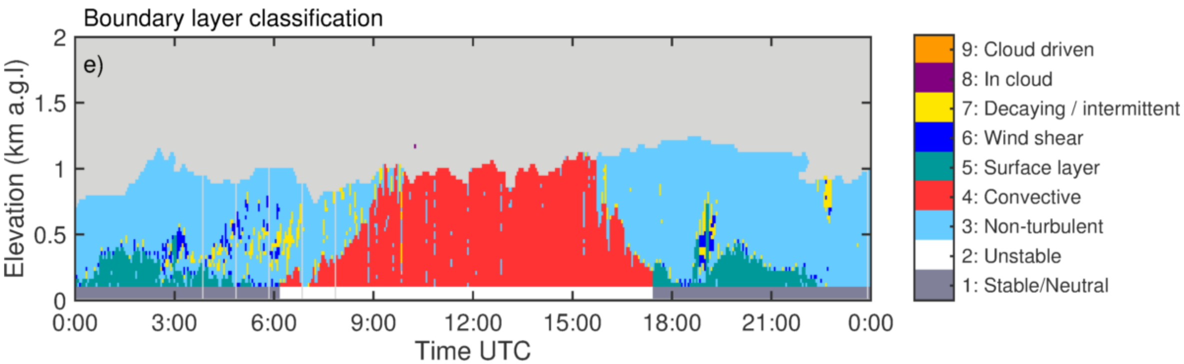
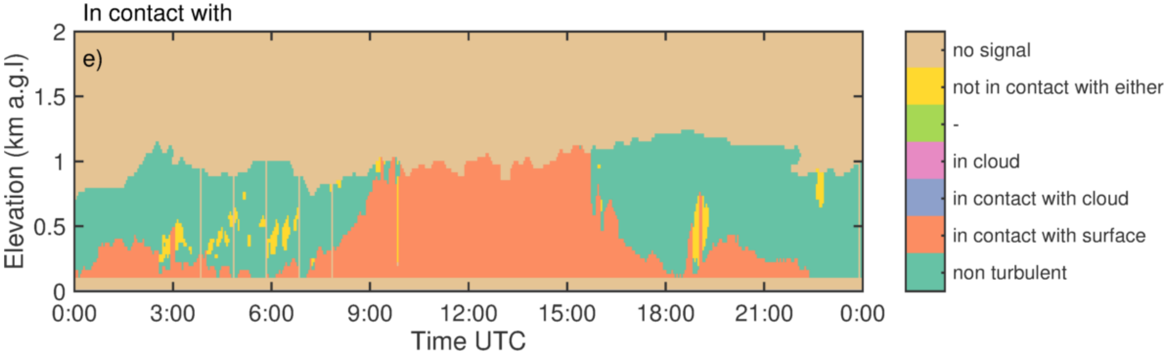
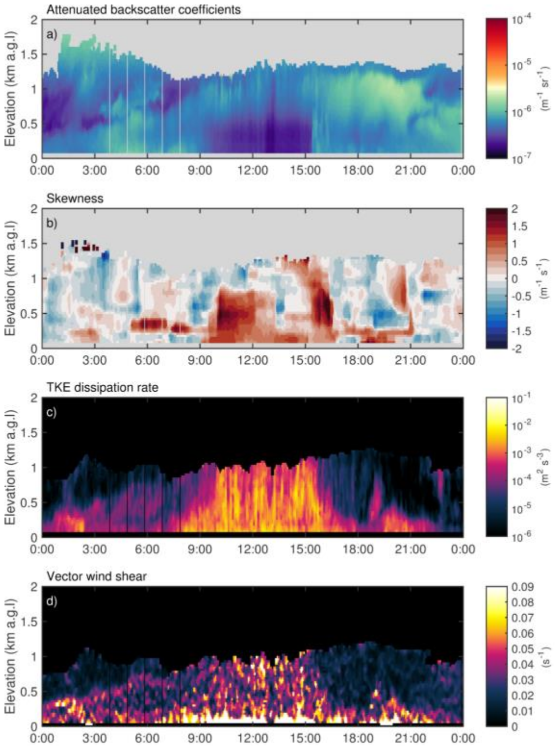


BL classification, Juelich

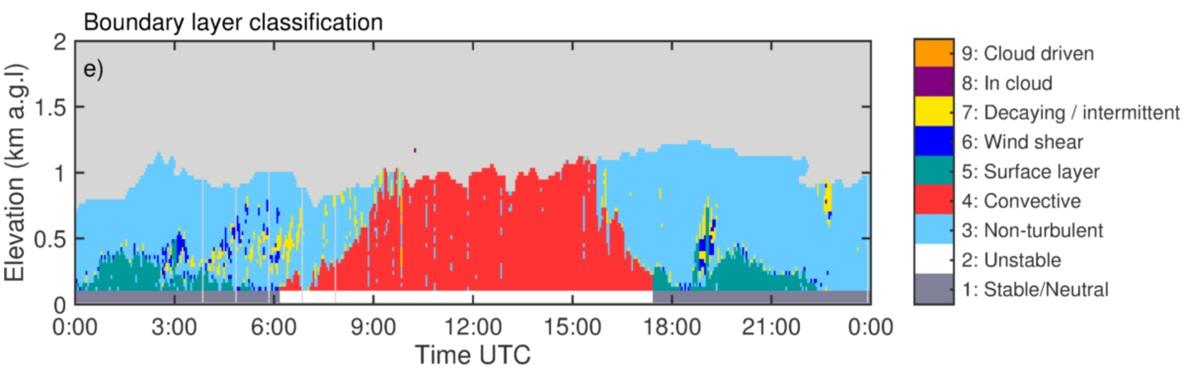
2016-3-9, Jülich, Germany clear sky case

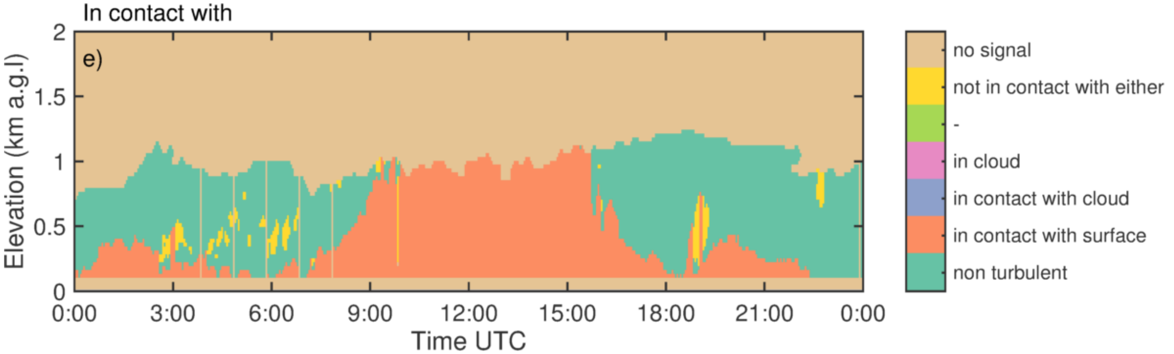


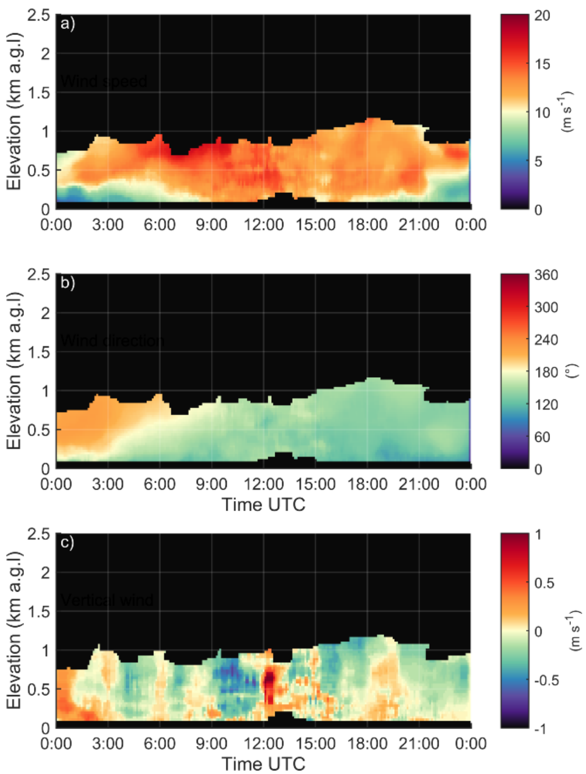




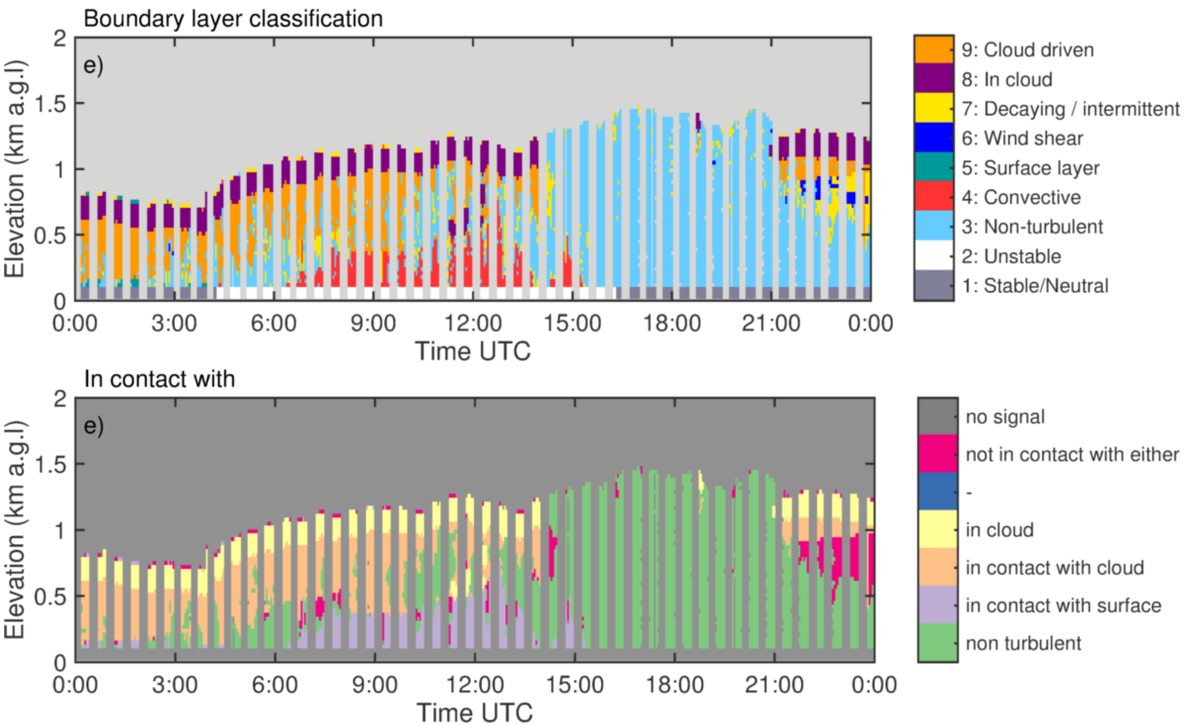
2016-3-9, Jülich, Germany clear sky case

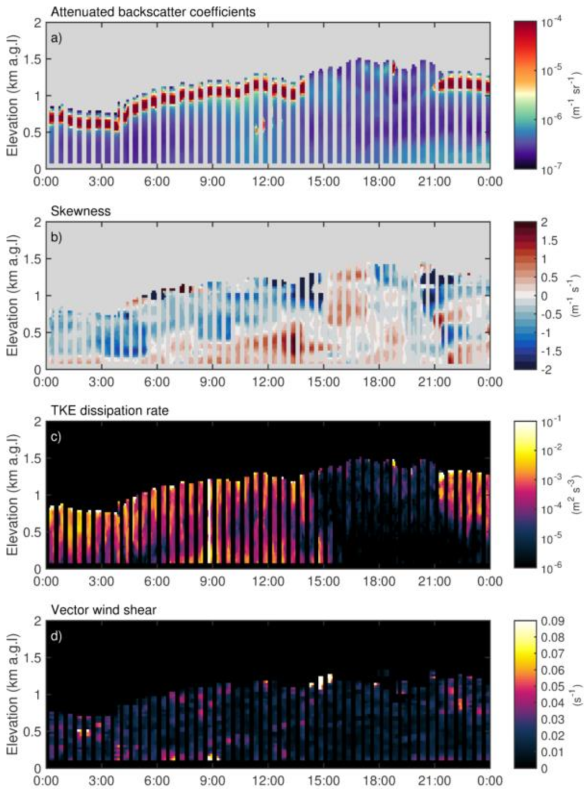






2016-9-22, Hyytiälä, Finland cloud-topped





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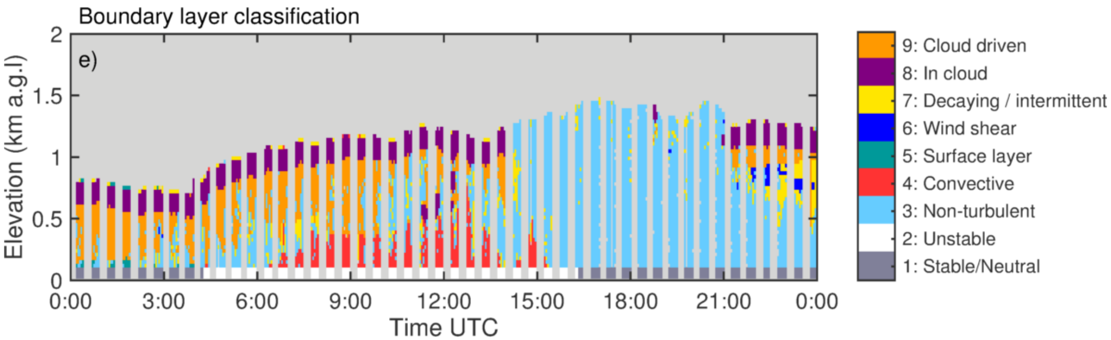
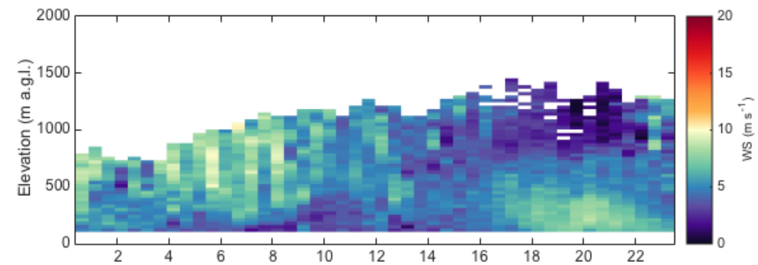
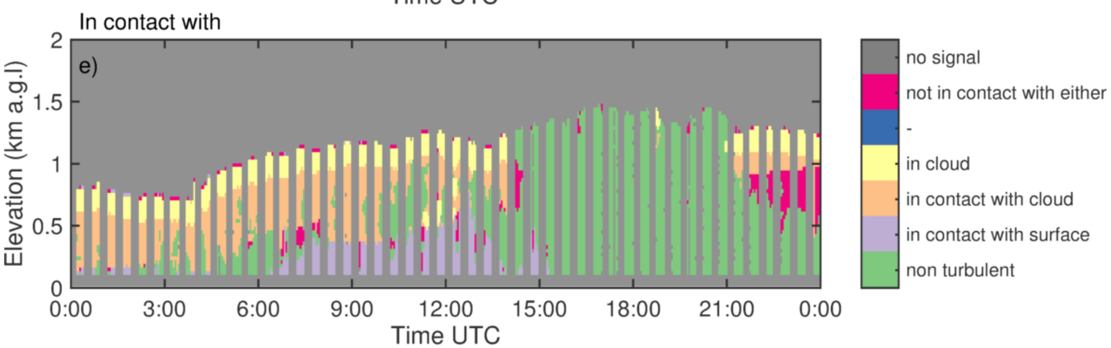
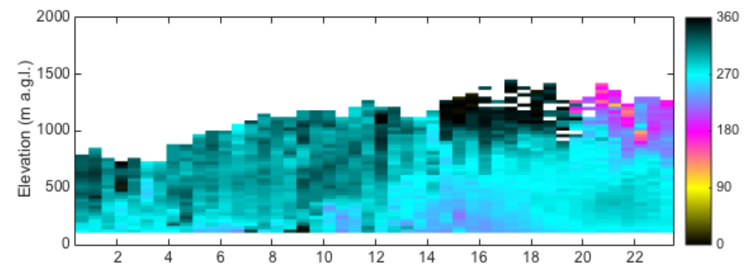
2016-9-22, Hyytiälä, Finland cloud-topped

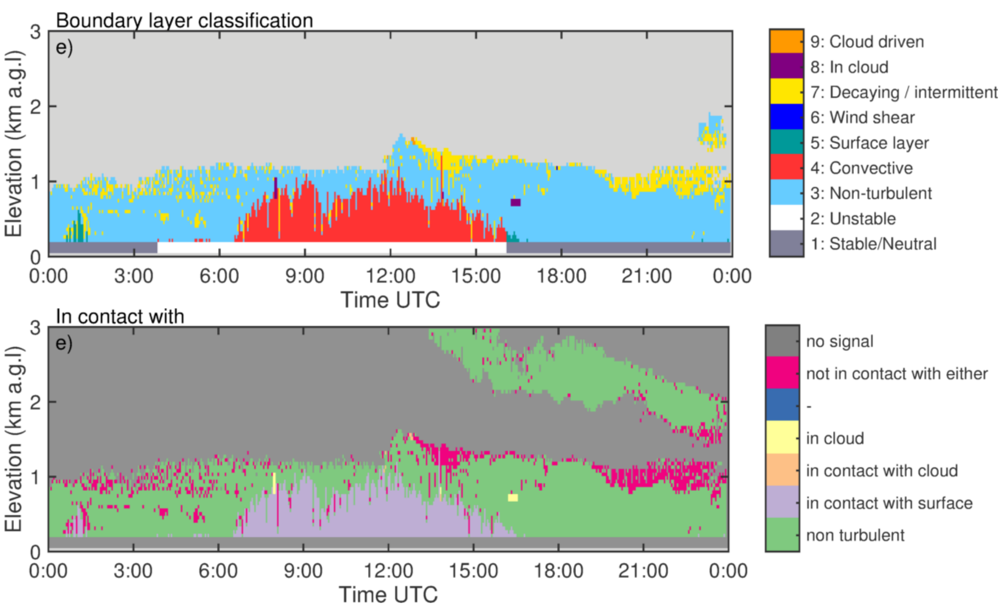


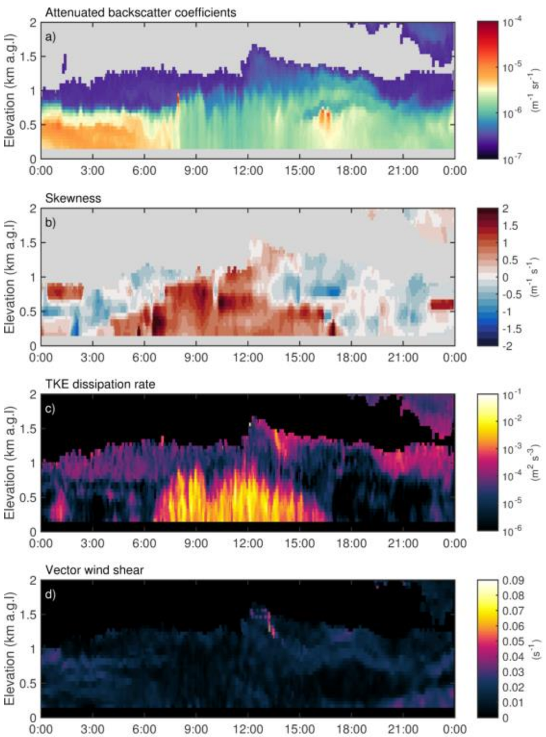




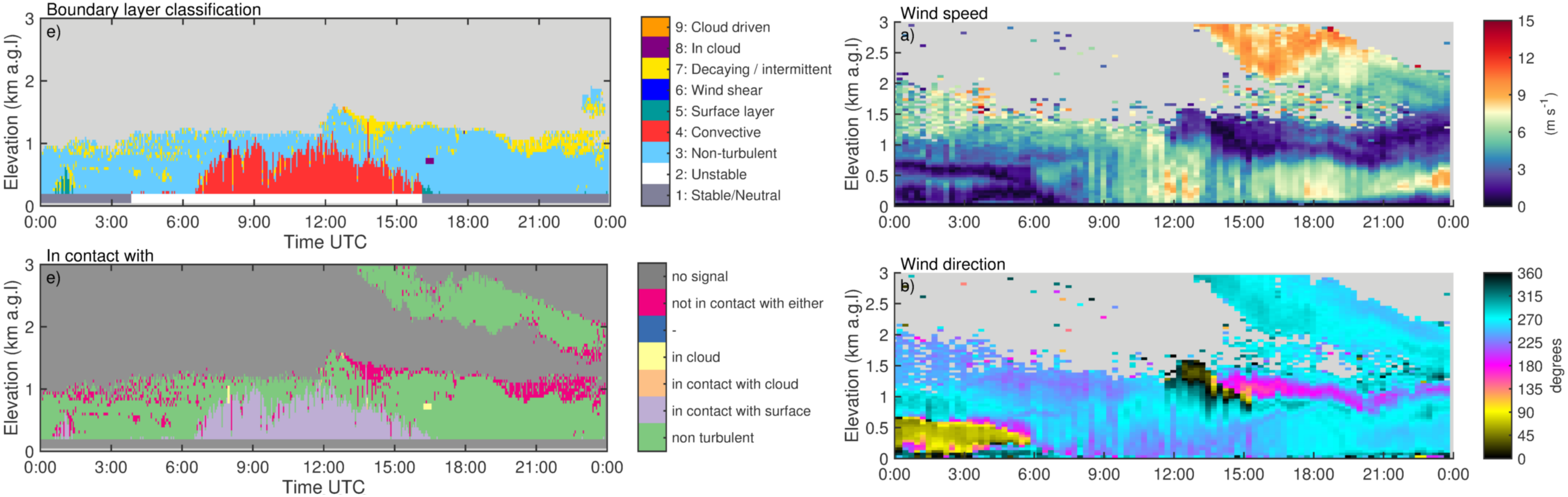


27 March 2017, Limassol Cyprus, cloud free

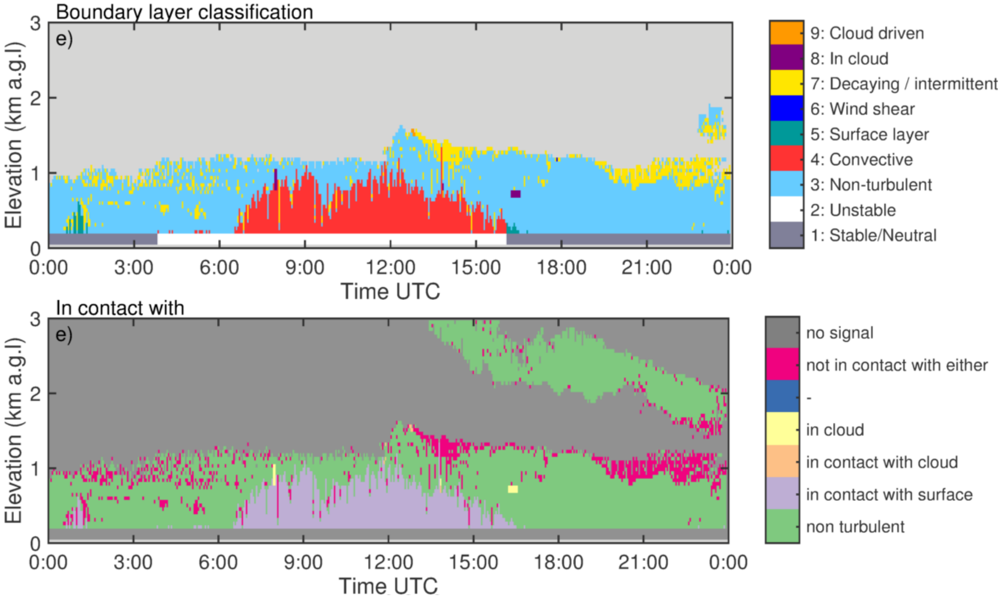


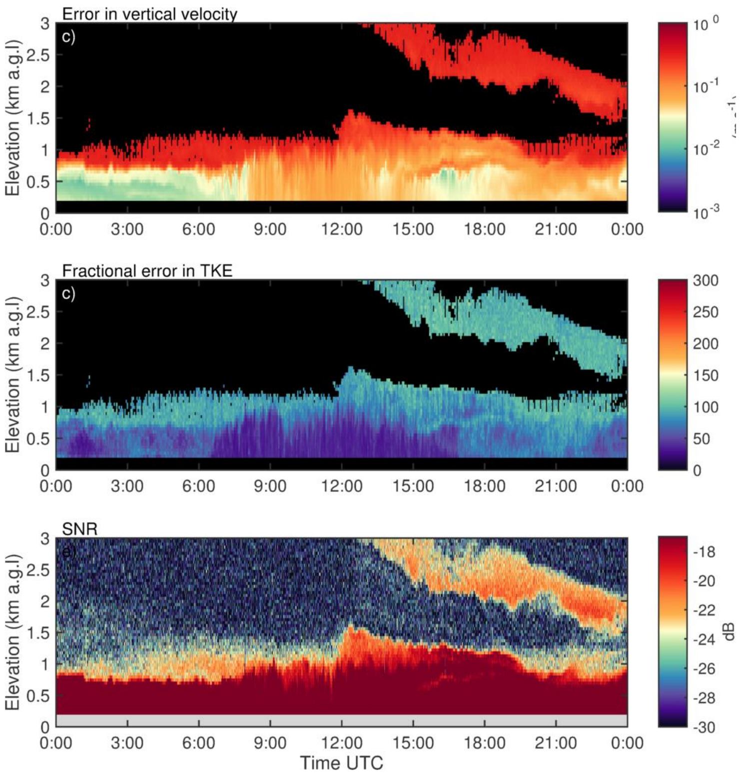


27 March 2017, Limassol Cyprus, cloud free



27 March 2017, Limassol Cyprus, cloud free





Network

- **Currently research-orientated**
  - Scanning strategies determined by research requirements
    - Account for instruments operating with different specifications, environments and operating requirements
  - Realtime data available from certain sites
  - More sites can provide datasets for verification

- **Selected sites are ready to send wind data to E-Profile hub**

- **Many potential applications**

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Network

Operational

Campaigns

Future operational

Outlook

- **Harmonised consistent retrievals across Europe providing high resolution:**
  - Horizontal wind profiles in the BL
  - Turbulent properties including gusts
  - BL description together with source of turbulence
- **All retrievals include uncertainties**
- **Suitable for forecasters, assimilation, verification, and process studies**