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CCRES Training School
Doppler lidar
(and Doppler radar winds)

CCRES Training School, September, 2025

Motivation

- We want the vertical profile of horizontal wind
  - High resolution (time and vertical)

Motivation

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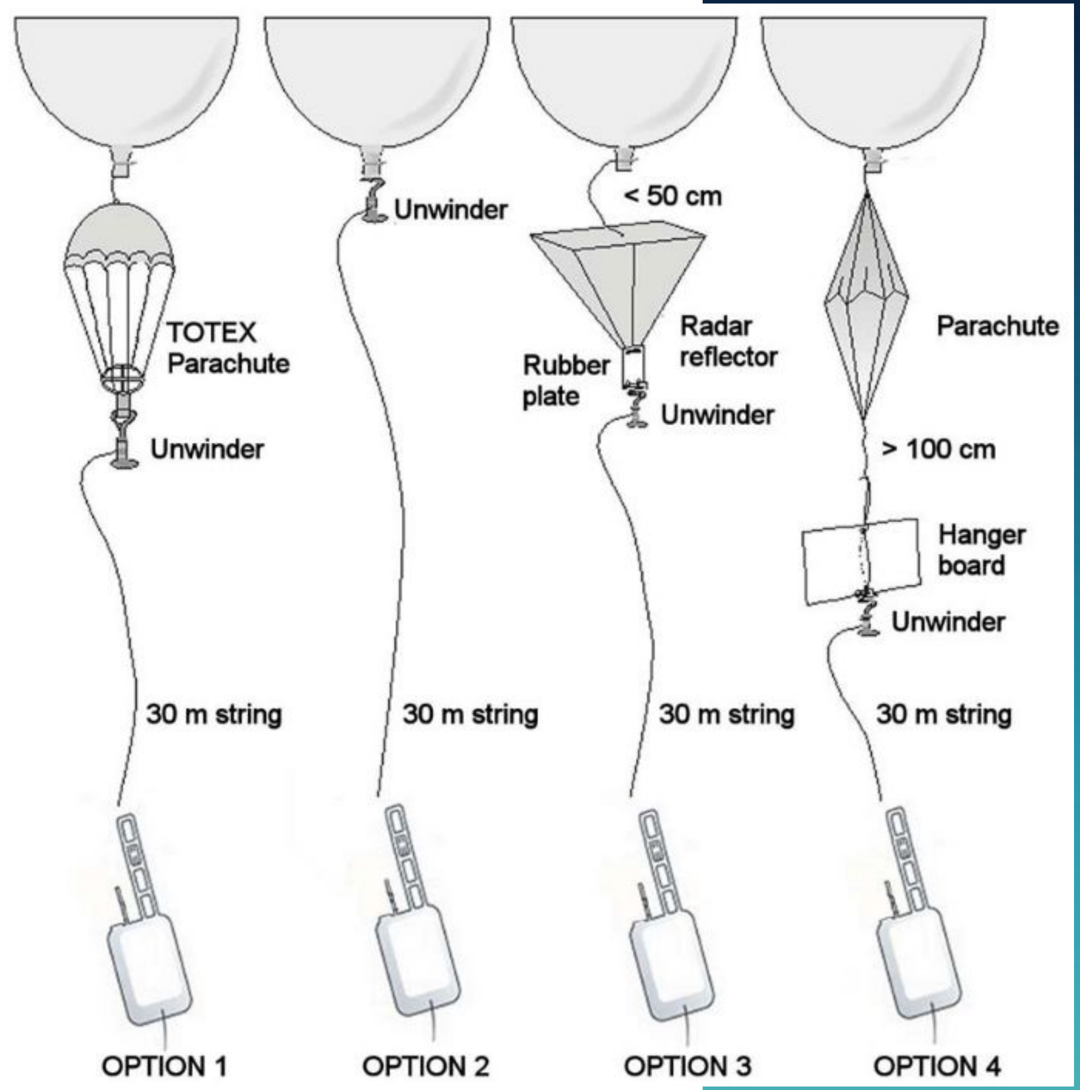
- We want the vertical profile of horizontal wind
  - High resolution (time and vertical)

- How can we obtain the wind profile?

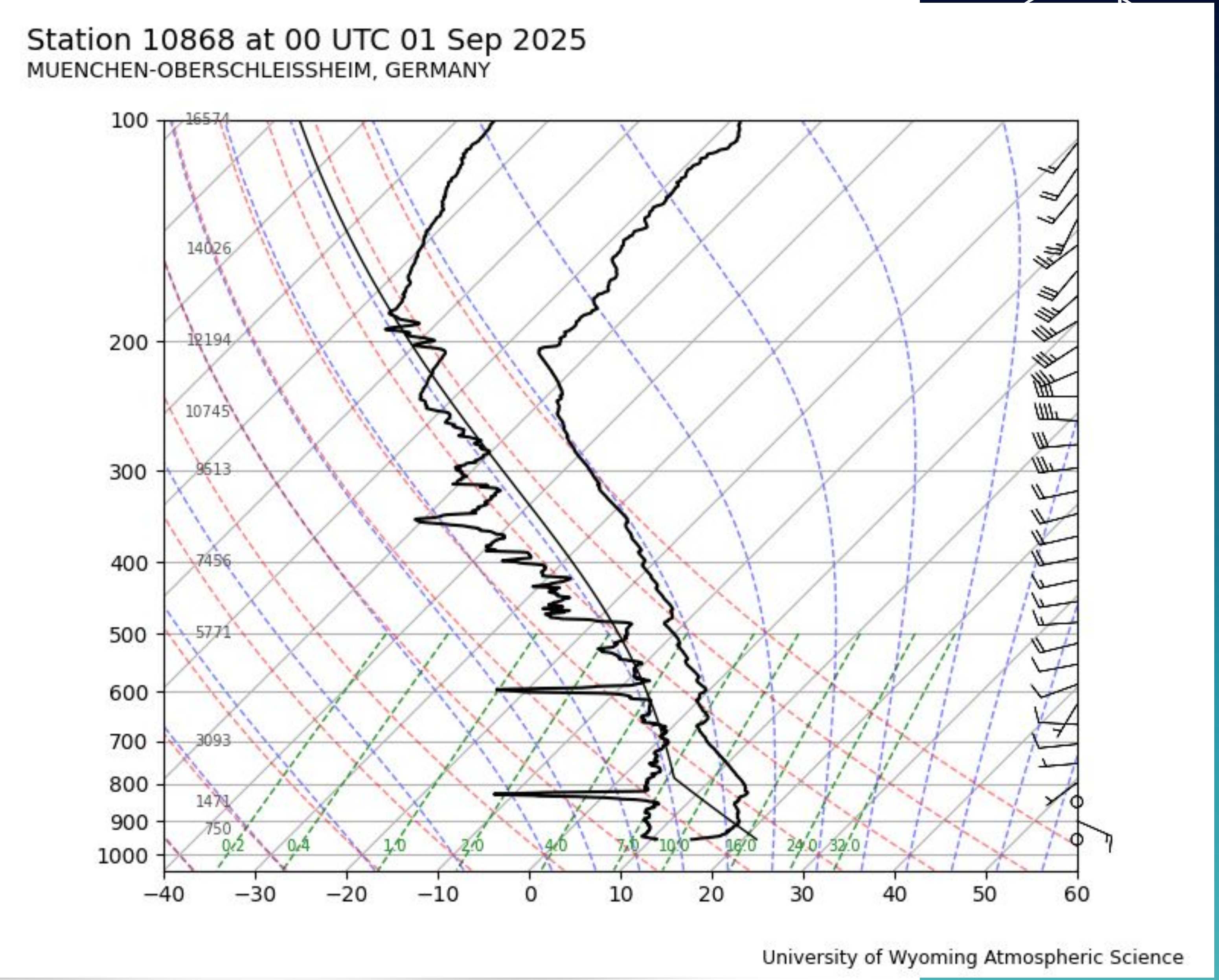
- Doppler lidar
  - Instrument and basic theory
- Measuring wind
  - Scanning methods
- Measuring turbulence

- Practical applications

Wind profile from radiosonde



Wind profile from radiosonde



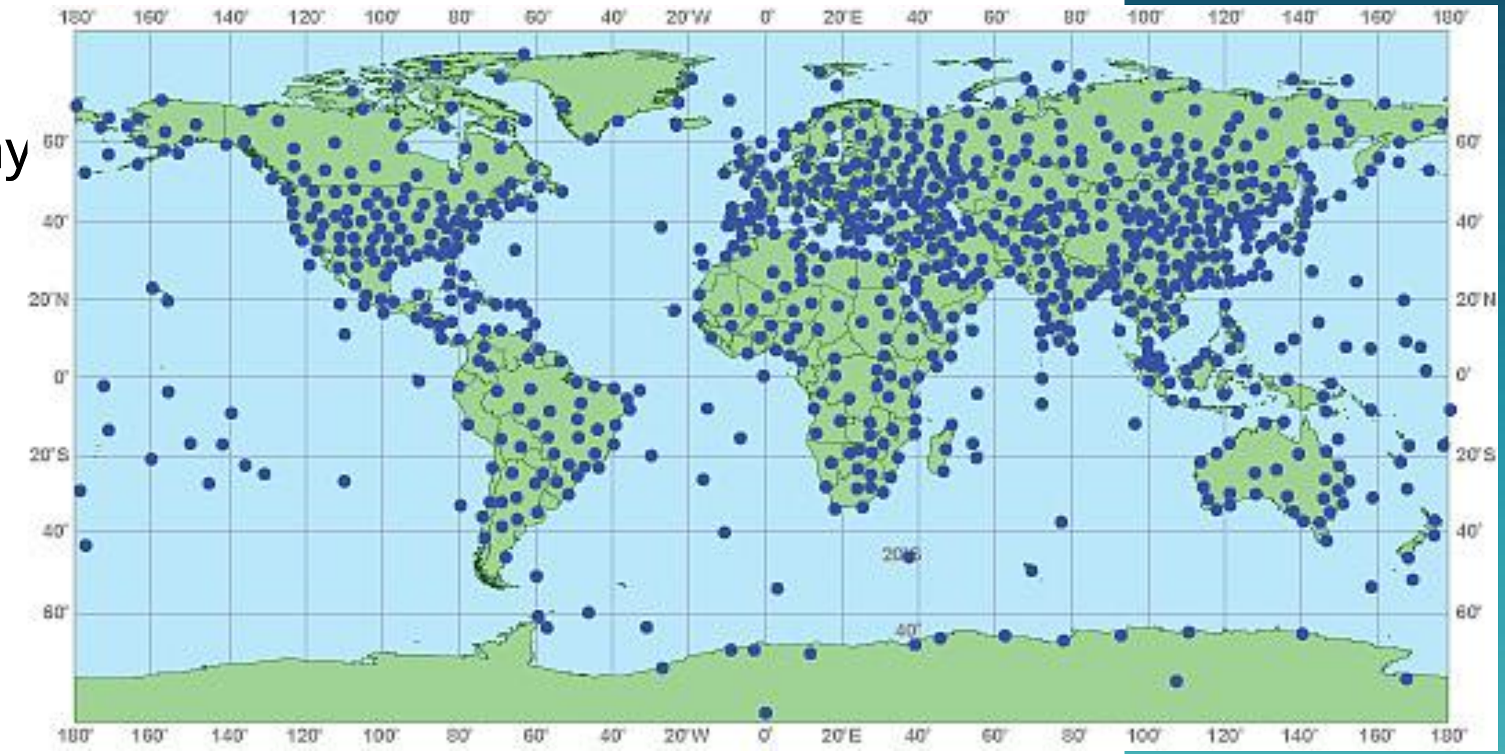
Wind profile from radiosonde

- In situ measurement

- Expensive!
  - Need helium (or hydrogen if allowed)
  - Single use

- Only 1 or 2 profiles (launches) a day from most stations

- Still a very valuable resource
  - Reference standard
  - Assimilated by NWP



Remote Sensing methods

- **Doppler radar**
  - Weather radar
  - Wind profiler
  - MST (mesosphere – stratosphere)

- **Sodar**

- **Doppler lidar**
  - Direct detection
  - Coherent detection

Weather radar

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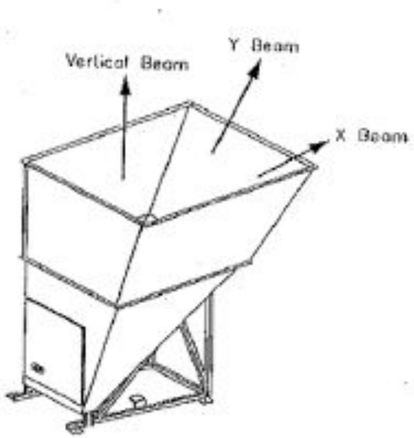
Radar Wind Profiler

Figure 1: Aerial view of the 482 MHz radar wind profiler site at the Meteorologisches Observatorium Lindenberg. The HALO Photonics Streamline lidar is visible in the foreground.

Sodar



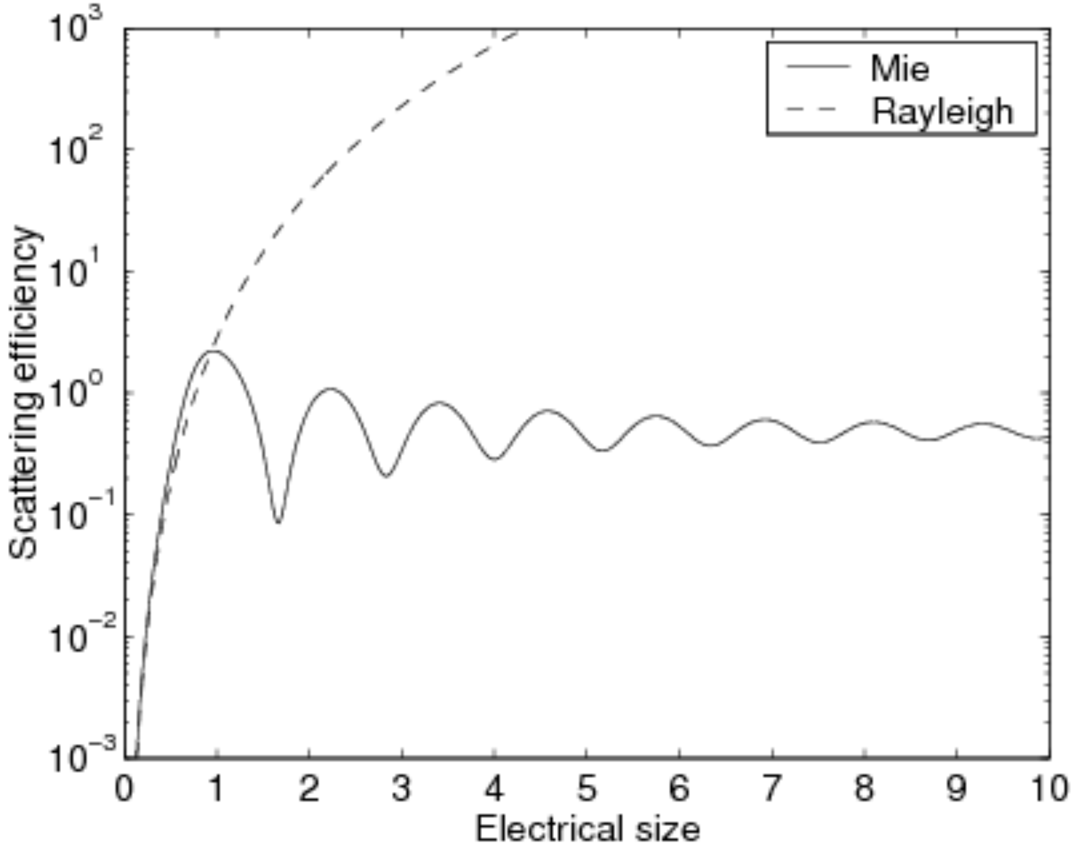
Doppler lidar

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

Scattering properties

- Rayleigh or Mie
  - Depends on particle size vs transmitted wavelength
- Scattering properties of atmospheric particles
  - Aerosol, Cloud droplets, Ice, Rain
- Terminal fall velocity
  - Depends on particle size and density

Scattering properties

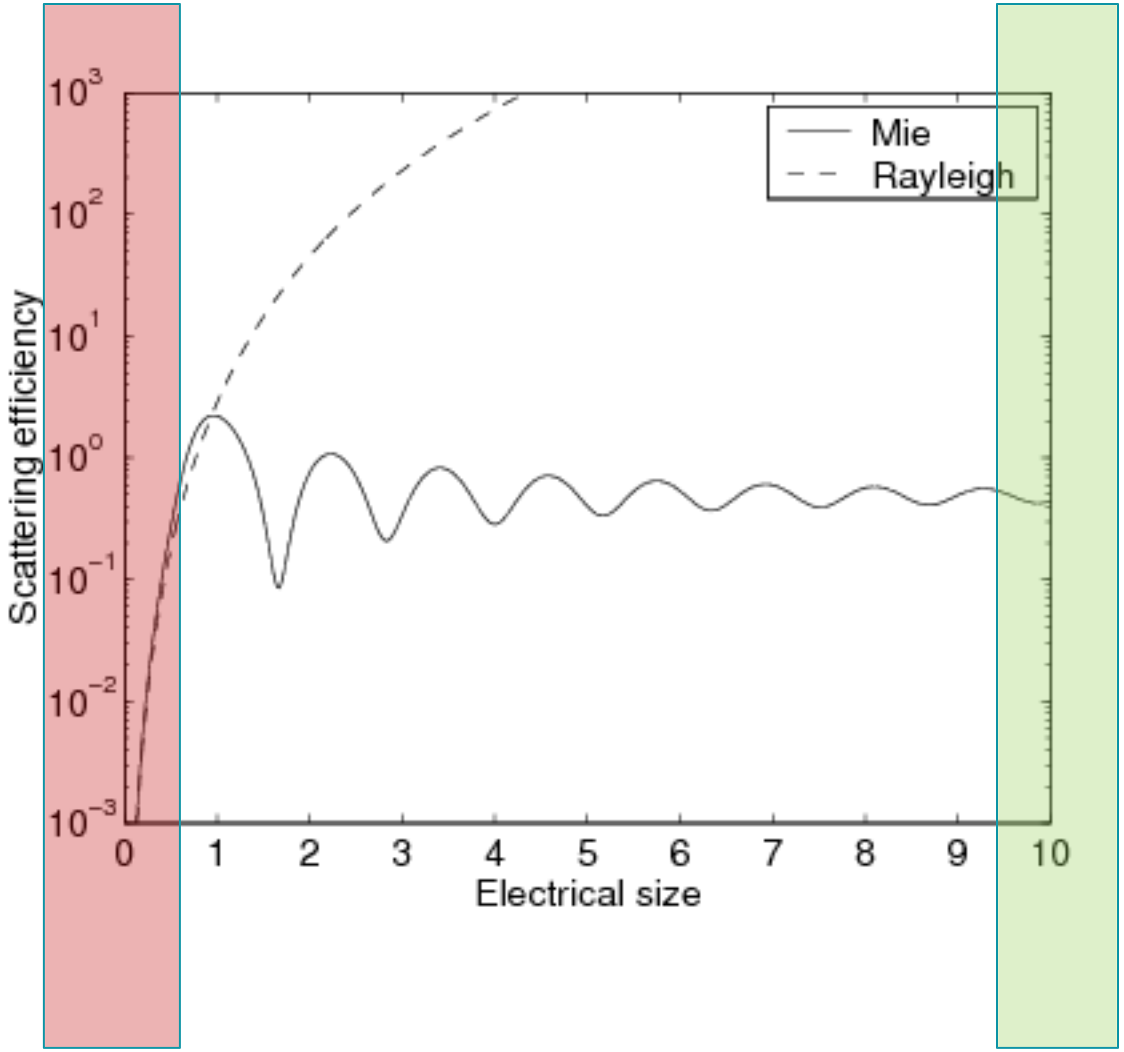


Electrical size = 2πr / λ

Radar: λ=1e-2 m

Lidar: λ=1e-6 m

Scattering properties



Electrical size = 2πr / λ

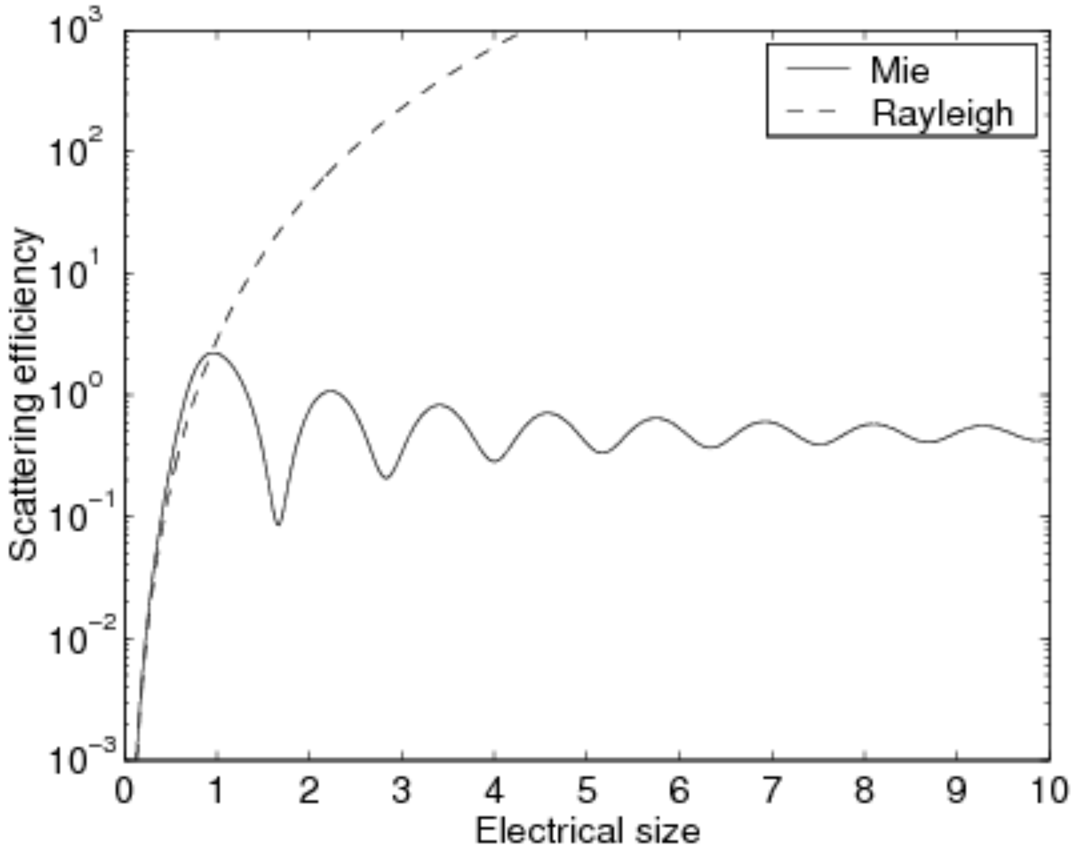
Lidar: λ=1e-6 m

Aerosol: r~5e-7 m

Cloud: r~5e-6 m

Drizzle: r~2e-4 m

Scattering properties (Mie)



extinction

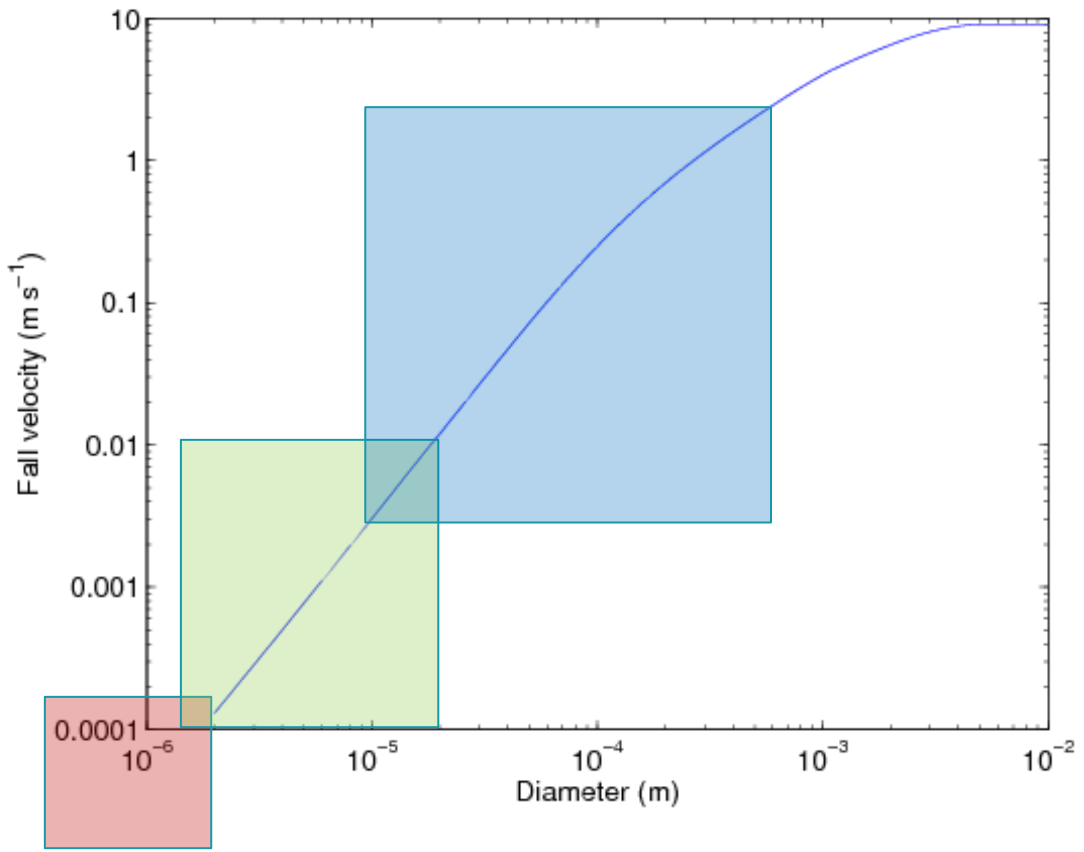
$$\alpha = \frac{\pi}{2} \int_0^\infty n(D)\, D^2\, dD$$

backscatt
er

$$\alpha = S\beta,$$

$$\beta'(z) = \beta(z) \exp\left(-2 \int_0^z \alpha(z')\, dz'\right).$$

Terminal fall velocity (Beard et al., 1976)



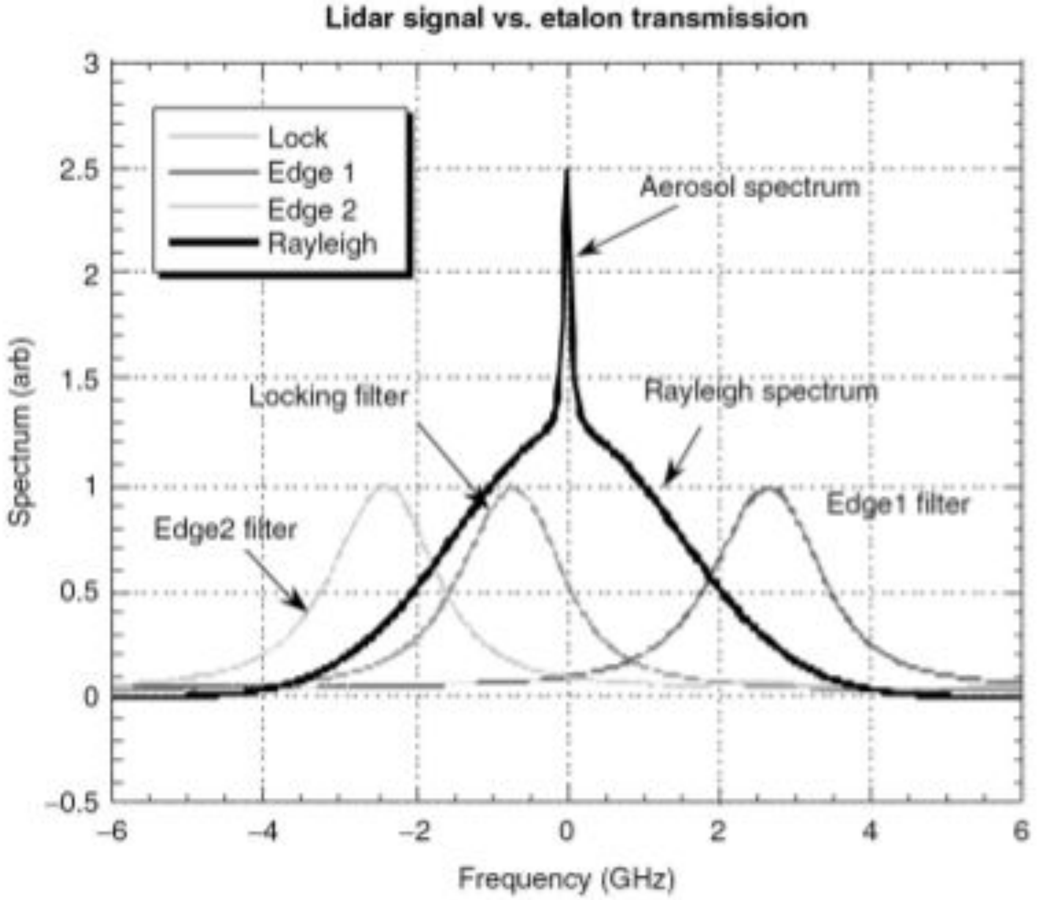
For water spheres

Fall speed varies slightly with pressure and temperature

Aerosol:	r~5e-7 m
Cloud:	r~5e-6 m
Drizzle:	r~2e-4 m

Direct Detection Doppler lidar

- **Doppler lidar**
  - Direct detection
    - Resonance
    - Rayleigh-Mie filter

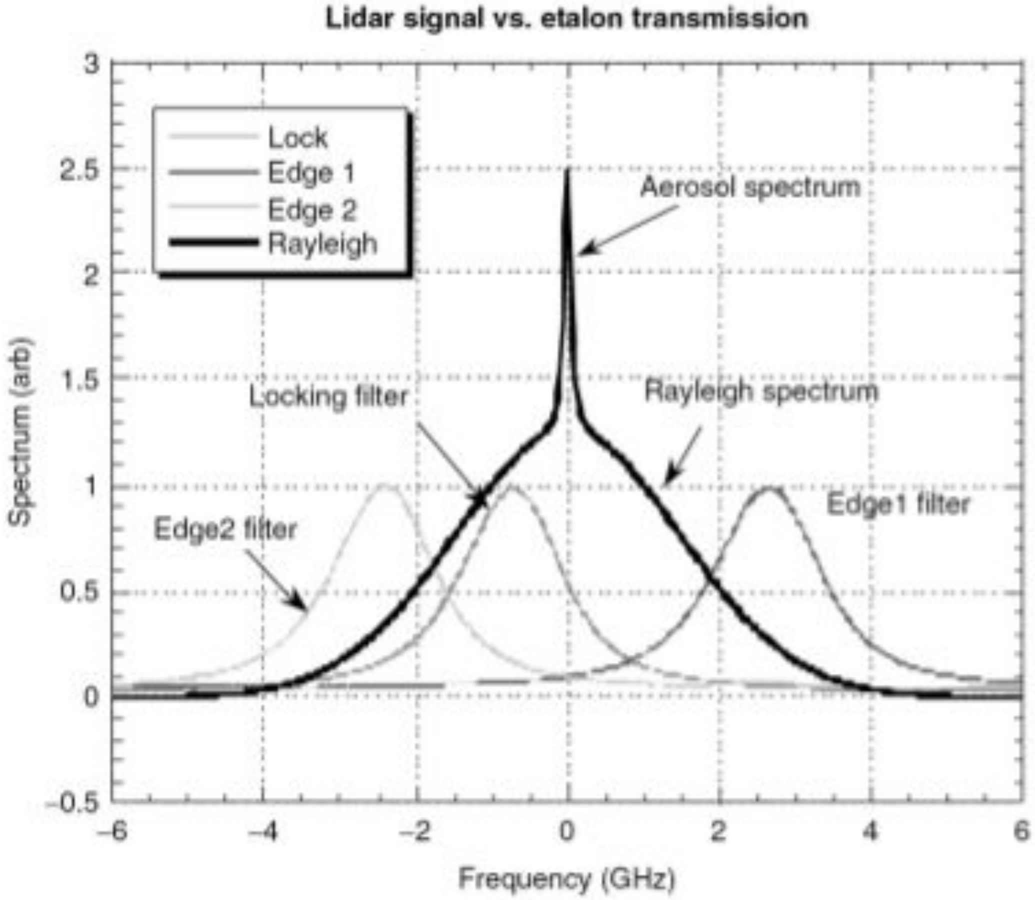


Direct Detection Doppler lidar

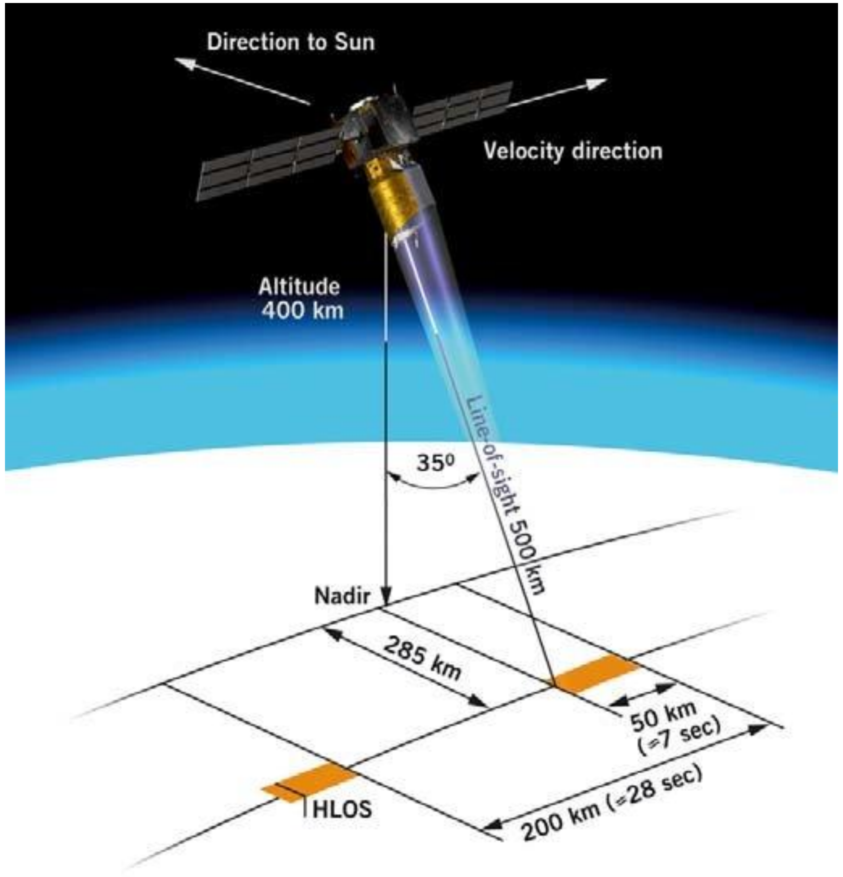
- **Doppler lidar**
  - Direct detection
    - Resonance
    - Rayleigh-Mie filter

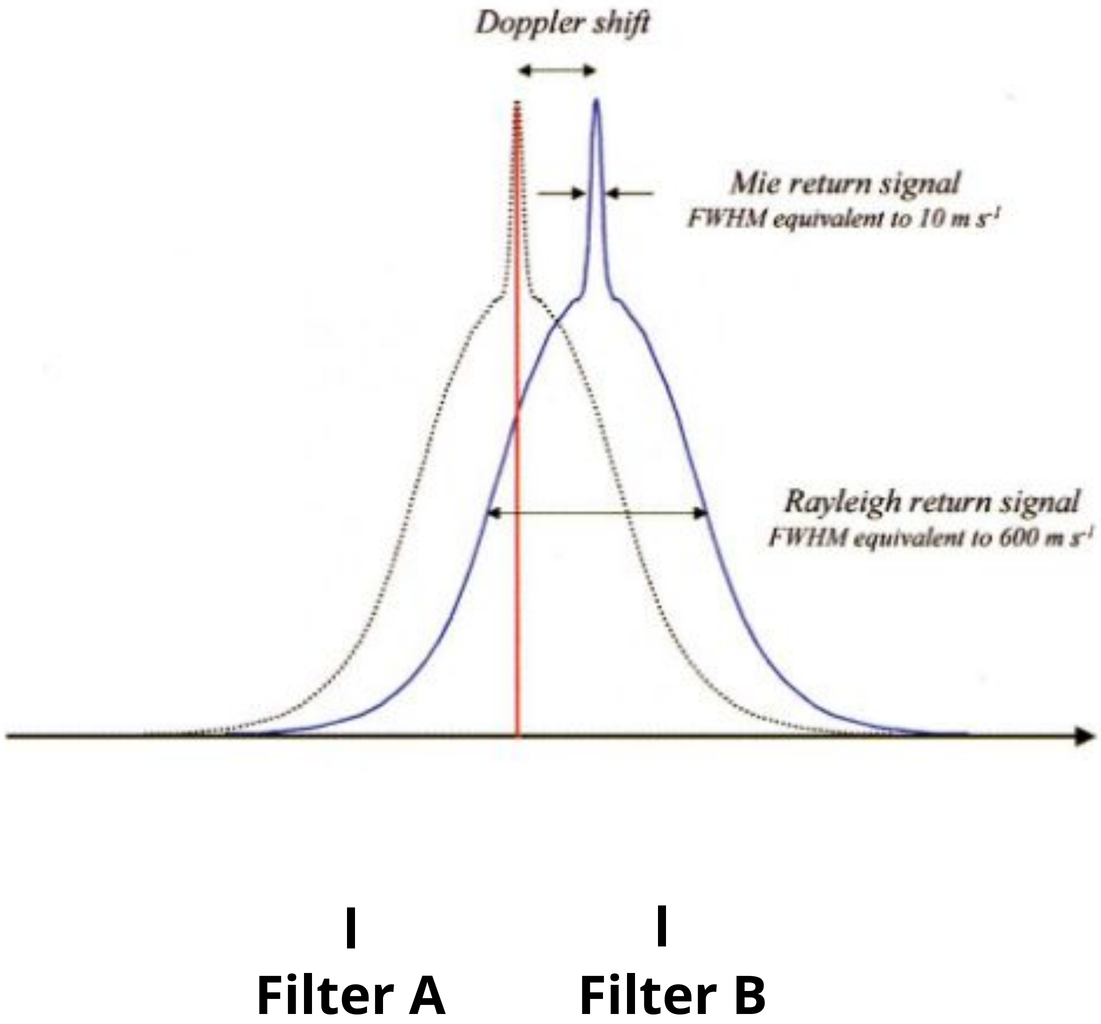
Double edge filter

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

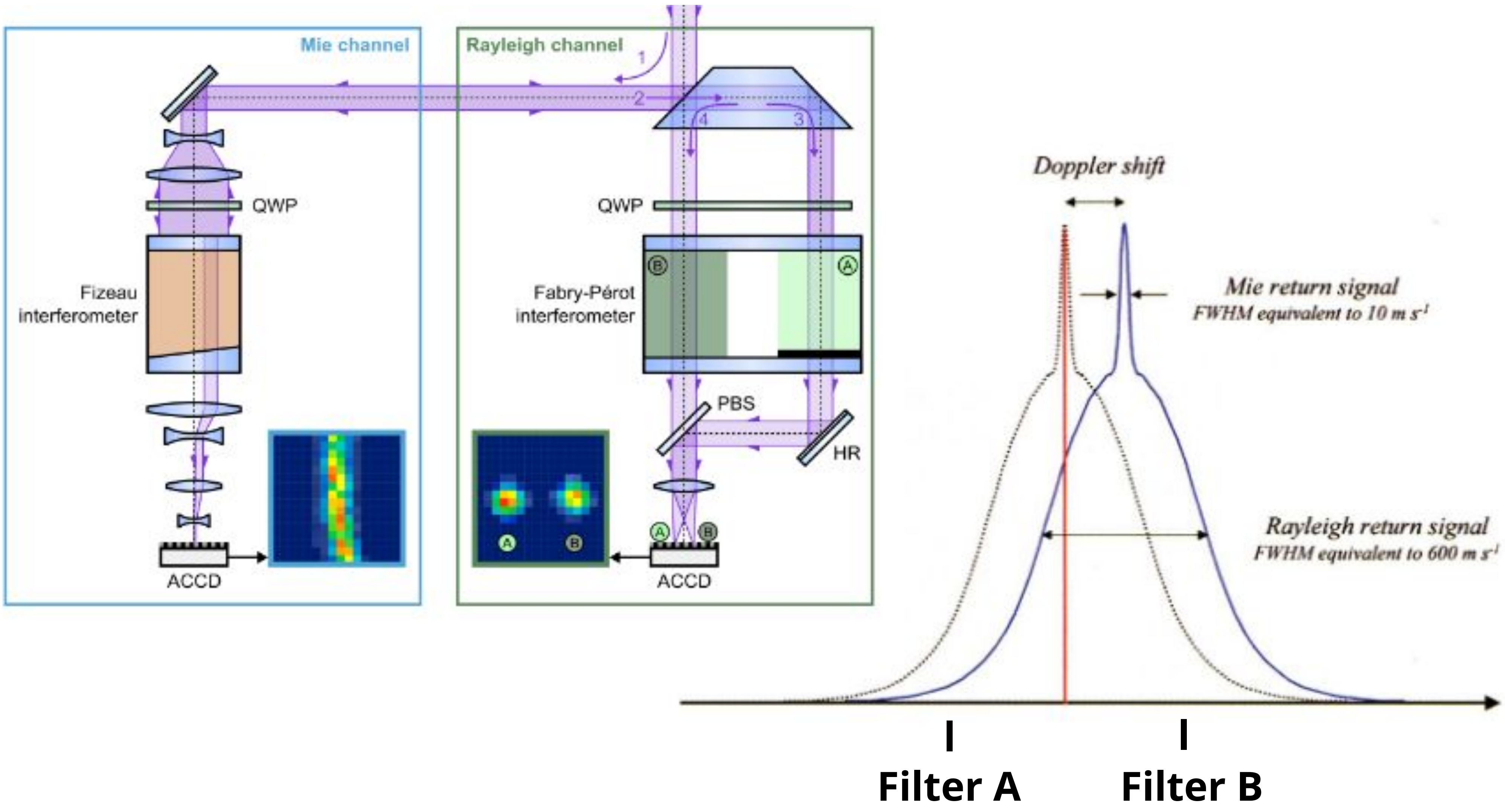


AEOLUS satellite

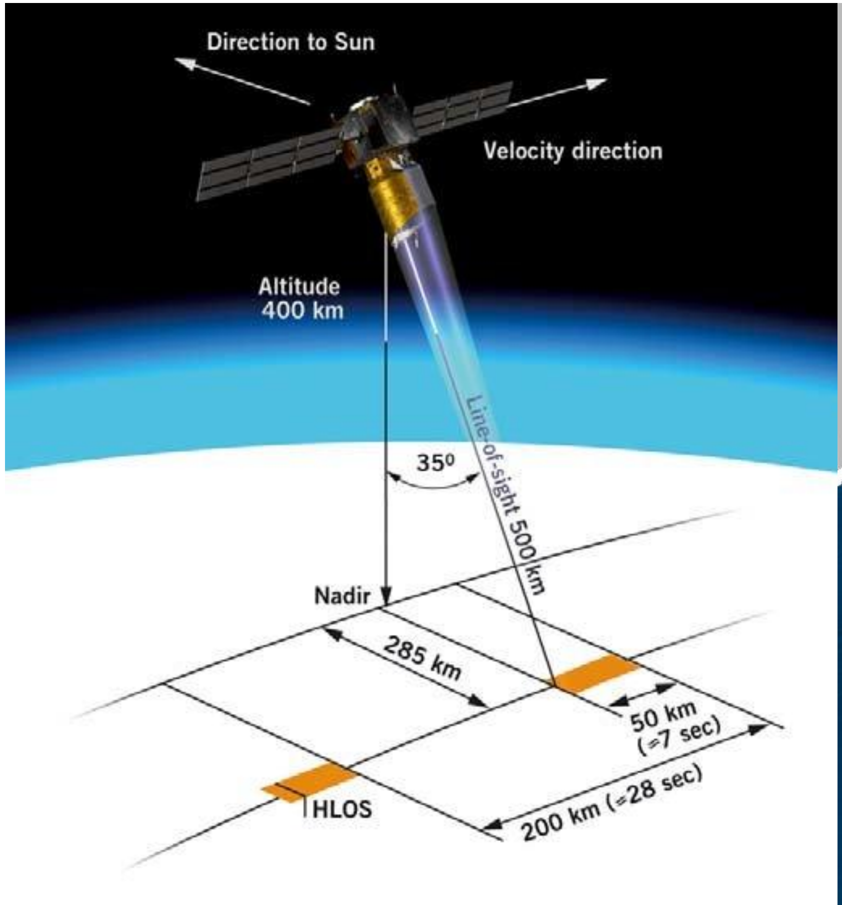


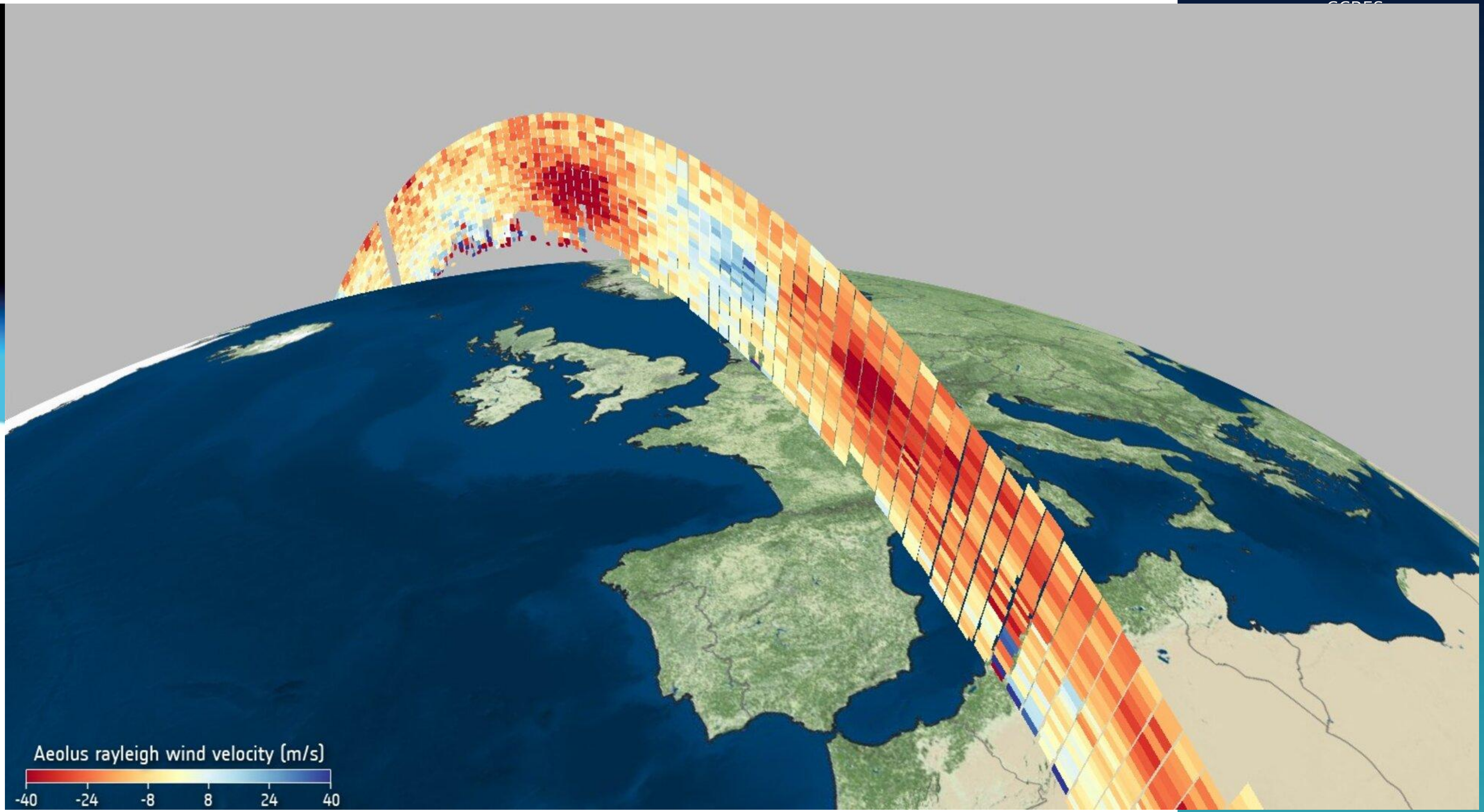


AEOLUS satellite



AEOLUS satellite





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

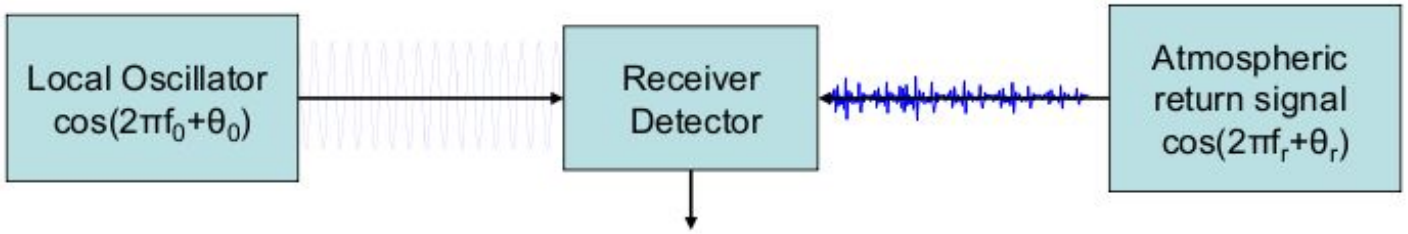
$$f_a = f_{Dopp} + f_{offset} + f_{LO}$$

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:

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

$$= A_a^2 |\cos(j2\pi f_a t + \varphi_a)|^2 + A_{LO}^2 |\cos(j2\pi f_{LO} t + \varphi_{LO})|^2$$

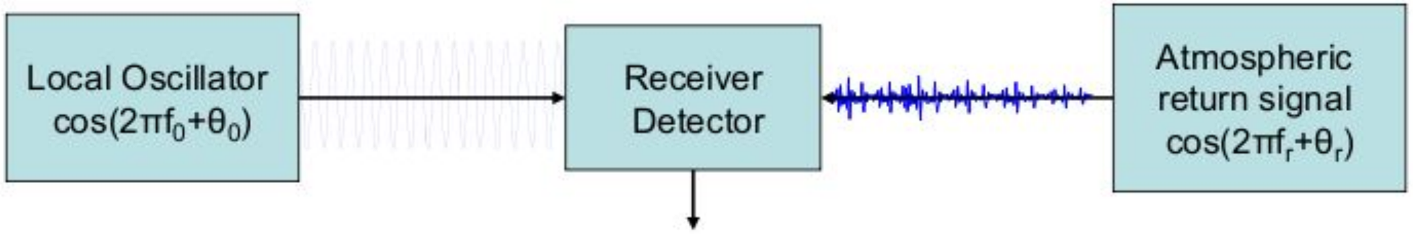
$$+ 2A_a A_{LO} \cos(j2\pi f_a t + \varphi_a)\cos(j2\pi f_{LO} t + \varphi_{LO})$$

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

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

$$+ 2A_a A_{LO} \cos(j2\pi (f_a + f_{LO})t + (\varphi_a + \varphi_{LO}))$$

$$+ 2A_a A_{LO} \cos(j2\pi (f_a - f_{LO})t + (\varphi_a - \varphi_{LO}))$$

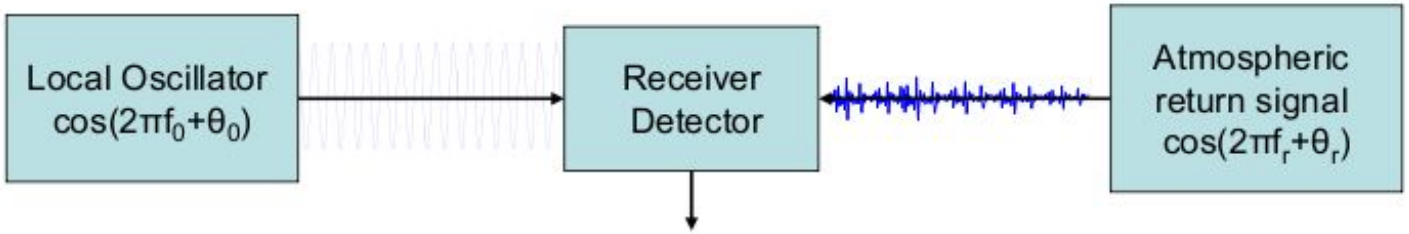


Coherent detection

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:

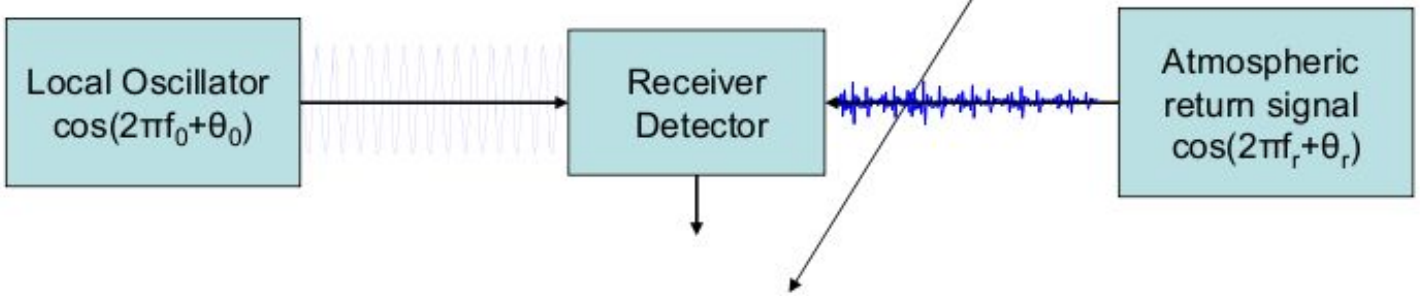


$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

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 $f_a - f_{LO} = f_{Dopp} + f_{offset}$ ~ Mhz

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

Doppler lidar uncertainty

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

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

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 uncertainty

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

Heterodyne detection

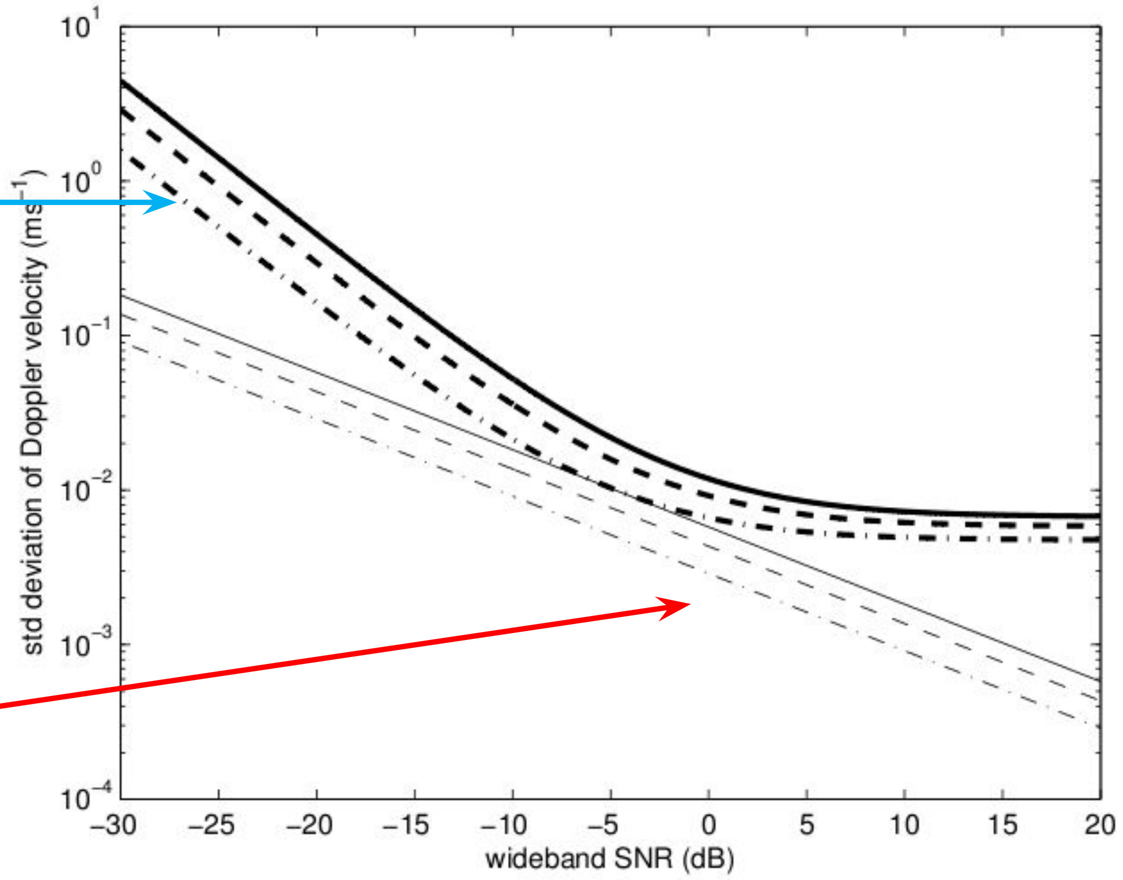
Lines indicate choice of

Δv

(signal spectral width)

Direct detection

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




WindTracer


WindTracer


HALO Photonics


WINDCUBE
200s

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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

Network

- Inhomogeneous network
  - Different instruments
  - Research instruments at many locations

- Must account for instruments operating:
  - With different specifications
  - In different environments
  - With different operating requirements

Original signal

1 Cloud screening
1.1 2D variance-based cloud screening
1.2 Final cloud screening utilising Cook's distance
1.3 Calculation of the background shape and refilling

2 Step detection
2.1 Multilevel 1D stationary wavelet decomposition
2.2 Peak detection from the wavelet decomposition output

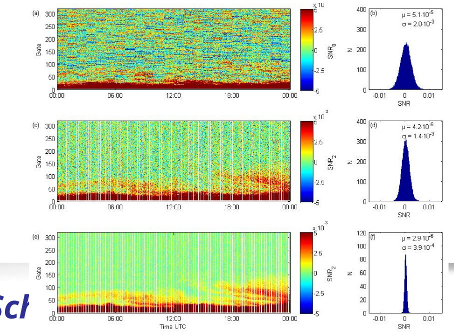
3 Correction of step changes and background shape
3.1 Calculation of the background shape of each step
3.2 Correction for the shape and amplitude of the background

4 Removal of possible remnant outlier profiles (optional)
4.1 Detection of outlier profiles from corrected background
4.2 Removal of the detected profiles

Background correction of signal

Recalculation of attenuated backscatter coefficients

Common processing toolbox for all systems



Scan types

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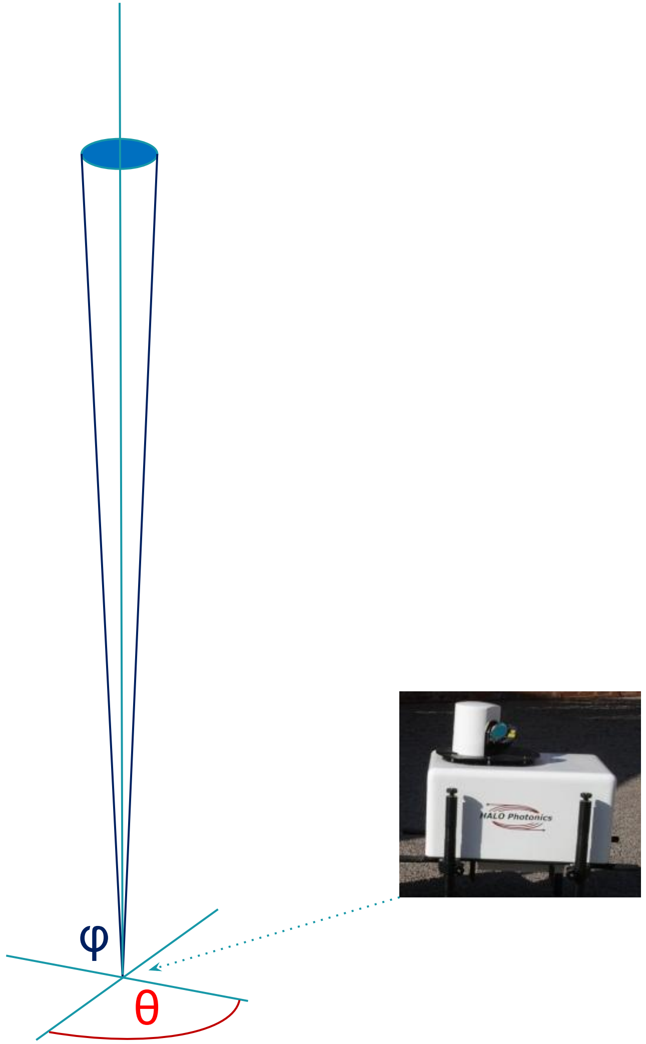
Stare
- θ - azimuth angle
- φ - elevation angle

- Vertical stare (zenith)
  - φ = 90º



Scan types

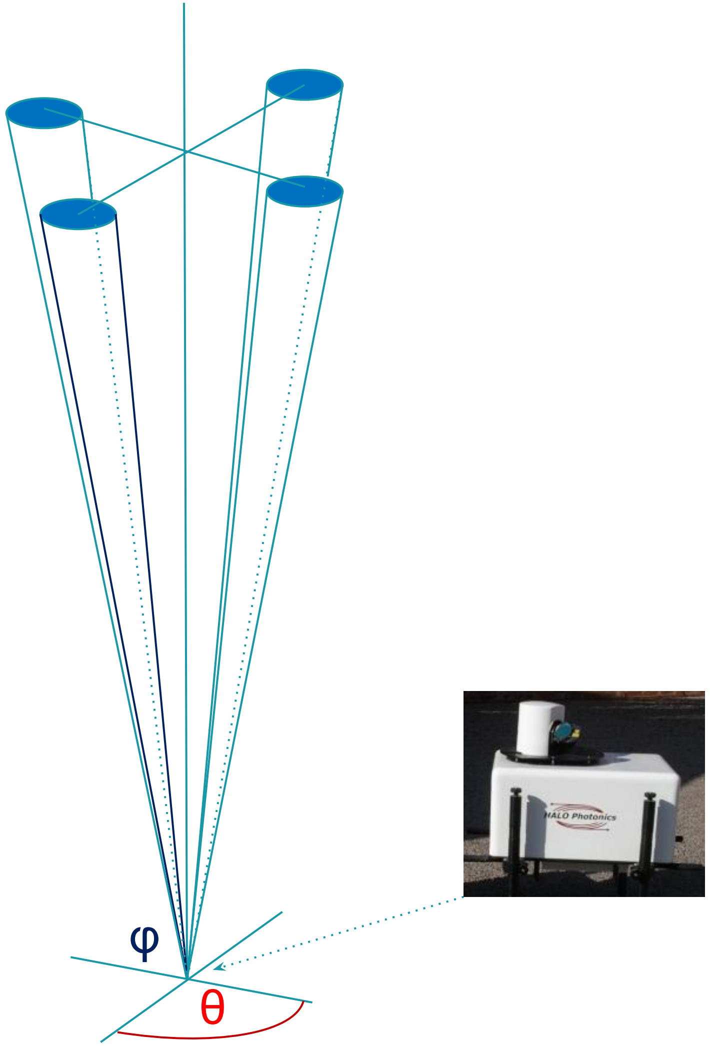
Doppler Beam Swing (DBS)

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

Scan types

Doppler Beam Swing (DBS)

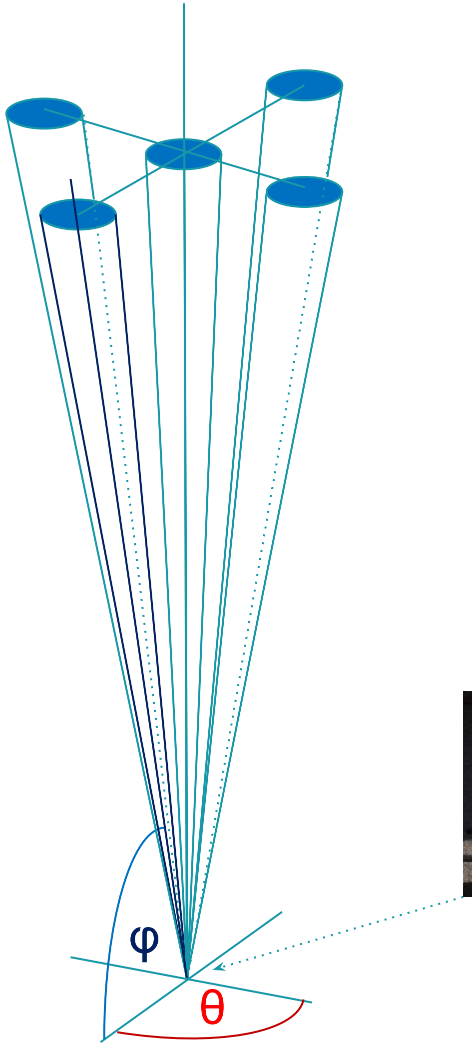
- 4-beam DBS
  - 4 off-zenith beams
  - θ = 90º, N, E, S, W
  - φ = 70º (typically)



Scan types

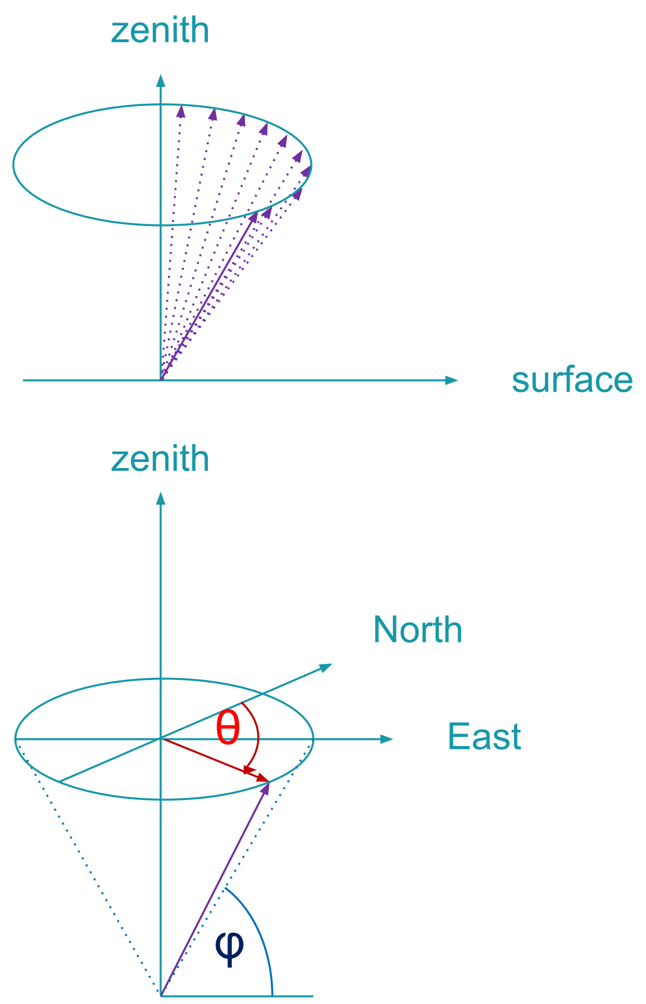
Doppler Beam Swing (DBS)

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



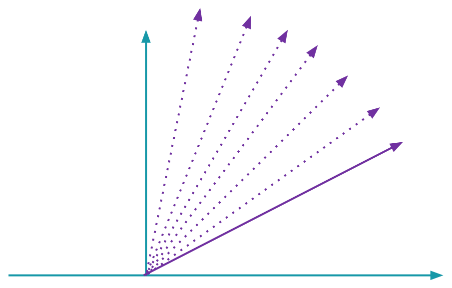
Scan types

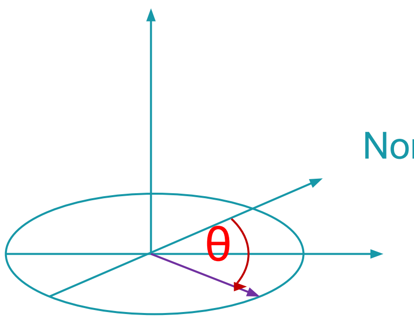
- Velocity Azimuth Display
  - VAD
  - Conical scan
  - N off-zenith beams
  - θ = 0:360
  - φ = constant



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 – 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

Horizontal winds from radial velocities

- 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..

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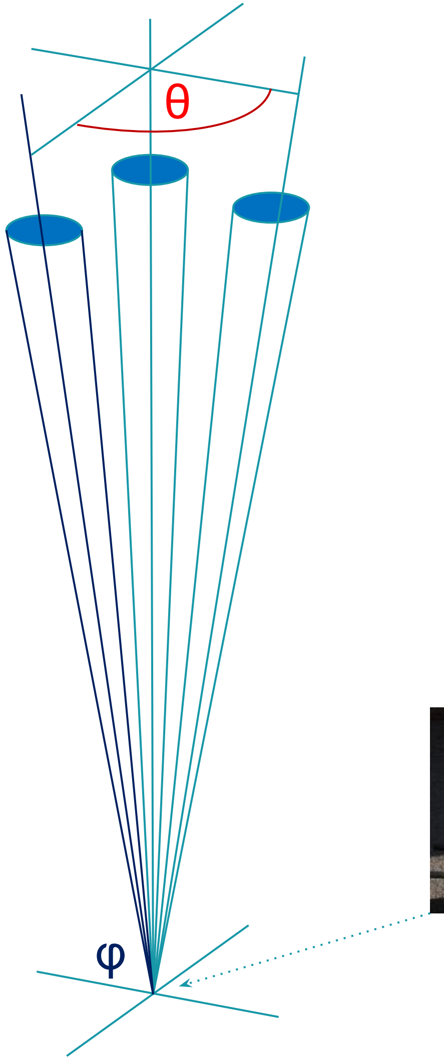
Scan types

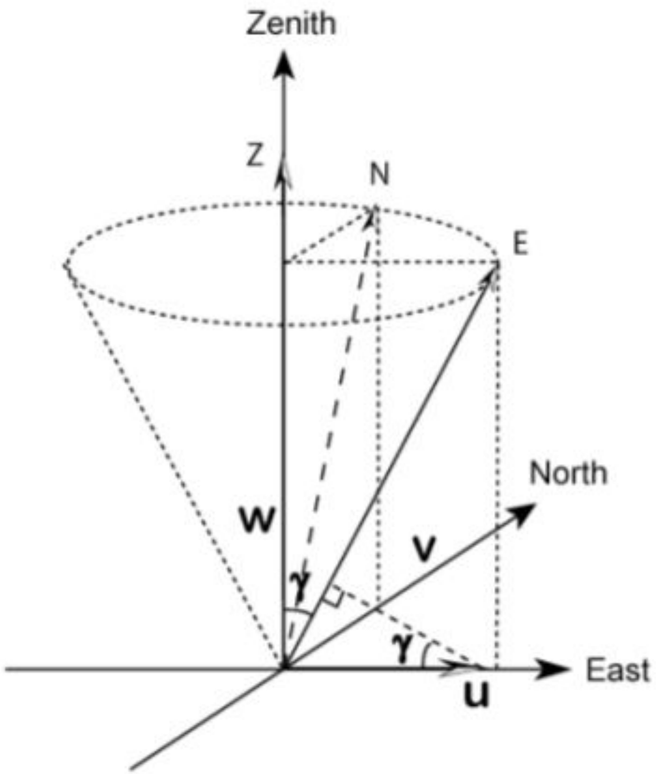
Doppler Beam Swing (DBS)

- 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 velocities

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



γ is the off-zenith angle

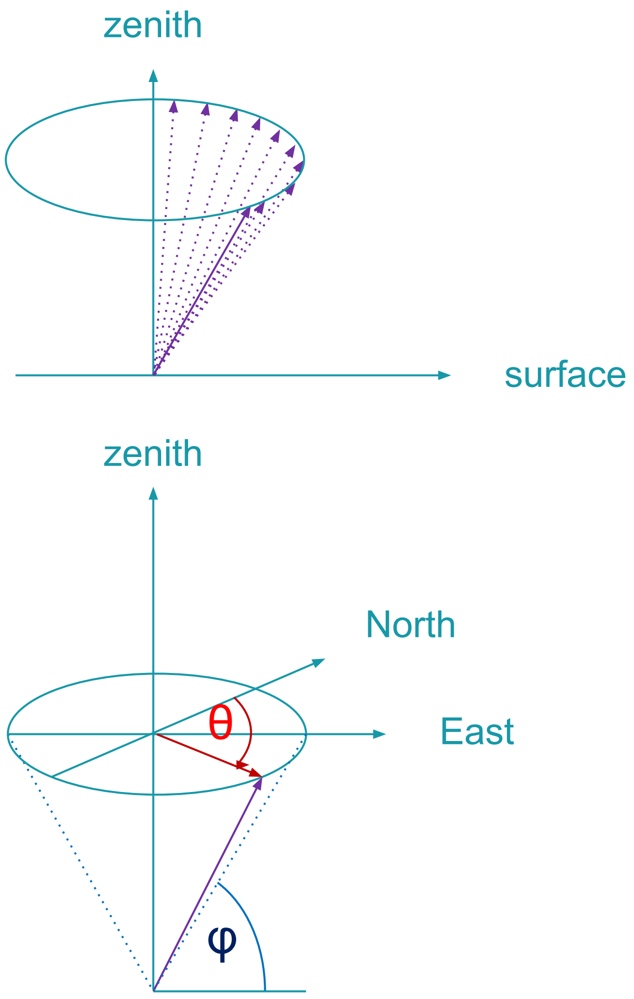
$$V_{RE} = u \sin\gamma + w \cos\gamma$$
$$V_{RN} = v \sin\gamma + w \cos\gamma$$
$$V_{RZ} = w$$

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

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

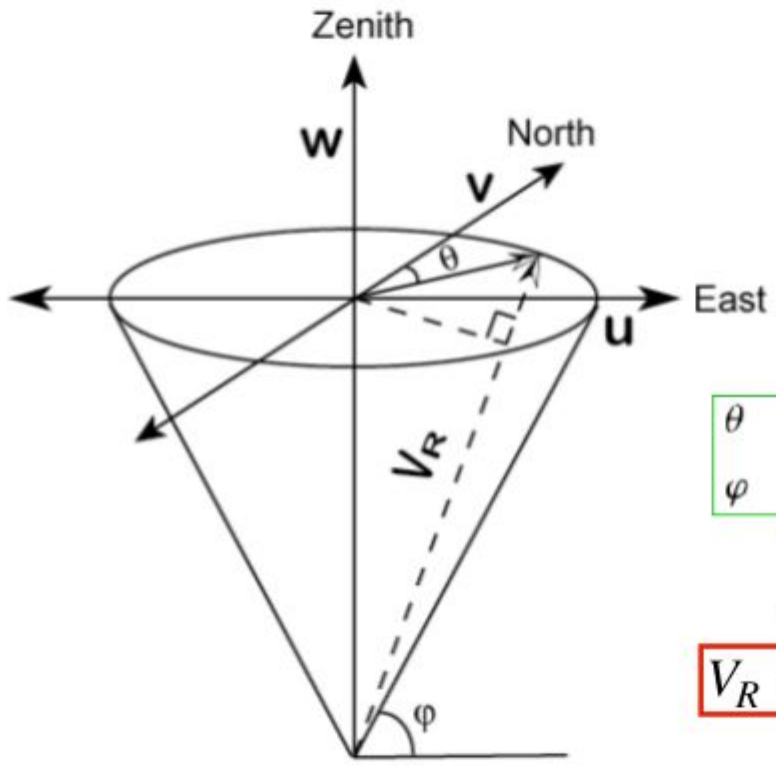
Scan types

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



Horizontal winds from radial velocities

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.

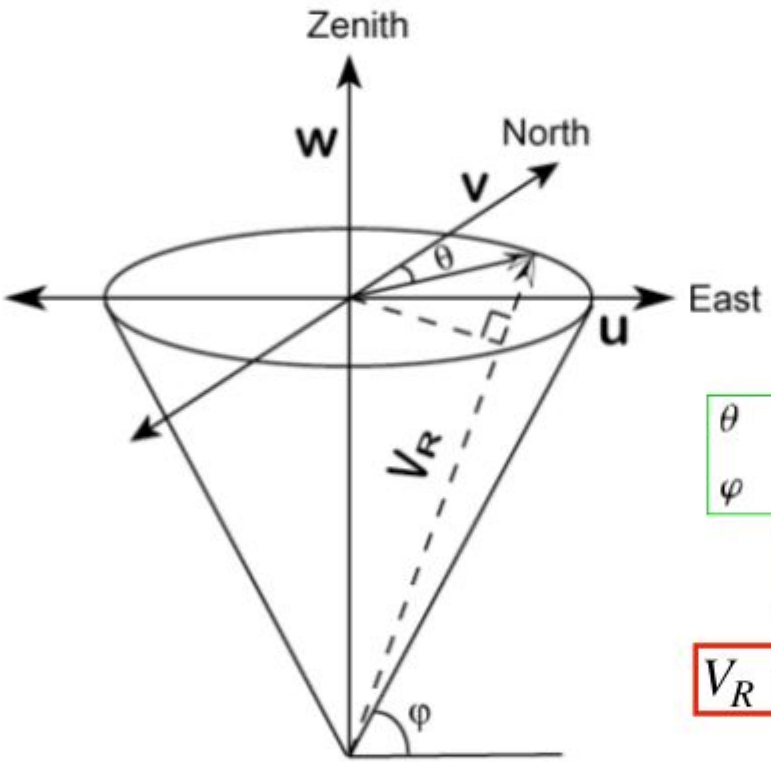
$$\theta_N = 0^\circ, \theta_E = 90^\circ, \theta_S = 180^\circ, \theta_W = 270^\circ$$

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

21

Horizontal winds from radial velocities

Velocity Azimuth Display (VAD) Technique



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

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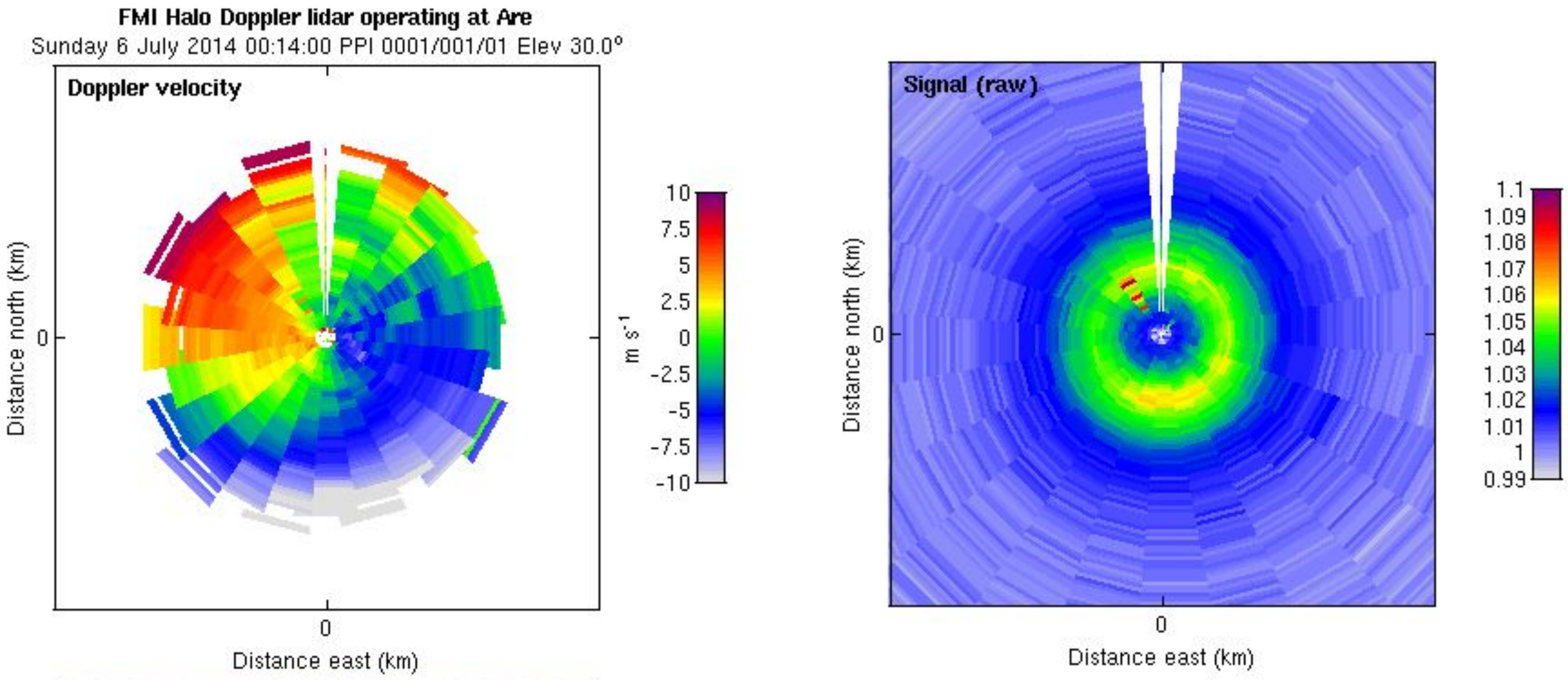
$$V_R = u \sin\theta \cos\varphi + v \cos\theta \cos\varphi + w \sin\varphi$$

21

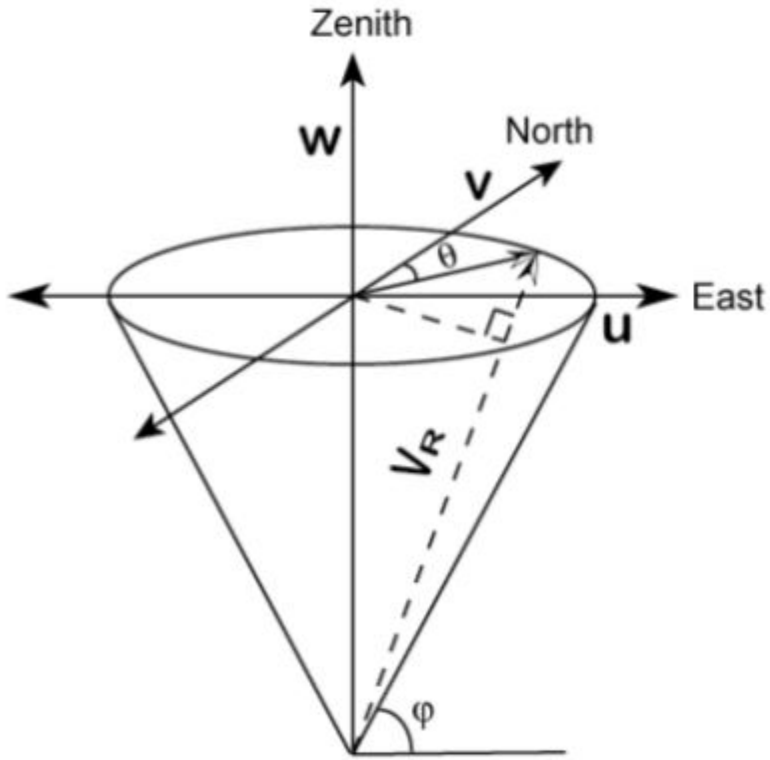
Horizontal winds from radial velocities

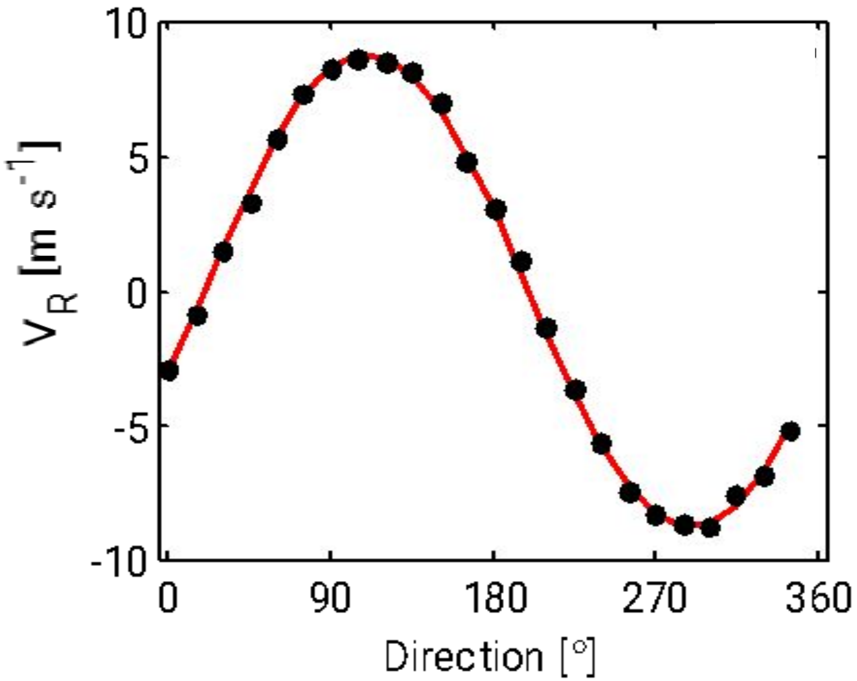
Velocity Azimuth Display (VAD) Technique



Horizontal winds from radial velocities

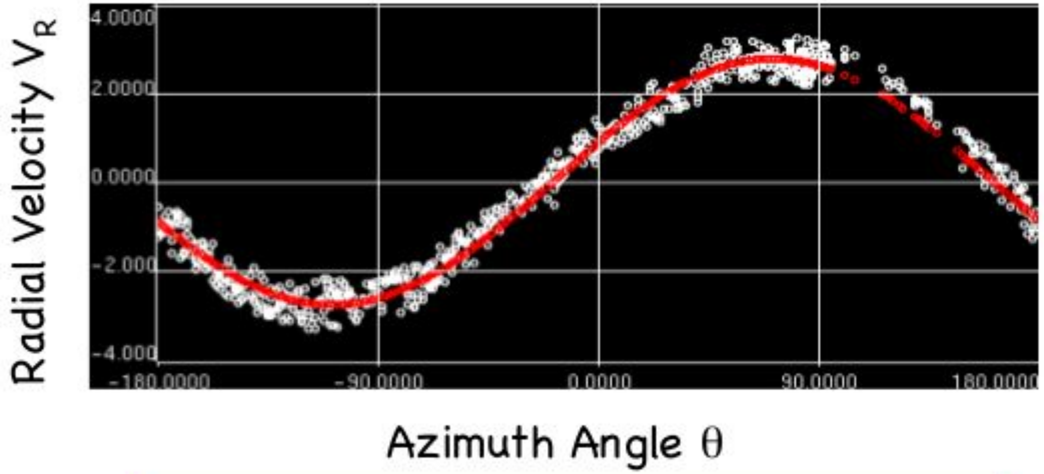
- Sinusoidal fit for horizontal wind
- Residuals from turbulence and non-turbulent changes in wind





Horizontal winds from radial velocities

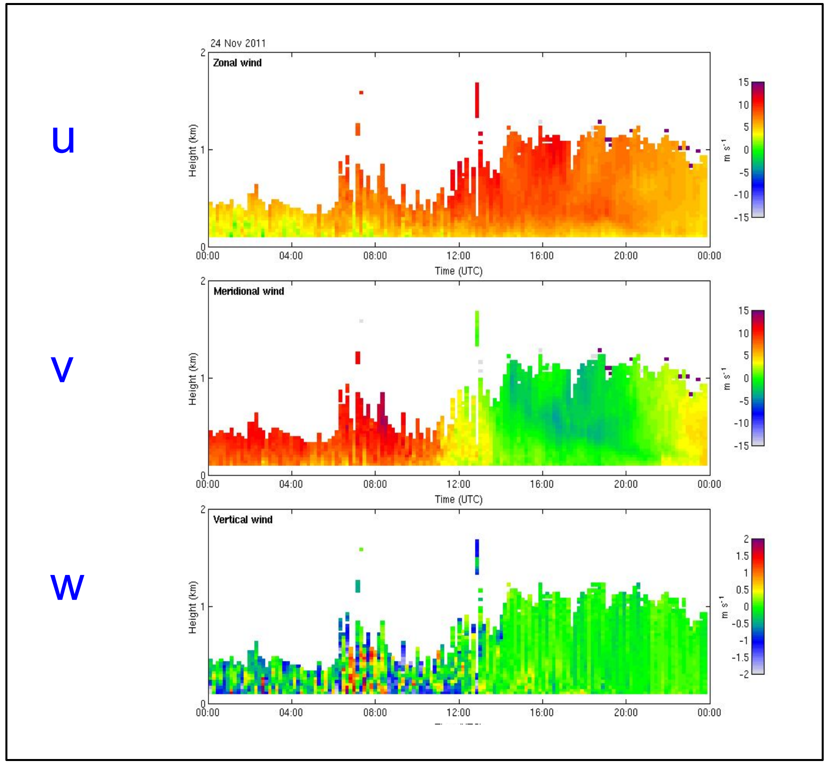
Velocity Azimuth Display (VAD) Technique

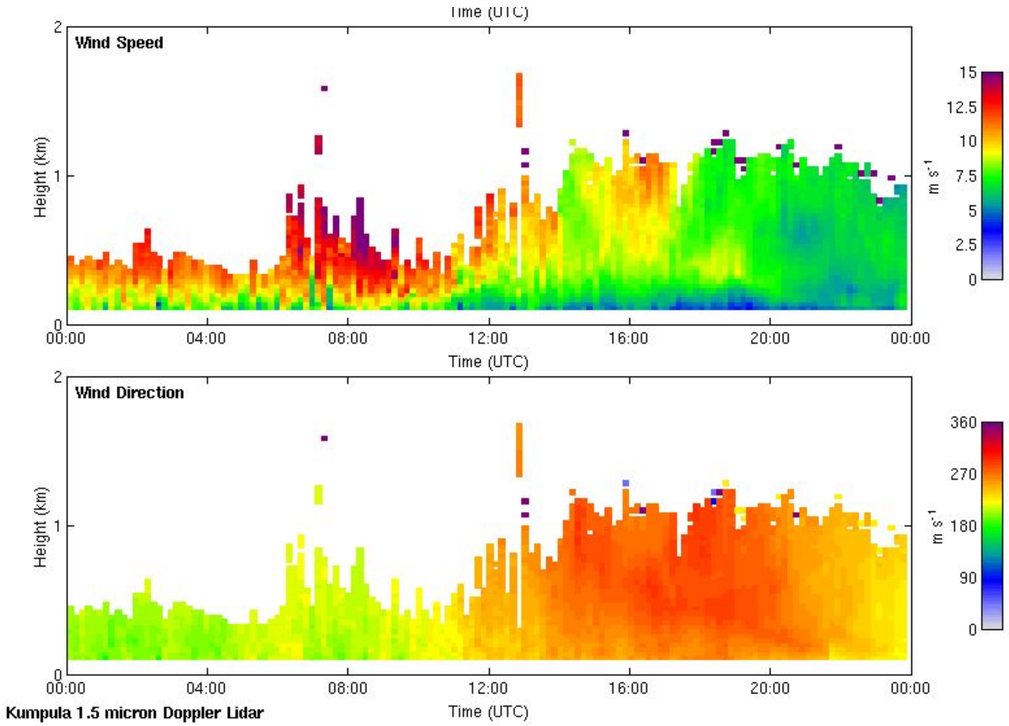


$$V_R = u \sin\theta \cos\varphi + v \cos\theta \cos\varphi + w \sin\varphi$$

Horizontal winds from radial velocities

Wind speed





Wind direction

Horizontal winds from radial velocities

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- 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 elevation angle should we scan at?

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

What elevation angle should we scan at?

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

Elevation	0	30	60	75
Max velocity				

What elevation 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 elevation 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

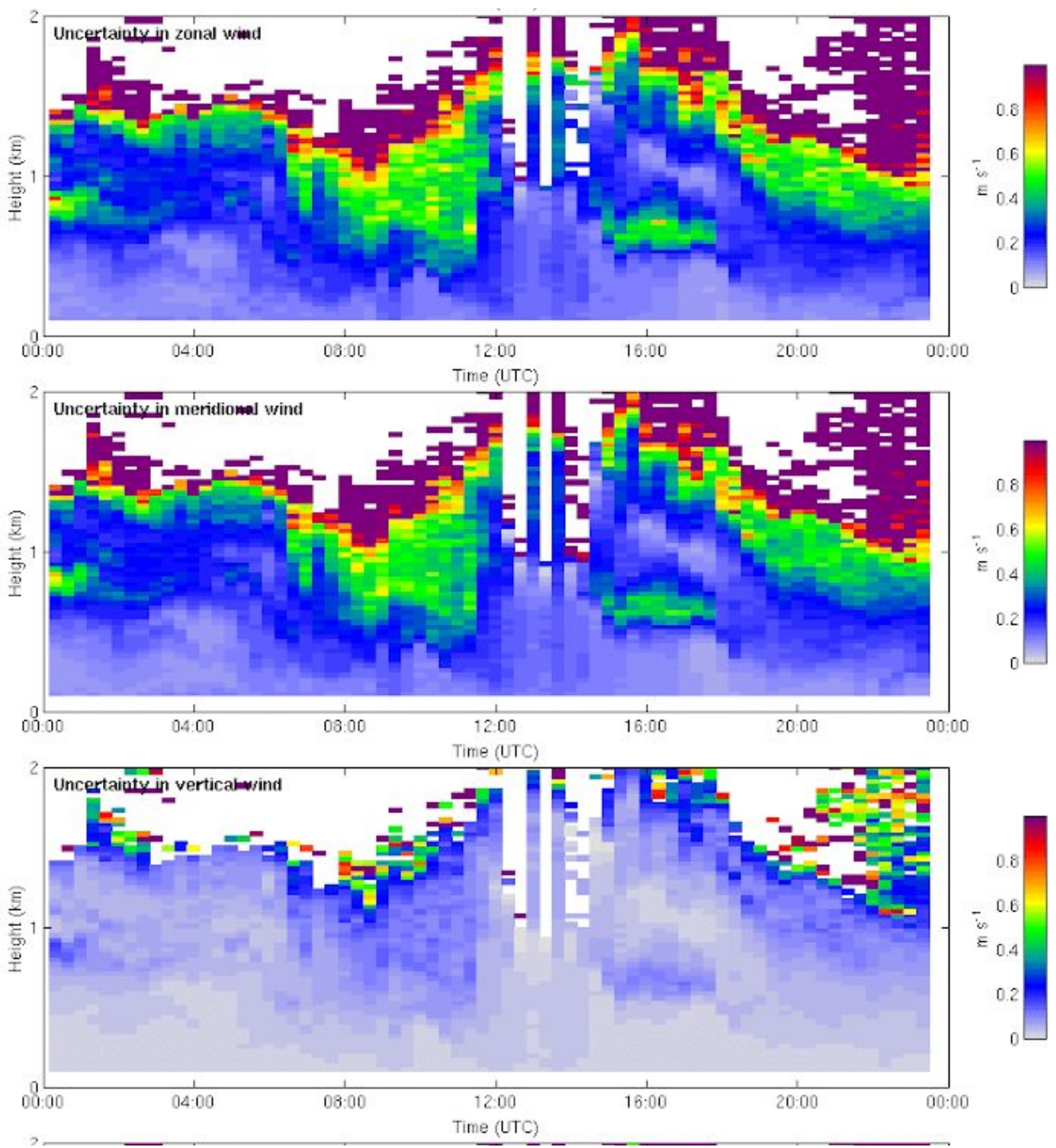
- What about measurement uncertainty?

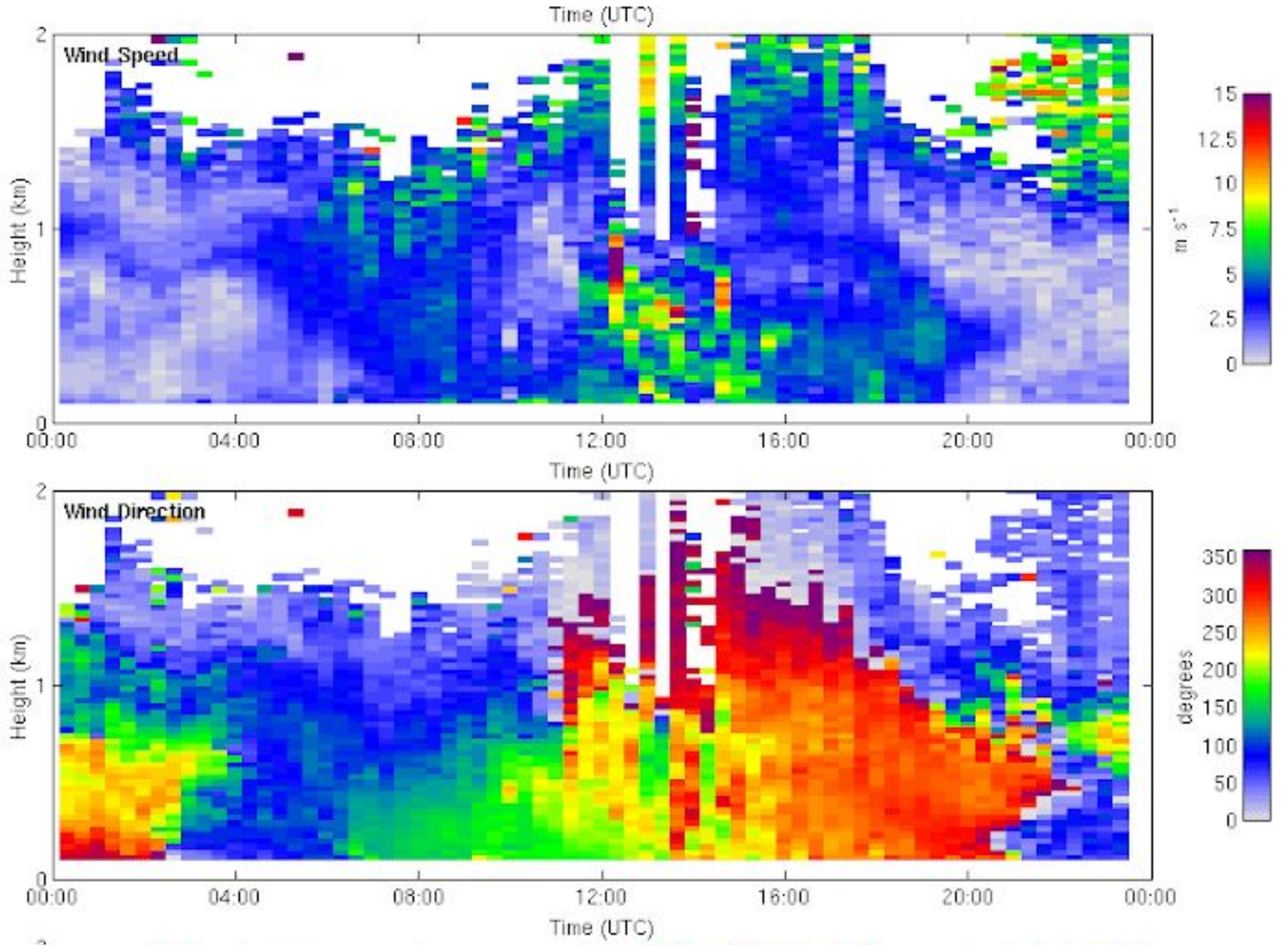
What elevation angle should we scan at?

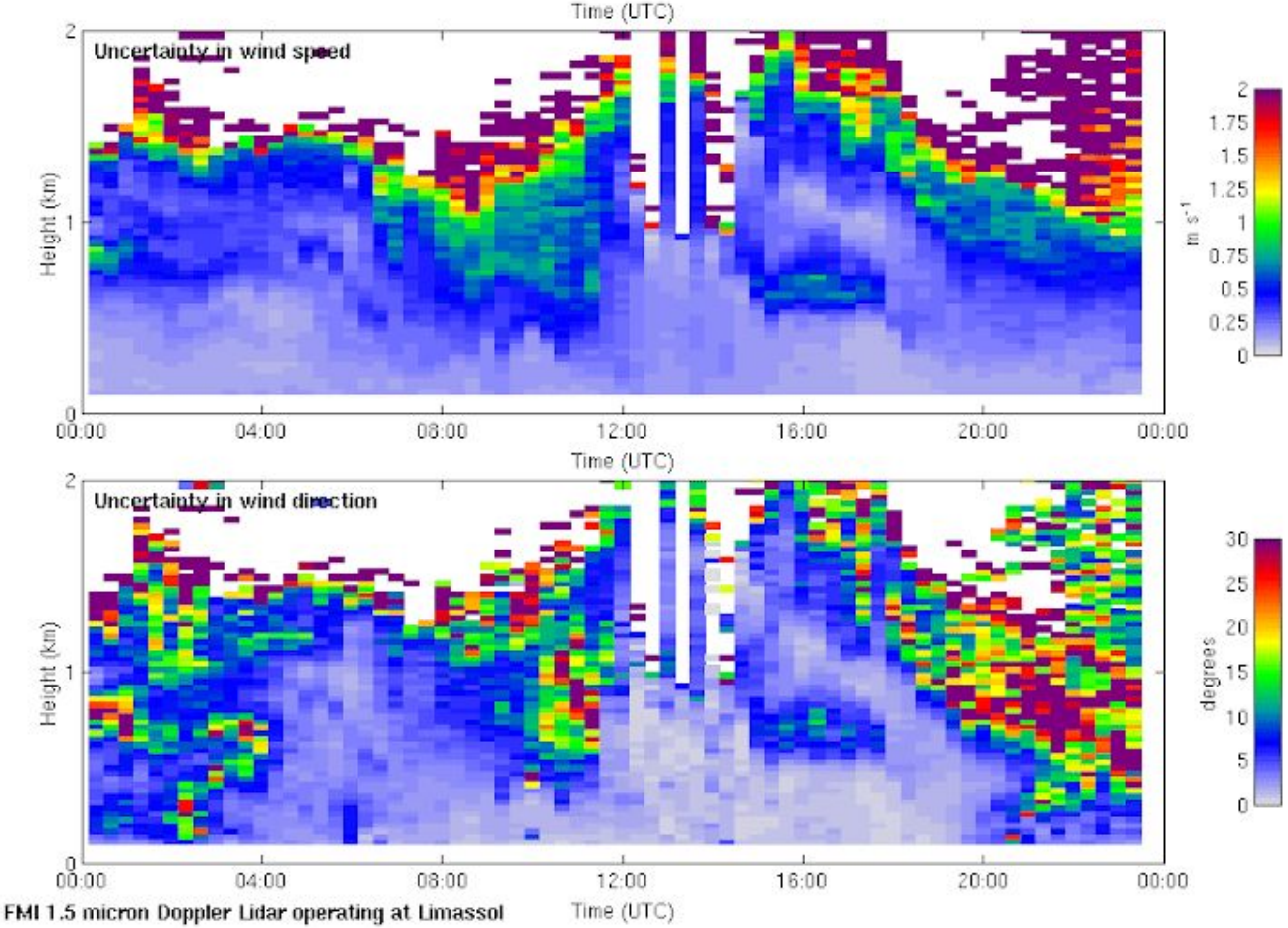
- Nyquist velocity is usually 20 or 40 m s^{-1}

Elevation	0	30	60	75
Max velocity	20	23	40	77

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


Uncertainty in zonal wind
Uncertainty in meridional wind
Uncertainty in vertical wind
Height (km)
Time (UTC)
00:00
04:00
08:00
12:00
16:00
20:00
00:00
0
1
2
m s⁻¹
0
0.2
0.4
0.6
0.8


Time (UTC)
Wind Speed
Height (km)
m s-1
15
12.5
10
7.5
5
2.5
0
00:00
04:00
08:00
12:00
16:00
20:00
00:00
Time (UTC)
Wind Direction
Height (km)
degrees
350
300
250
200
150
100
50
0
00:00
04:00
08:00
12:00
16:00
20:00
00:00
Time (UTC)

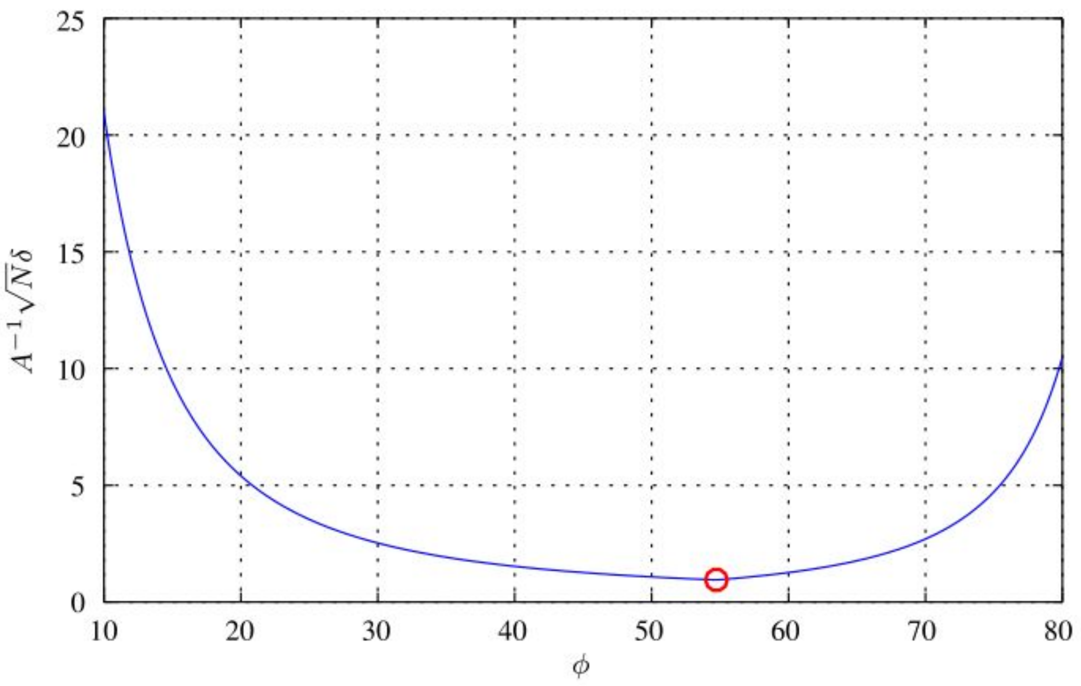

Time (UTC)
Uncertainty in wind speed
Height (km)
m s-1
Uncertainty in wind direction
degrees
00:00
04:00
08:00
12:00
16:00
20:00
00:00
Time (UTC)
FMI 1.5 micron Doppler Lidar operating at Limassol

What elevation angle should we scan at?

- Elevation angle
  - 35 degrees

- Method accounts
  - Constant bias

- Method provides
  - Explicit uncertainties



Zenith angle

Teschke, G. and Lehmann, V.: Mean wind vector estimation using the velocity–azimuth display (VAD) method: an explicit algebraic solution, Atmos. Meas. Tech., 10, 3265-3271, https://doi.org/10.5194/amt-10-3265-2017, 2017

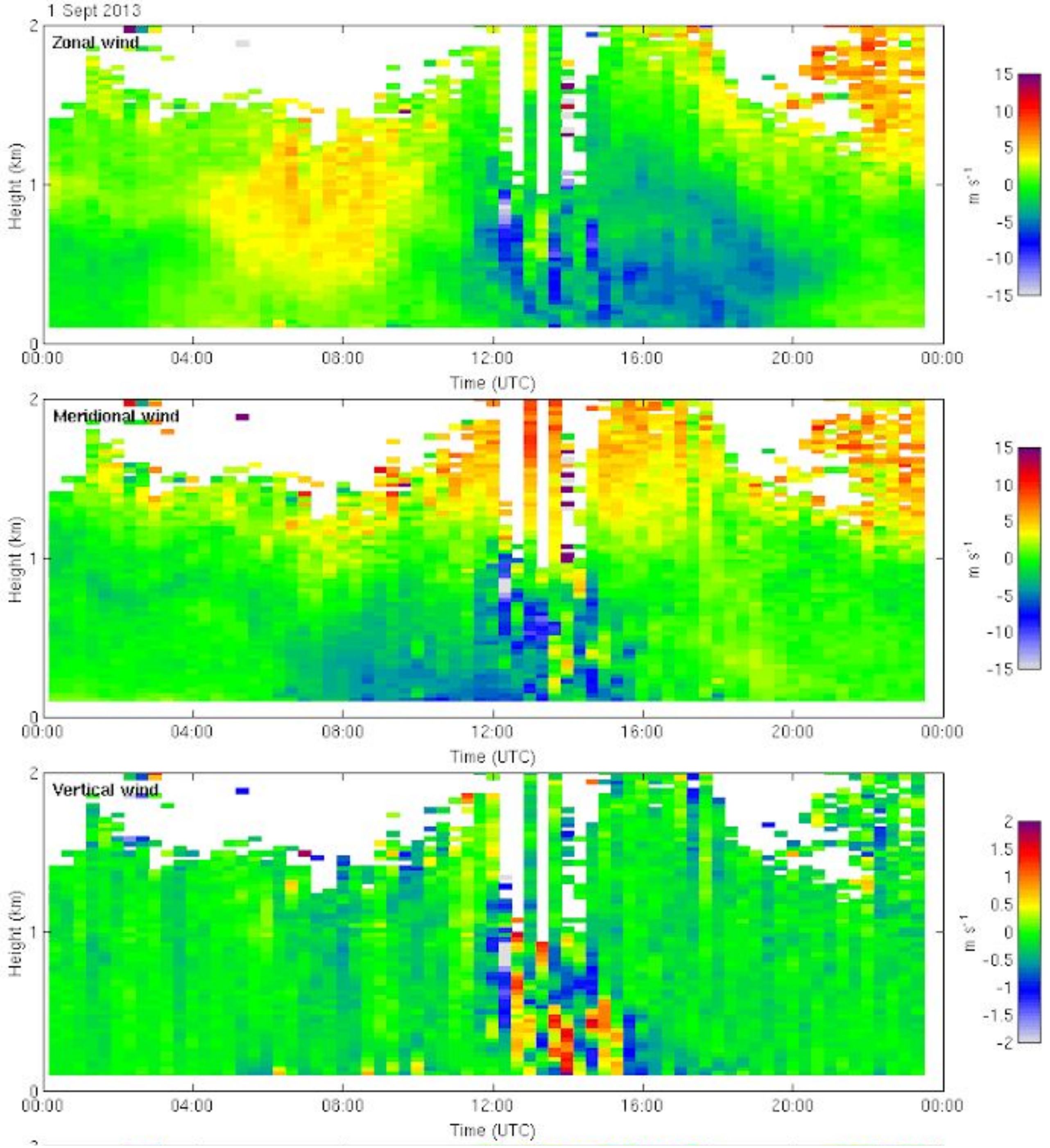
What elevation angle should we scan at?

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

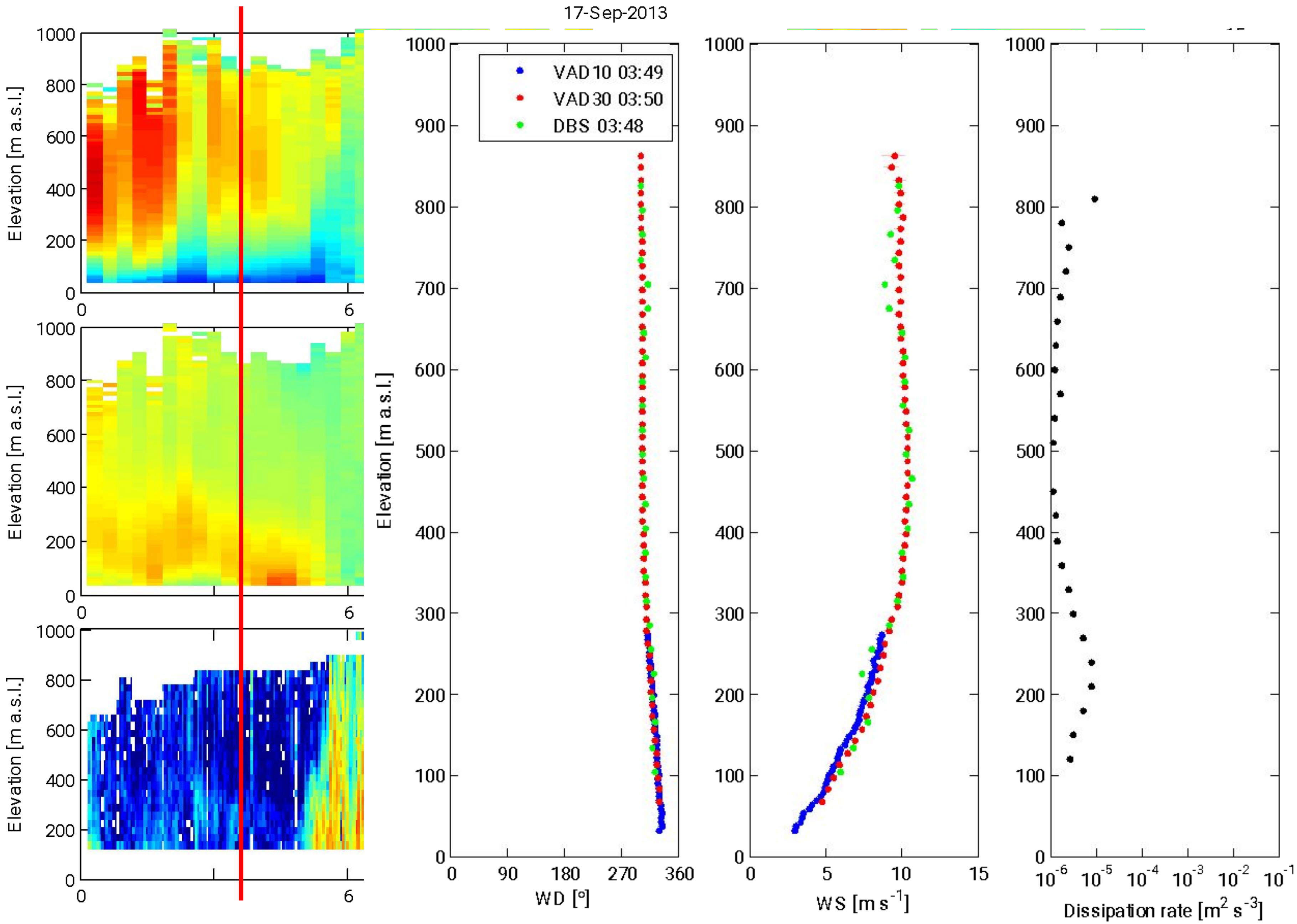
Elevation	0	30	60	75
Max velocity	20	23	40	77

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

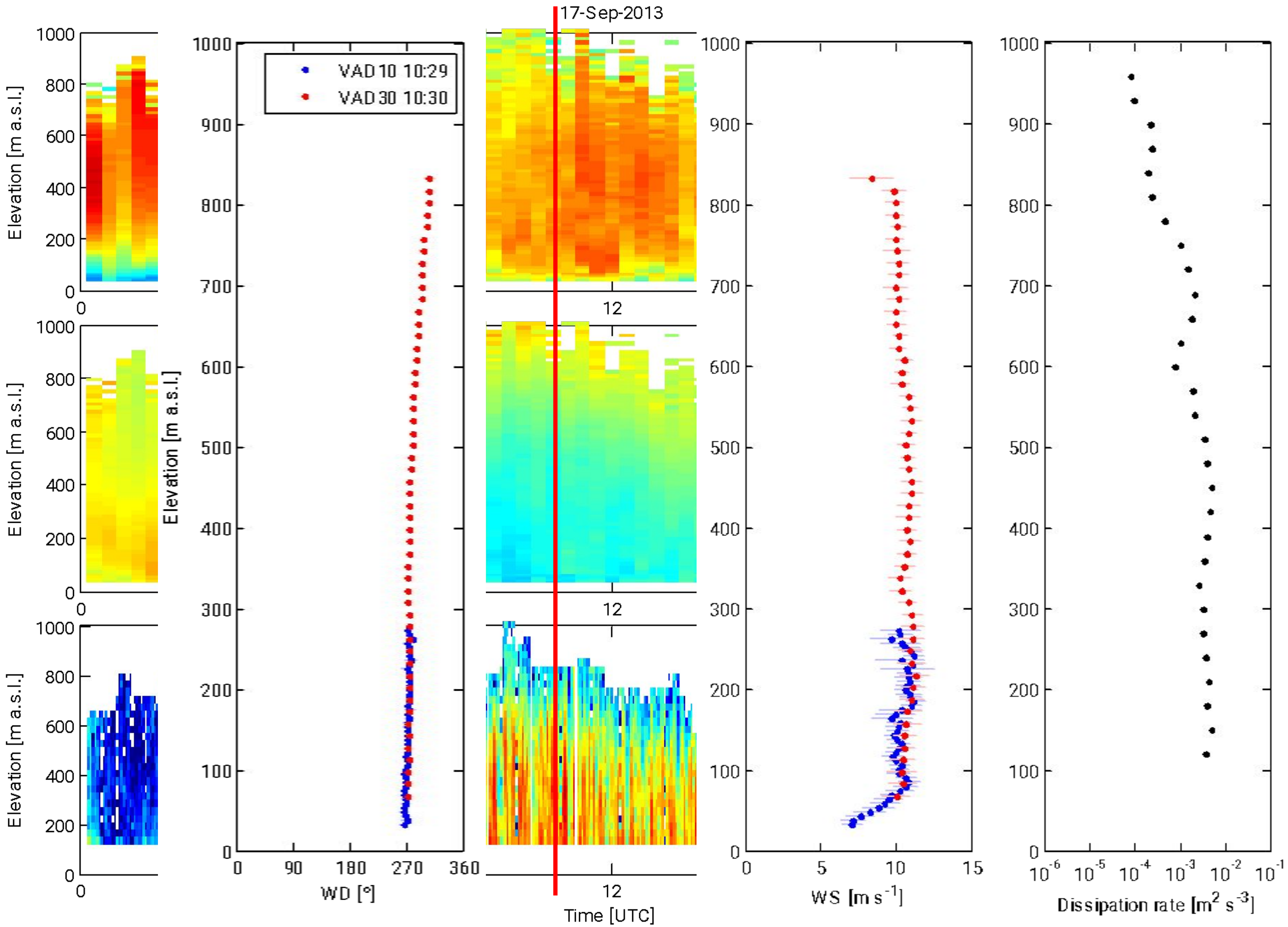
We have neglected turbulence!



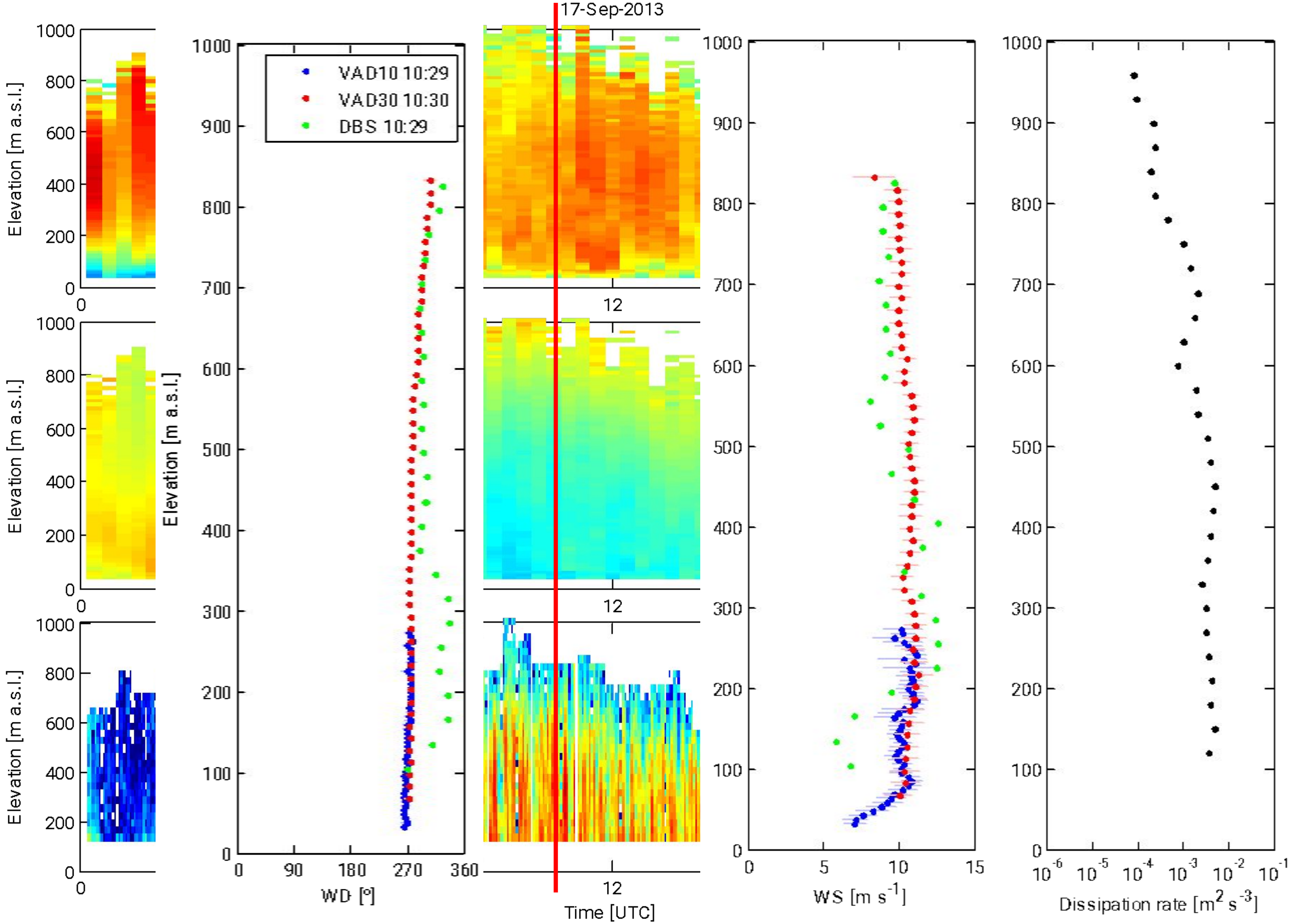
1 Sept 2013
Zonal wind
Meridional wind
Vertical wind
Height (km)
Time (UTC)
m s-1



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]



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



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 from radial velocities

- VAD is 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

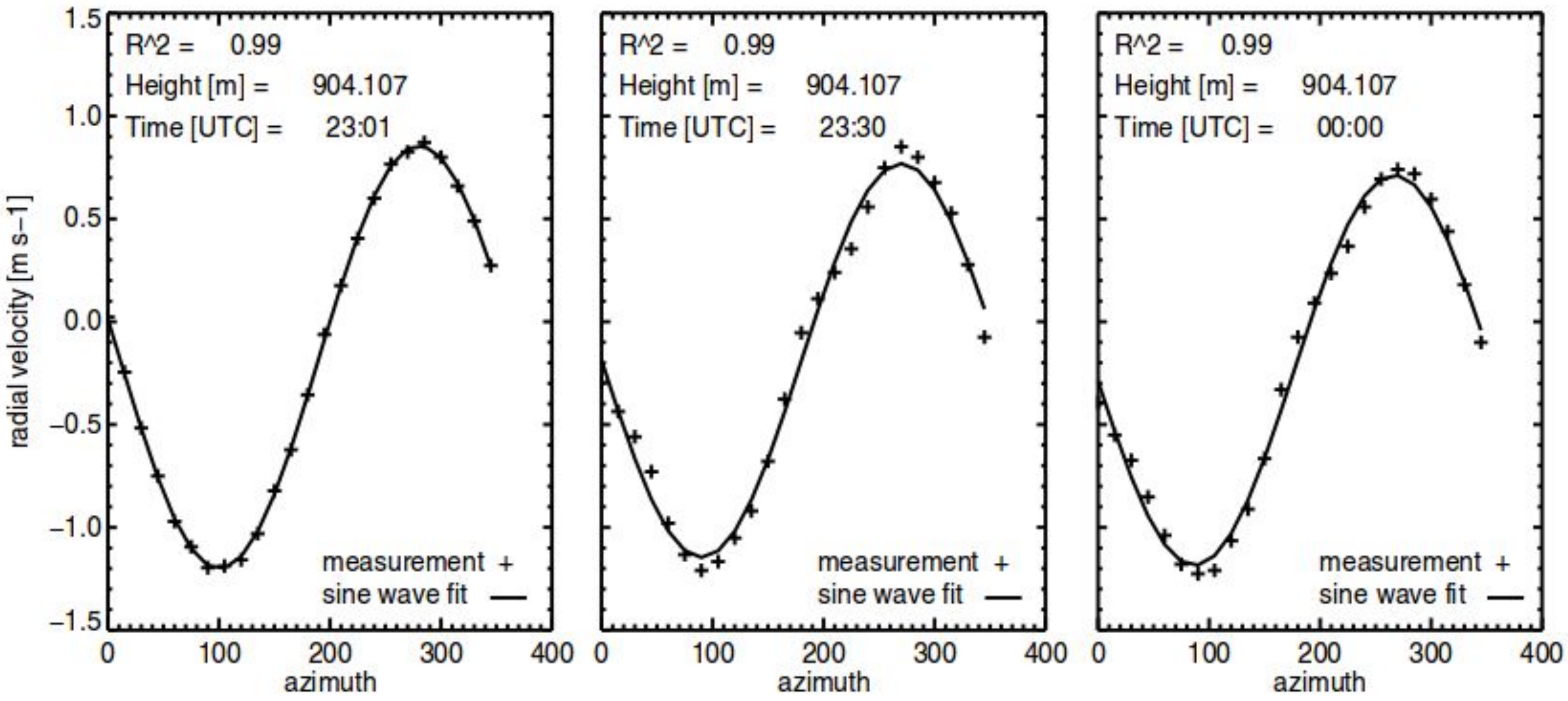
- Uncertainties propagated from radial winds

Wind uncertainty

- **VAD technique - Paeschke et al., 2015**
  - Identifies turbulent conditions
    - Bias mean wind
    - Bias uncertainty estimate
  - Quality Control – can you assume homogeneity?
    - Goodness of fit
    - Condition Number
- **ACTRIS: Common methodology**
  - **Recommendation may be location dependent!**

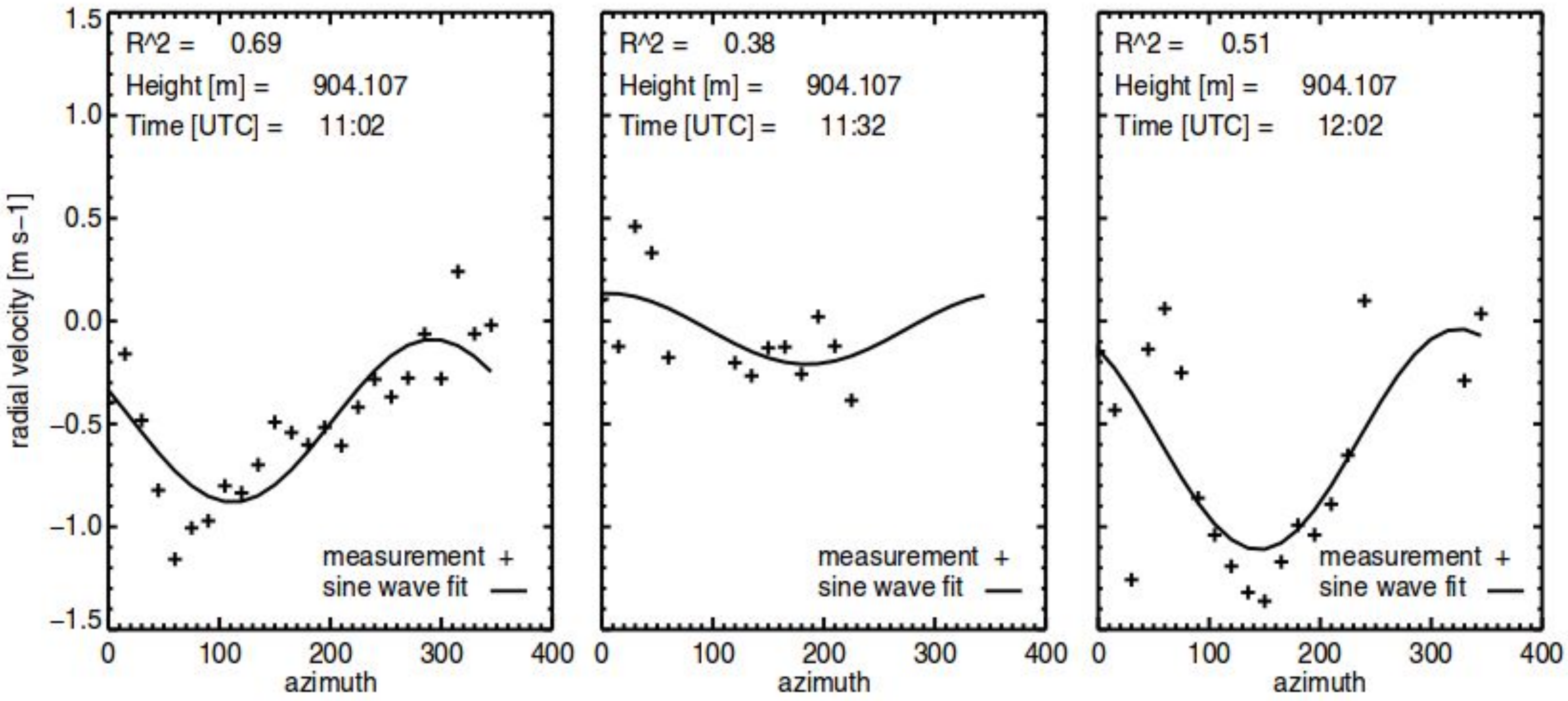
Päschke, E., Leinweber, R., and Lehmann, V.: An assessment of the performance of a 1.5 µm Doppler lidar for operational vertical wind profiling based on a 1-year trial, Atmos. Meas. Tech., 8, 2251-2266, https://doi.org/10.5194/amt-8-2251-2015, 2015

Wind uncertainty



Päschke, E., Leinweber, R., and Lehmann, V.: An assessment of the performance of a 1.5 μm Doppler lidar for operational vertical wind profiling based on a 1-year trial, Atmos. Meas. Tech., 8, 2251-2266, https://doi.org/10.5194/amt-8-2251-2015, 2015

Wind uncertainty



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Turbulent motions

Turbulent properties from Doppler lidar

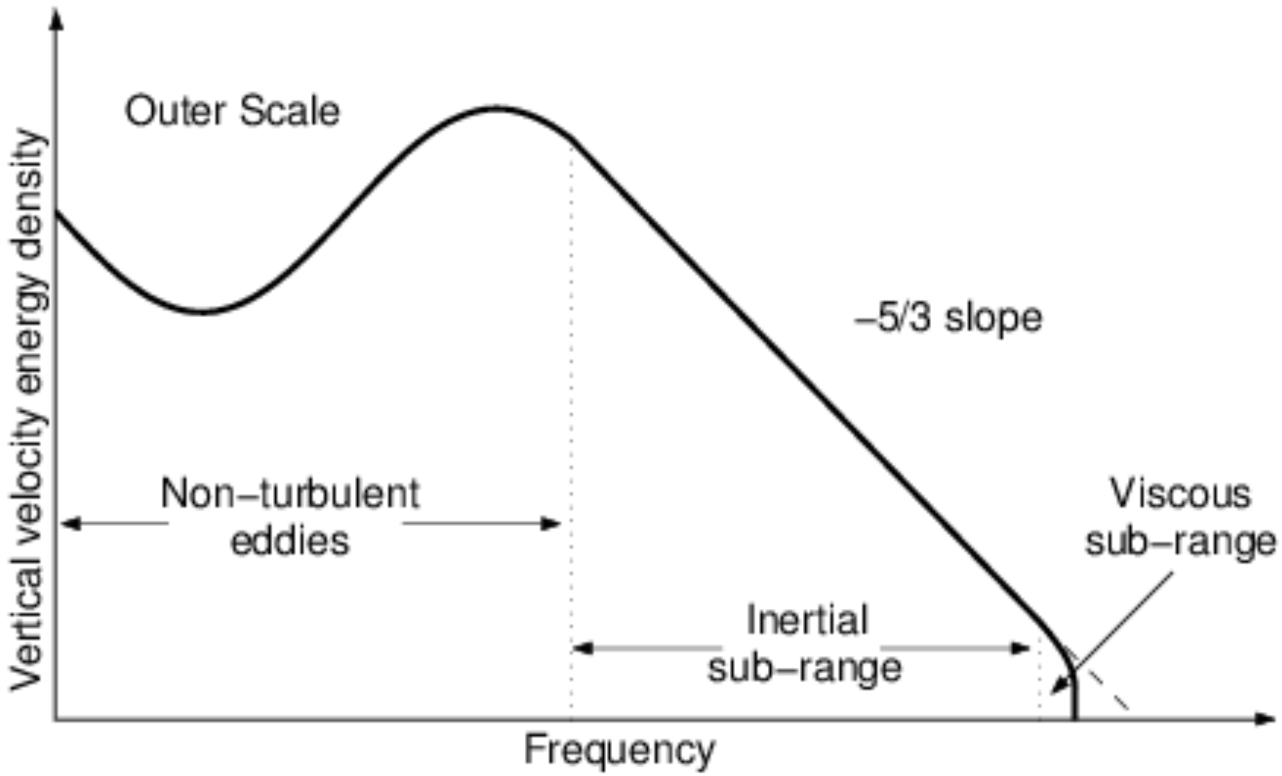
- Where can we retrieve turbulent properties?
  - Requires tracers and good sensitivity
    - Boundary layer aerosol
    - In-cloud
- Different methods available
  - Which method depends on scan capability

- Uncertainties
  - Requires accurate determination of radial velocities

Turbulent properties from Doppler lidar

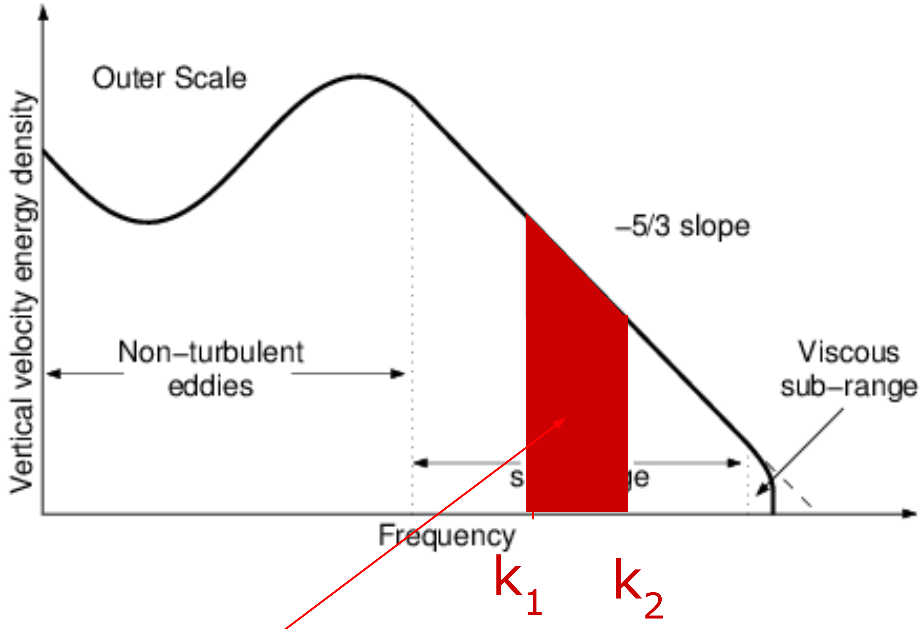
- Methods
  - Velocity statistics
    - Spectral width, skewness, kurtosis
  - Turbulent tensor: 4-beam DBS
  - Radial velocities
    - Incorporate within stochastic Lagrangian turbulence model
  - Kolmogorov hypothesis
    - Vertical pointing
    - VAD (conical) scanning

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)

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

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

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

Turbulent properties from Doppler lidar

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

Observed variance

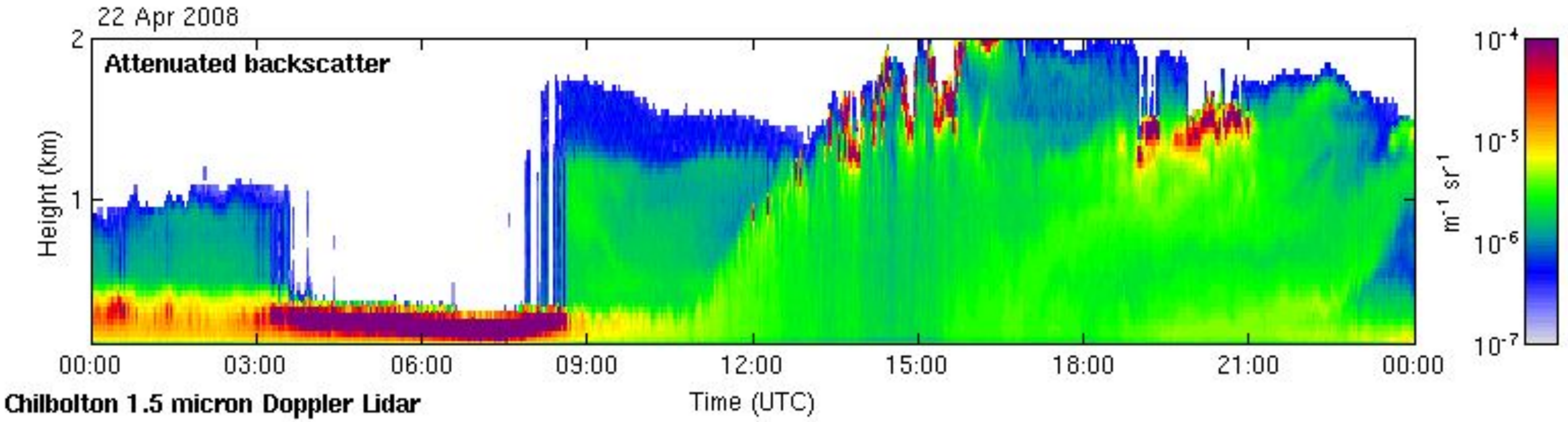
Droplet fall speed distribution

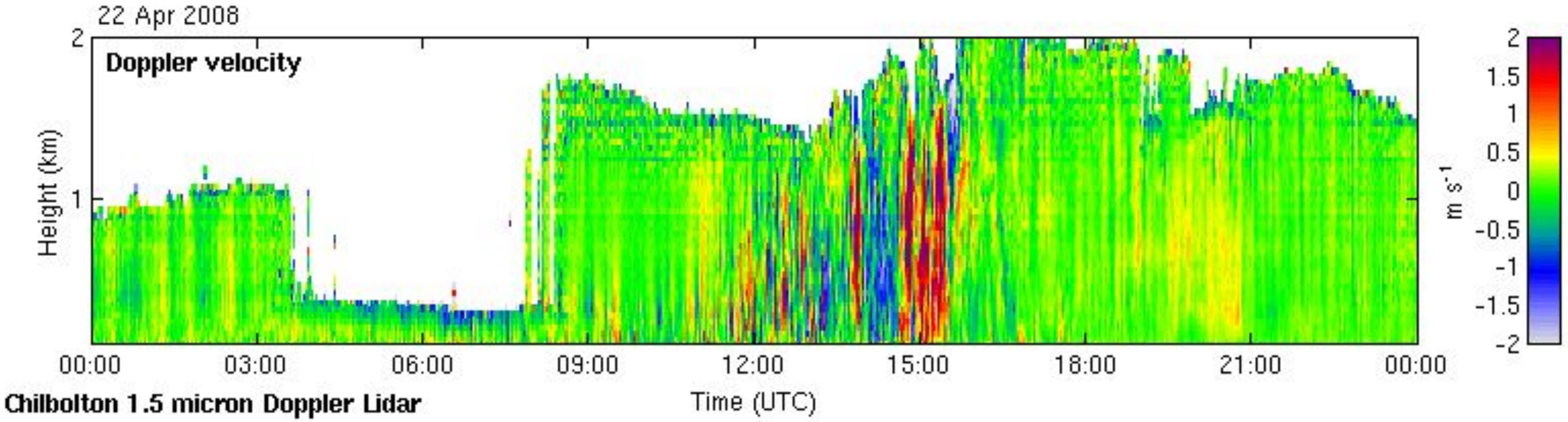
Turbulent term

Measurement uncertainty

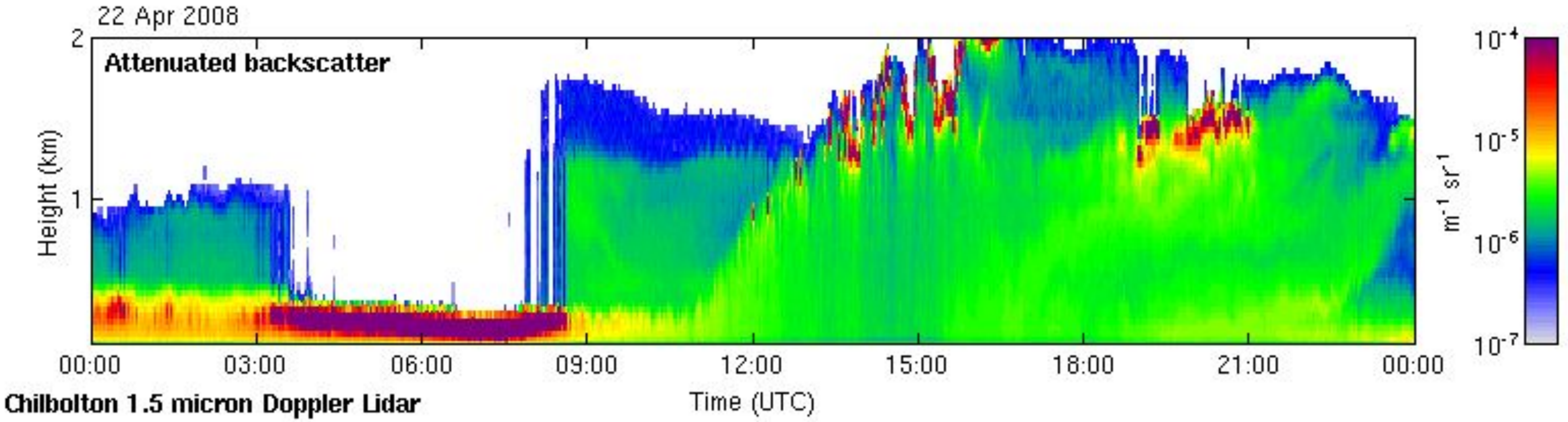
Requires reliable uncertainties!

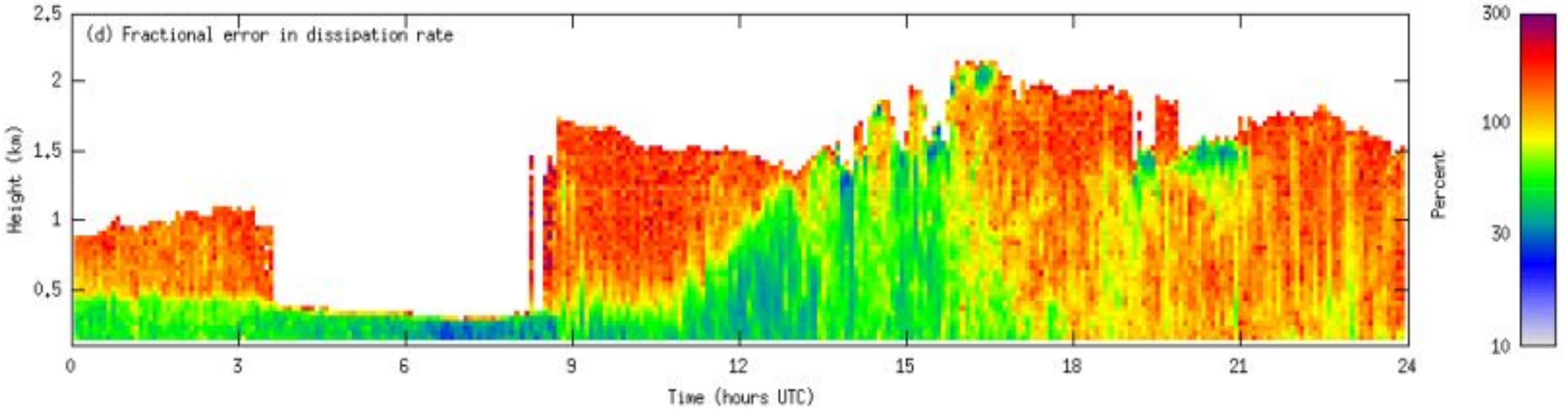
Turbulent properties from Doppler lidar





Turbulent properties from Doppler lidar





Turbulent properties from Doppler lidar

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Observed variance

Droplet fall speed distribution

Turbulent term

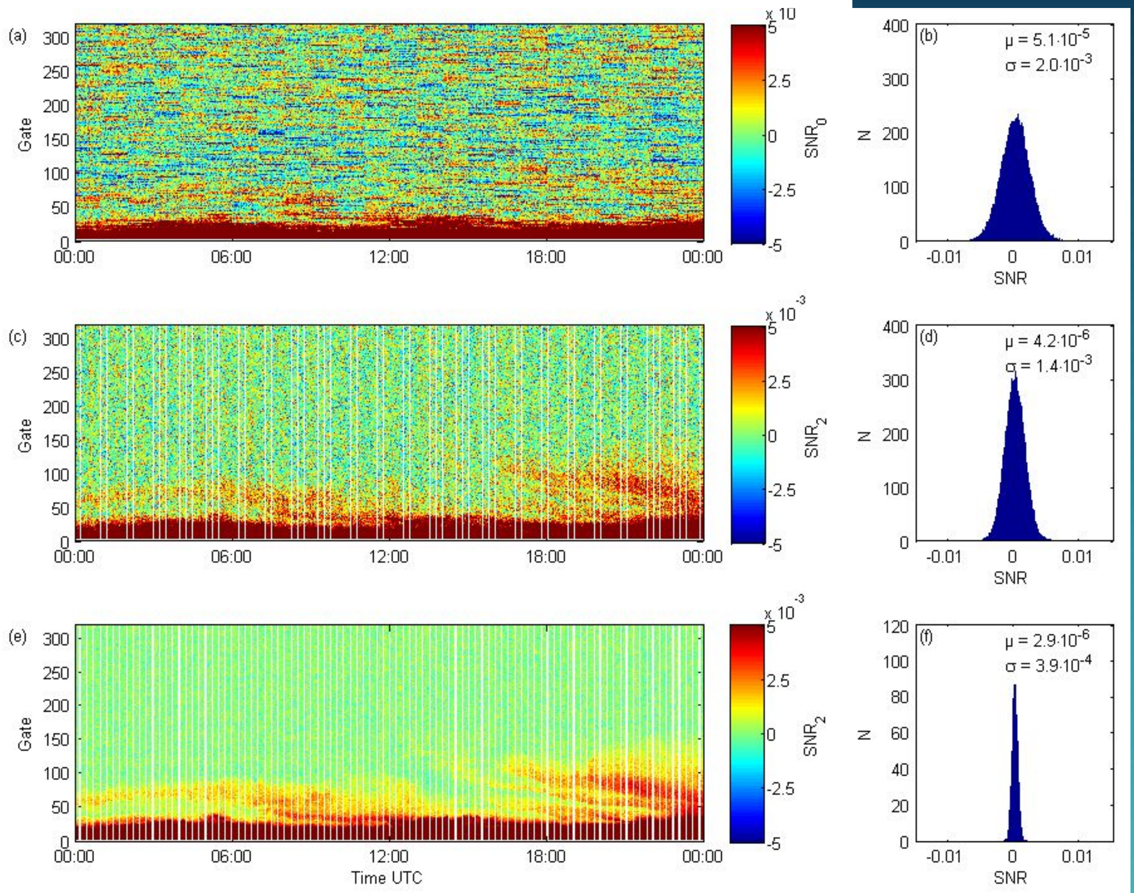
Measurement uncertainty

Requires reliable uncertainties!

Turbulent properties from Doppler lidar

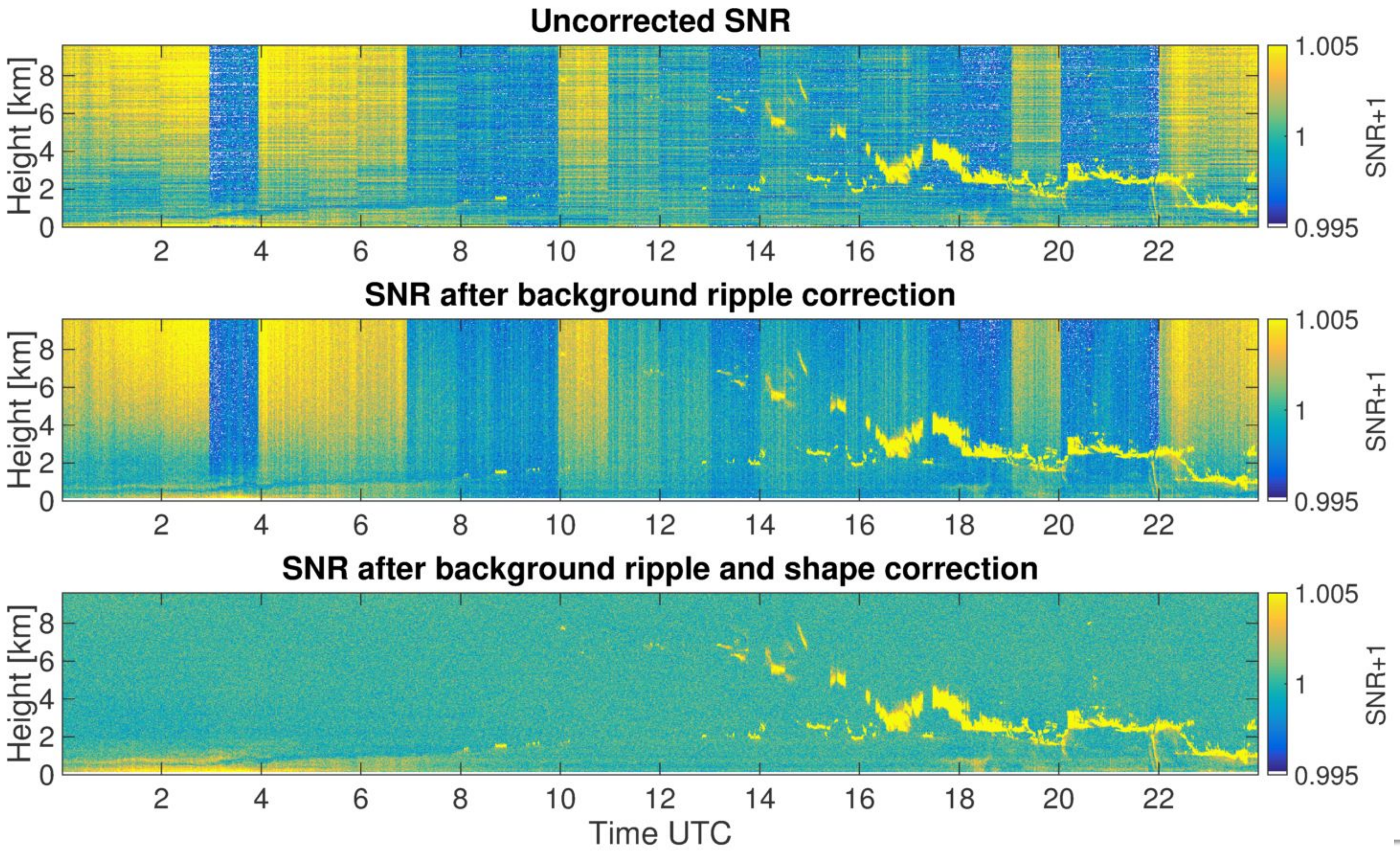
- Background shape and ripple correction
  - Manninen et al. (2016, AMT)
  - Vakkari et al. (2017, ready to submit)

- Recalculate all uncertainties
  - Crucial for turbulent properties



Turbulent properties from Doppler lidar

Halo data requires pre-processing



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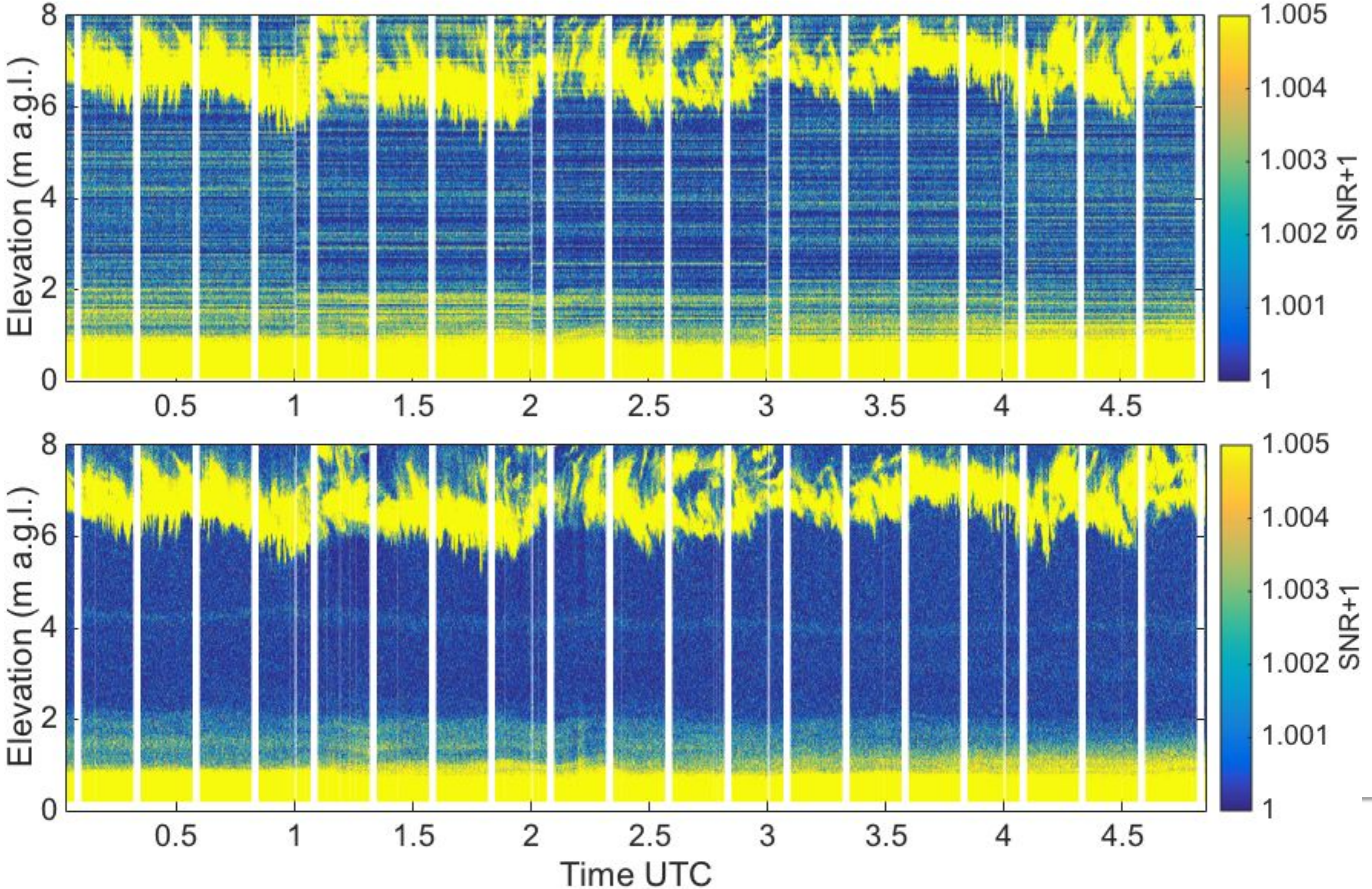
Turbulent properties from Doppler lidar

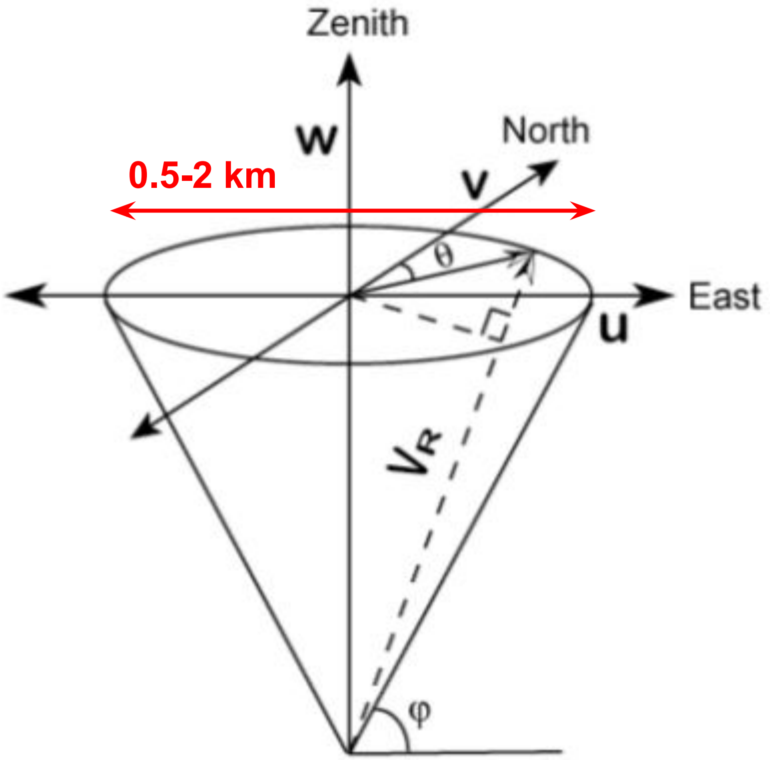
Halo data requires pre-processing

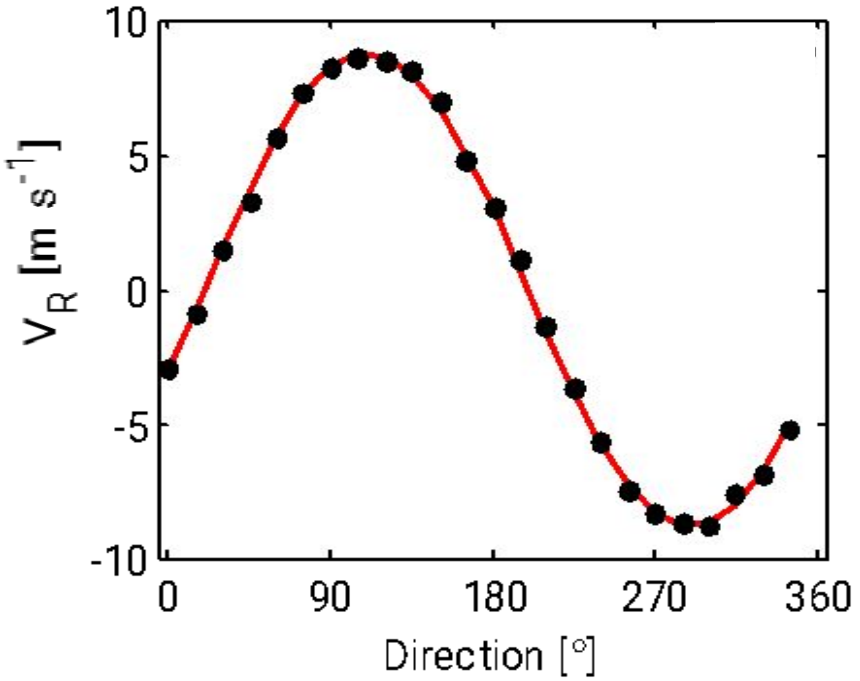
Limassol,
27 March 2017



Turbulence from VAD scans

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



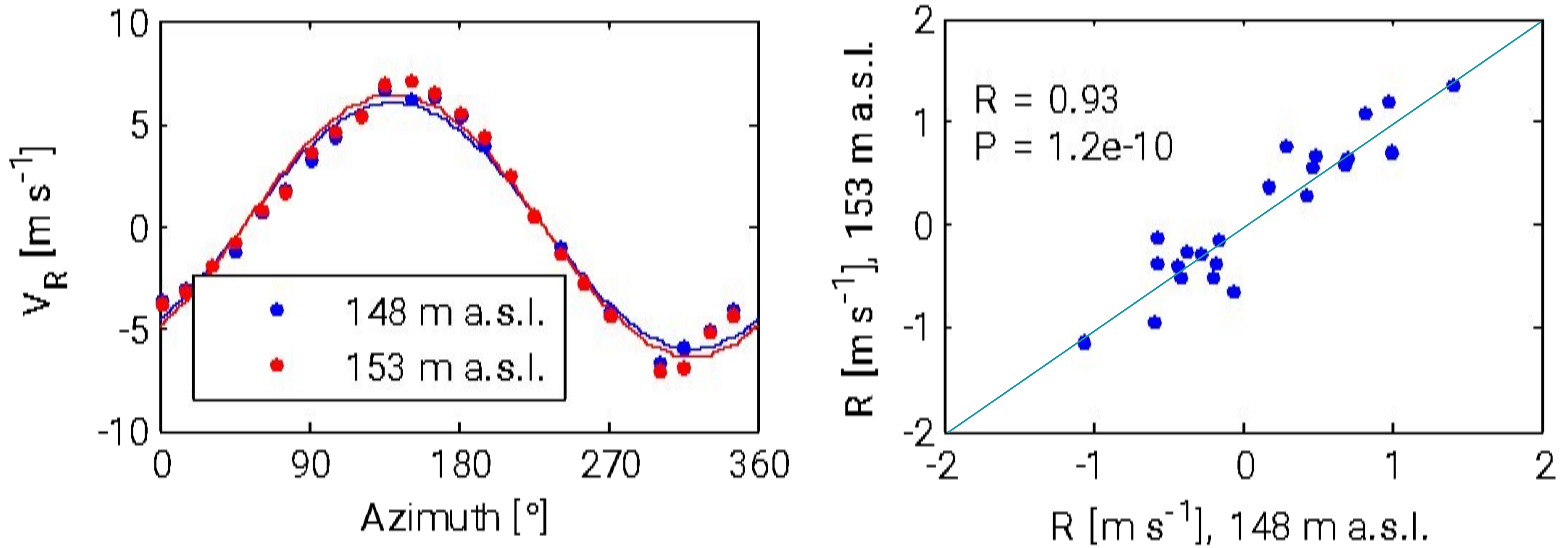


Remove non-turbulent residual

- 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

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

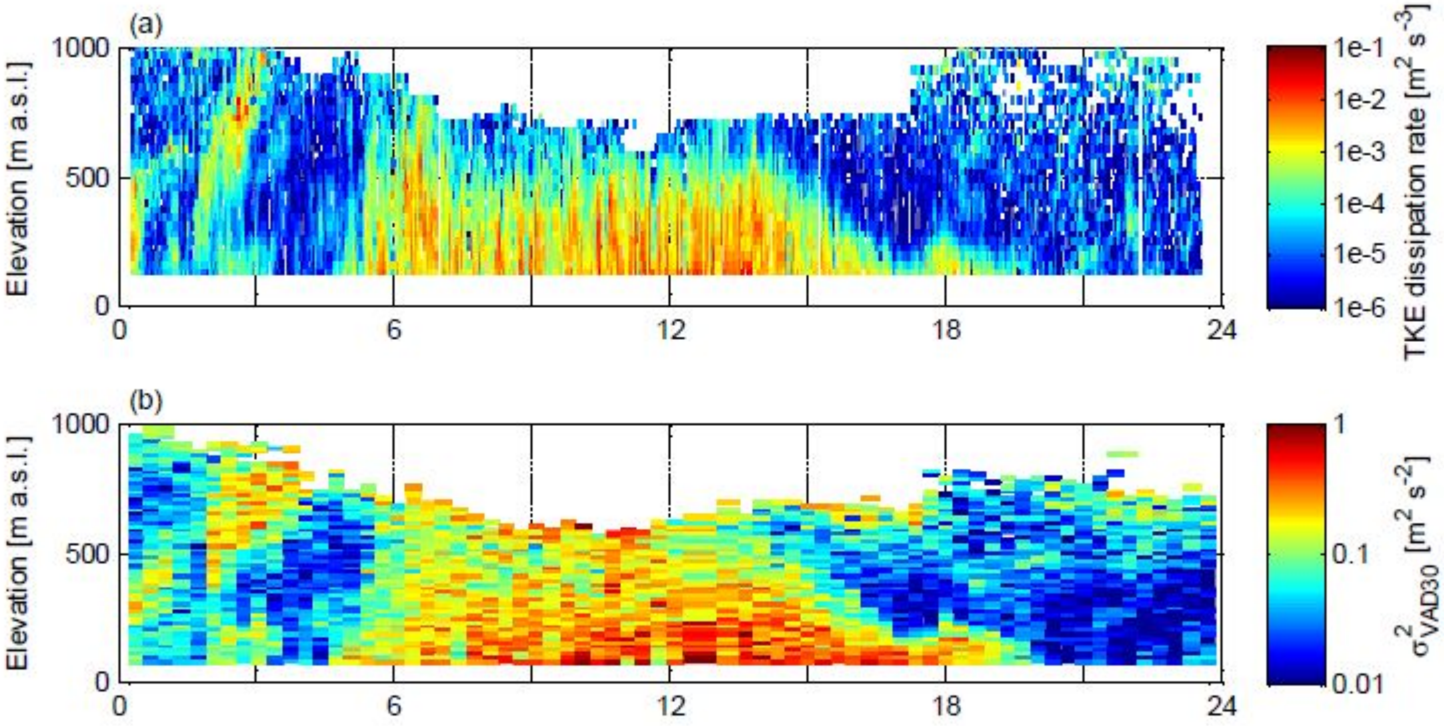
$$R(r) - R(r+30m) = \Delta R \approx \Delta V_{turb} + \upsilon$$



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

- 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)



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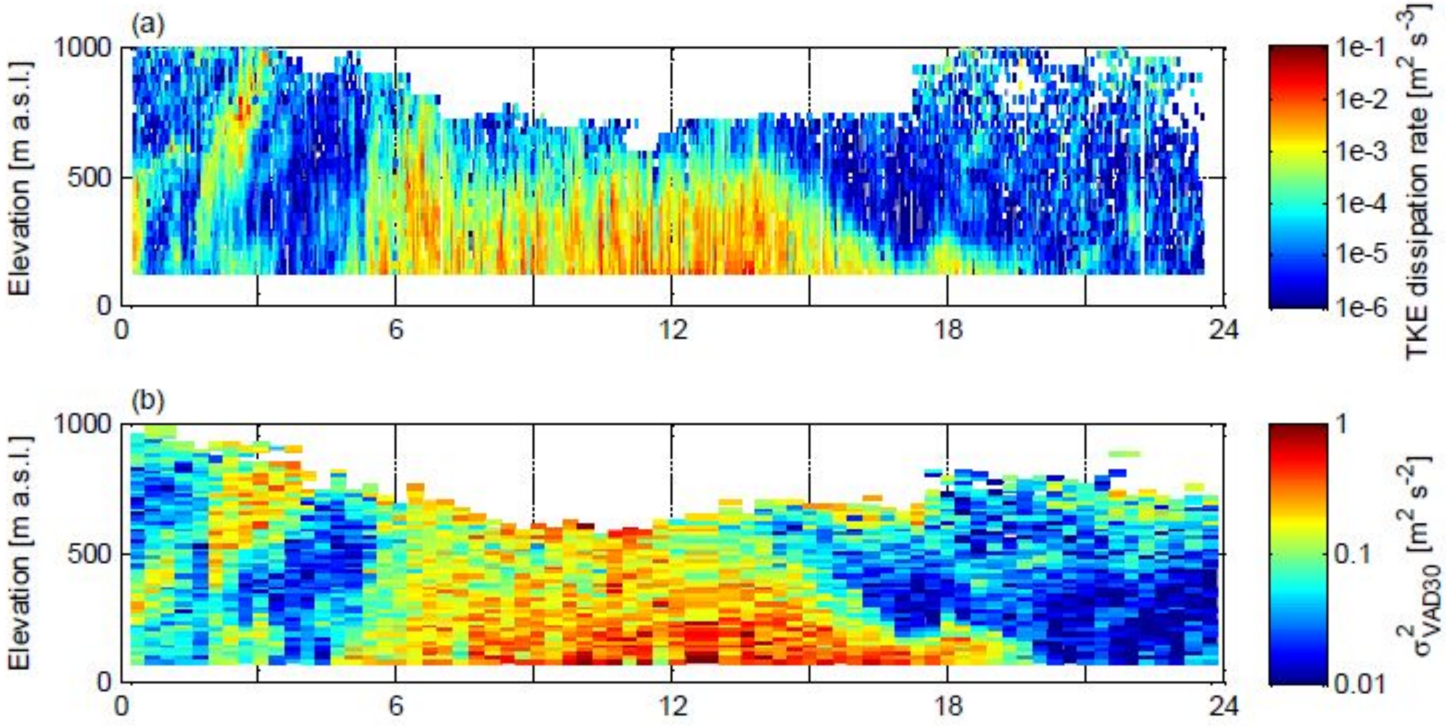
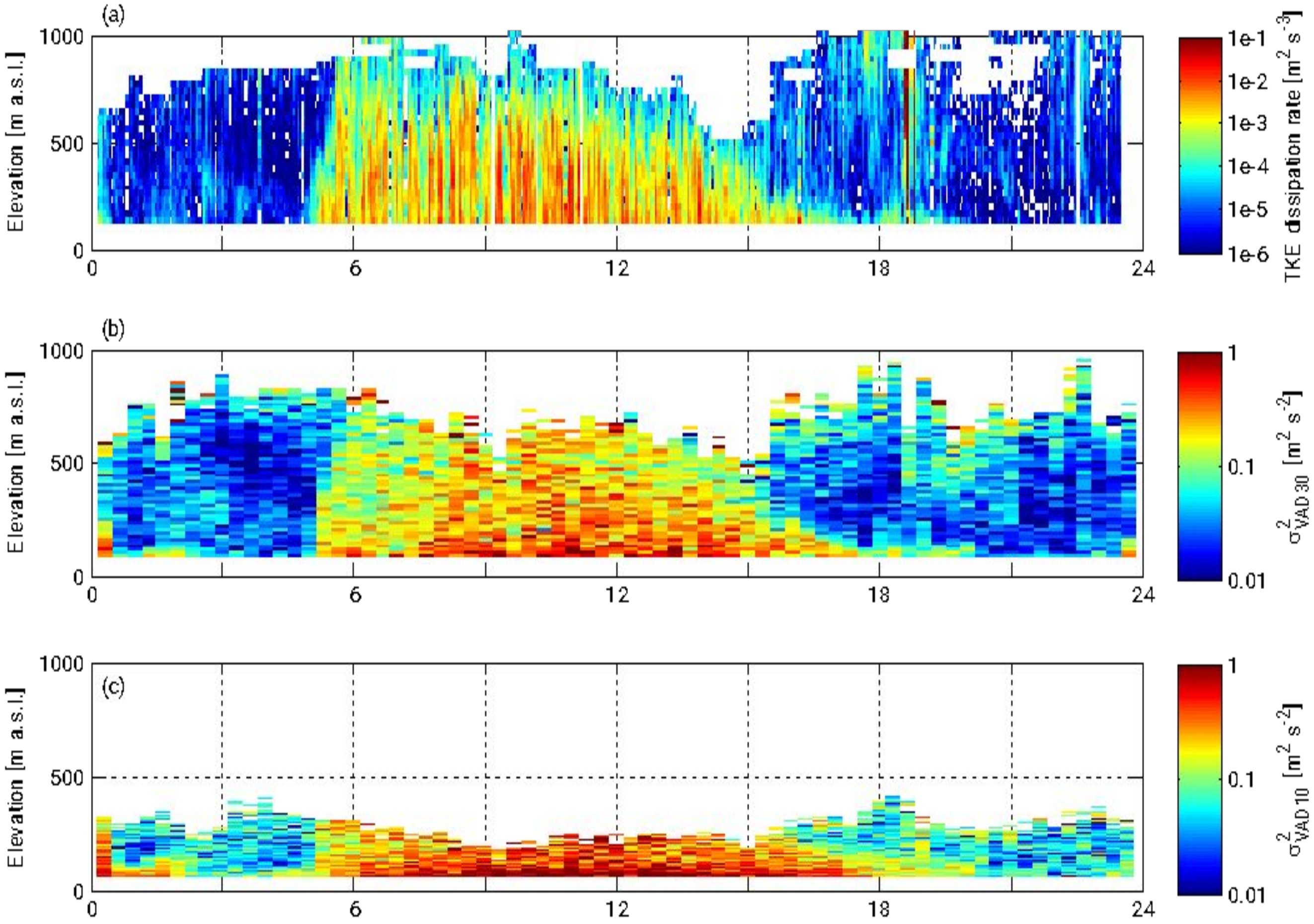
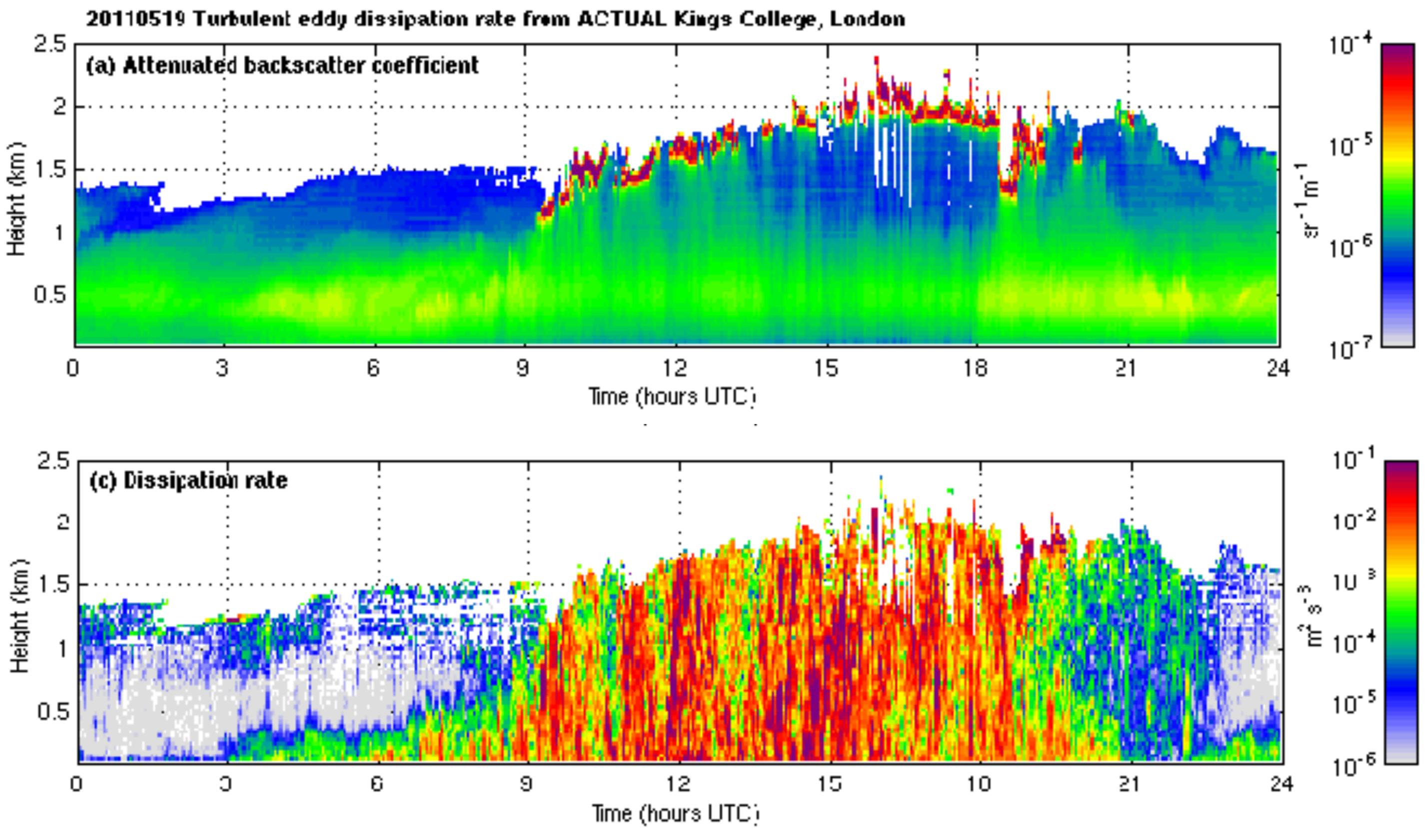


Turbulence from low-level VAD scans

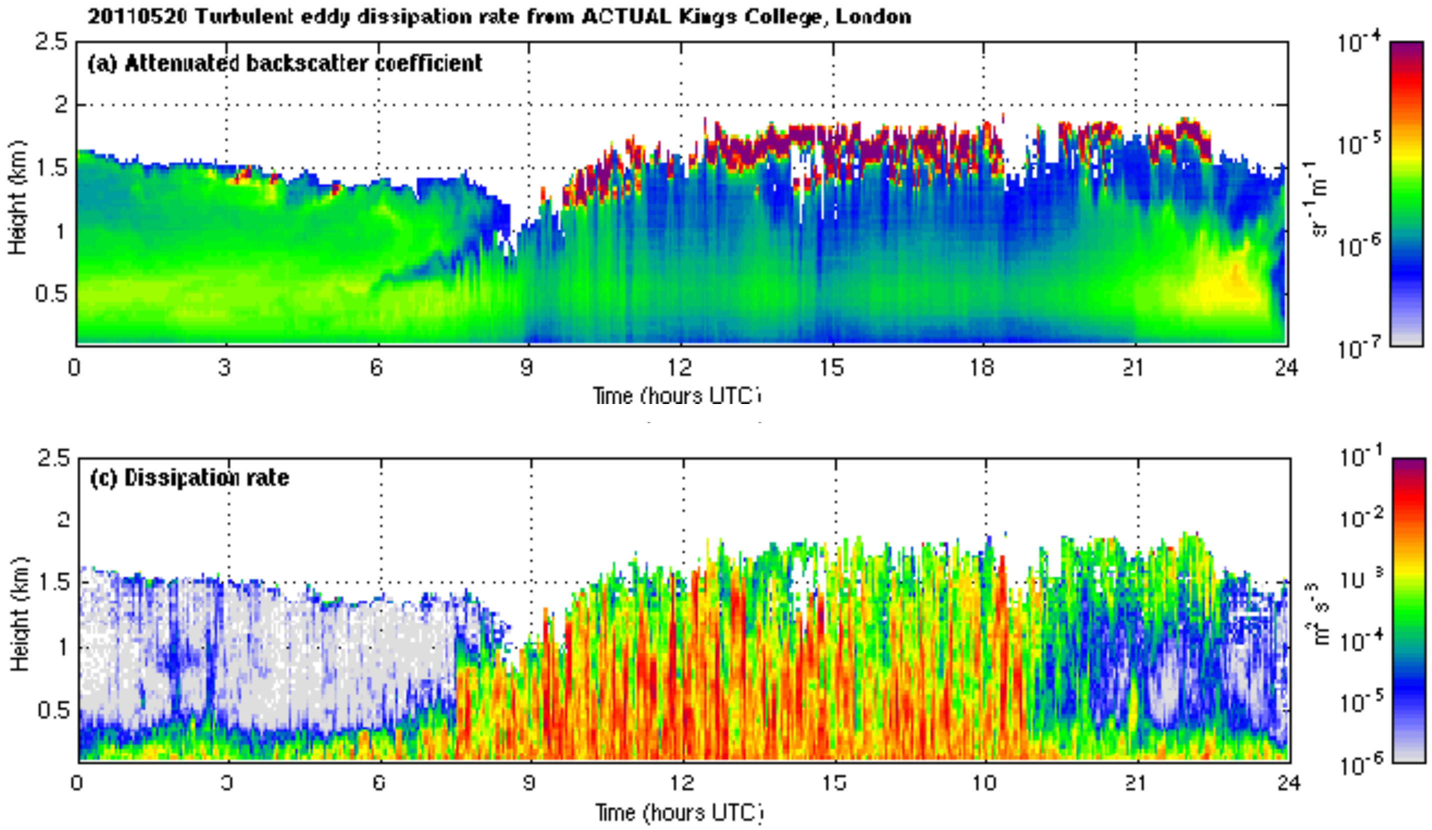
(Vakkari et al., 2015)



Turbulent properties from Doppler lidar

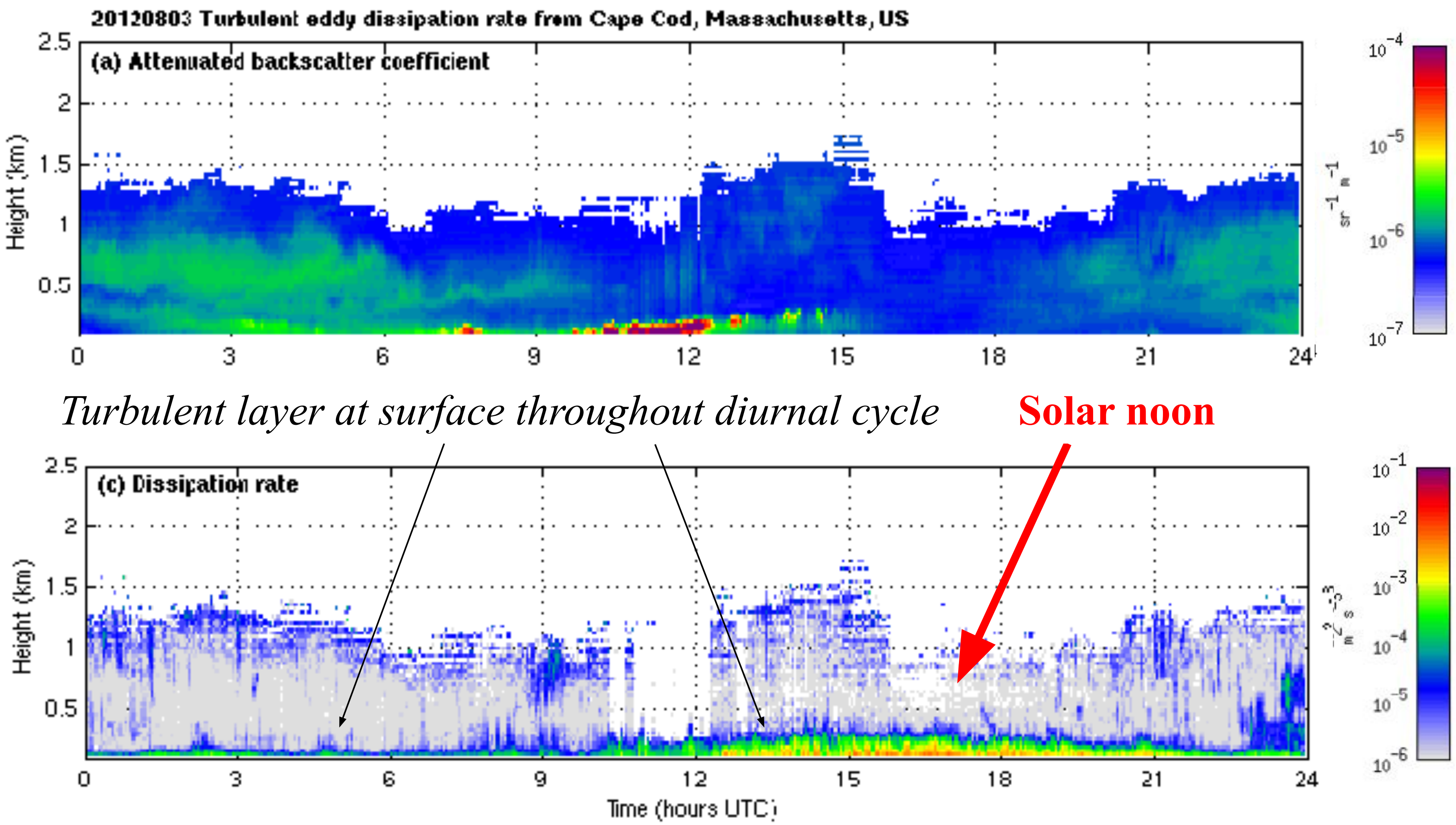


Turbulent properties from Doppler lidar

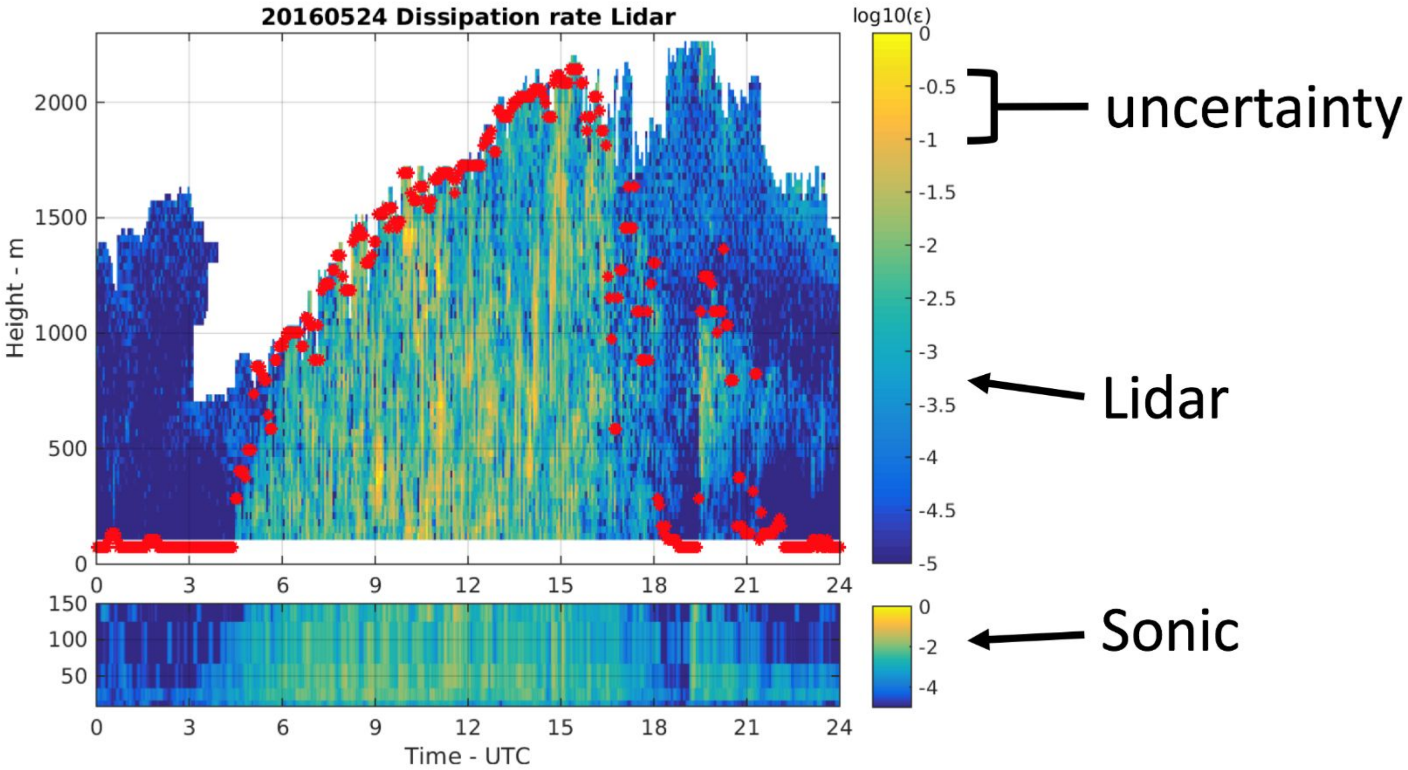


Turbulent properties from Doppler lidar

Cape Cod (Marine)



Evaluate DL turbulence using sonic anemometers



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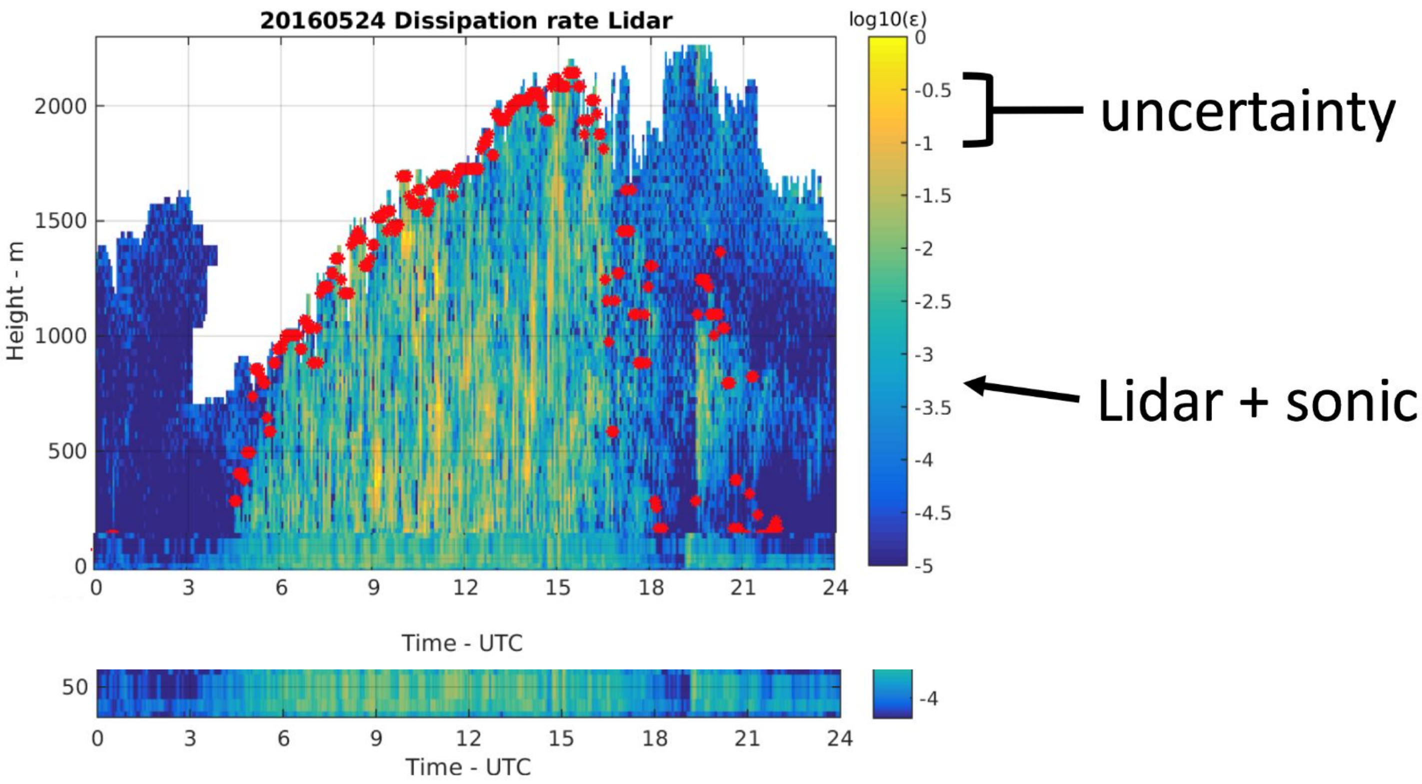
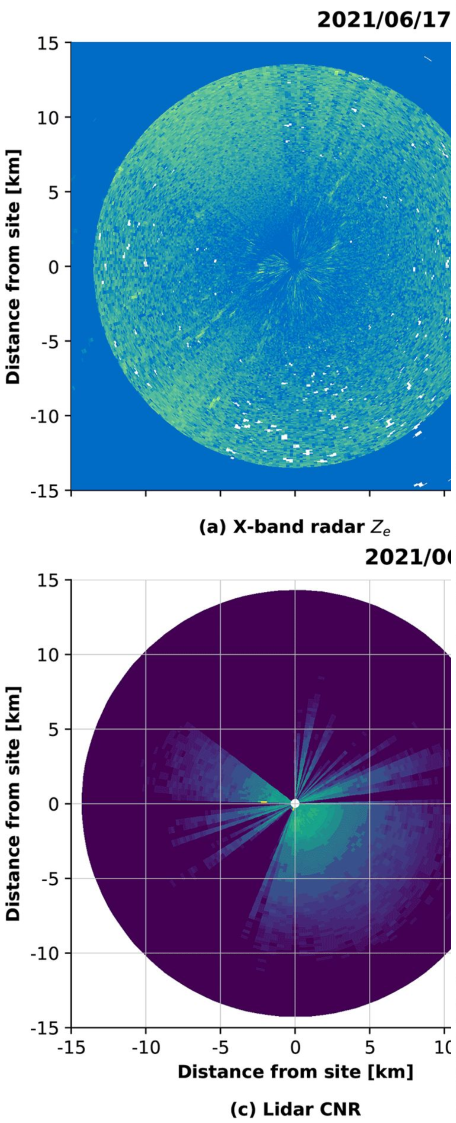


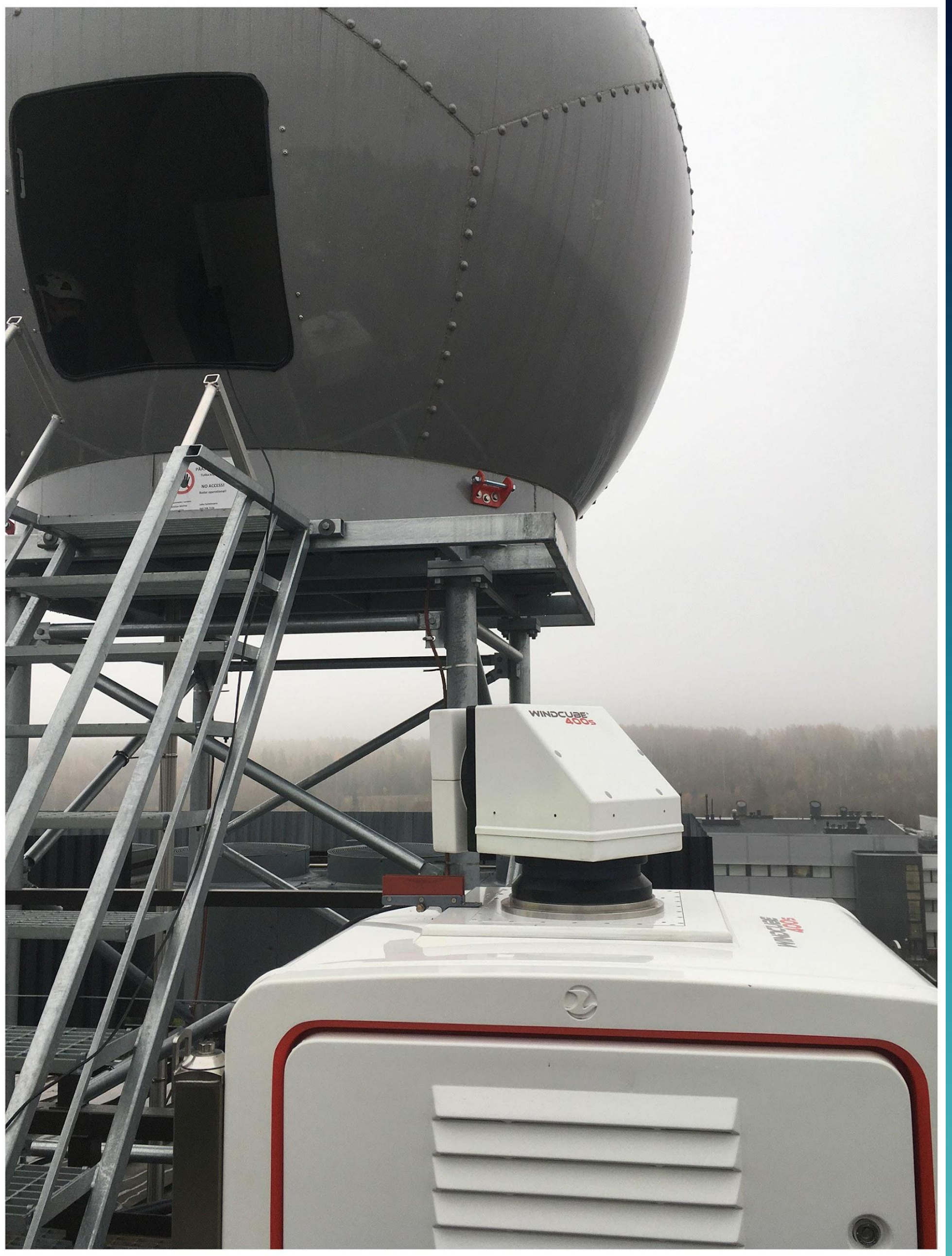
Combine lidar and radar - winds

Elevation angles closer to horizontal

Vaisala X-Band weather radar
Vaisala Windcube 400s

Clear day, aerosol and a few insects





Articles / Volume 15, issue 21 / AMT, 15, 6507–6519, 2022

https://doi.org/10.5194/amt-15-6507-2022

Article | Assets | Peer review

Research article | 🅭🅯

Complementarity of wind measurements from co-located X-band weather radar and Doppler lidar

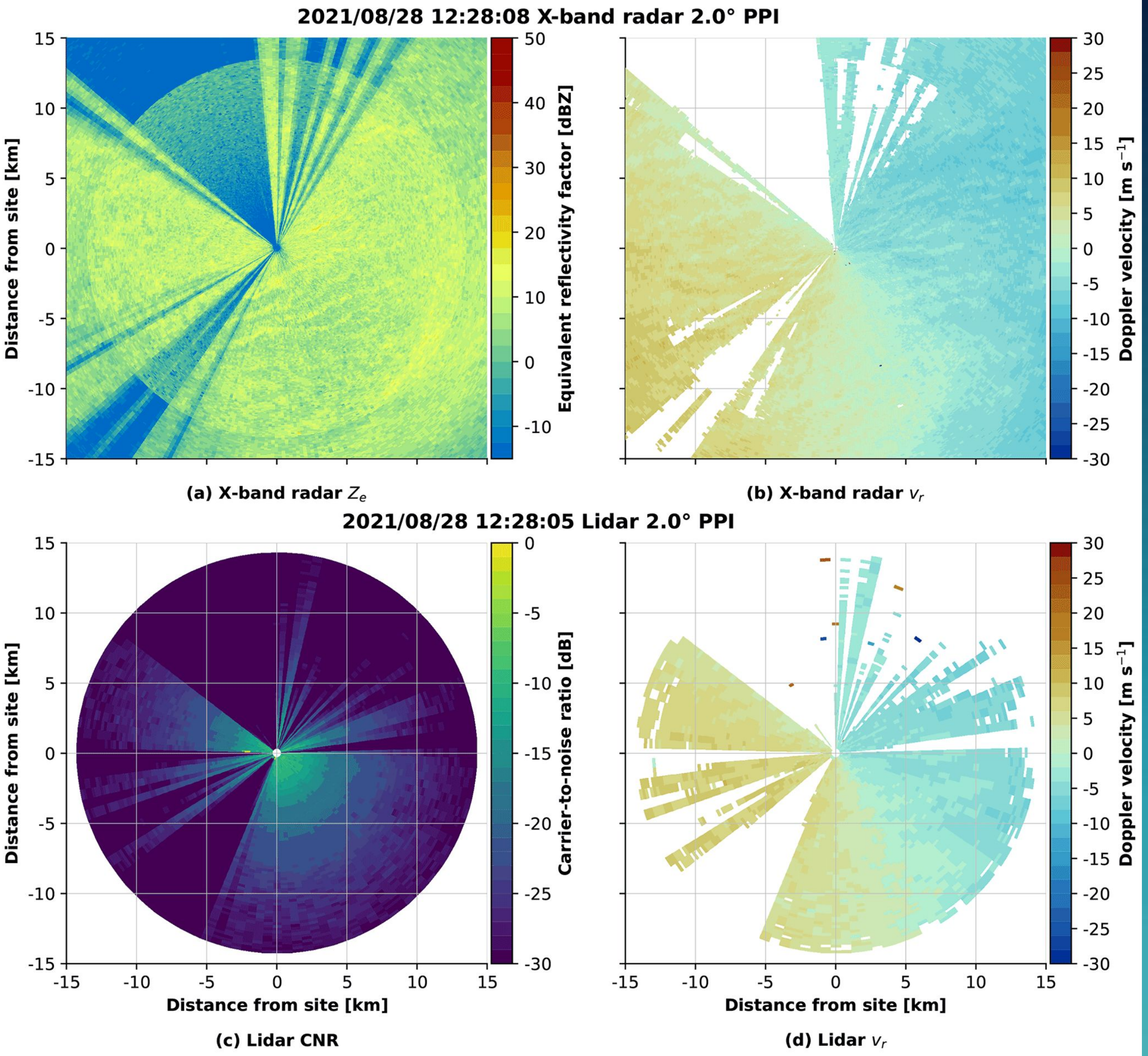
Jenna Ritvanen, Ewan O'Connor, Dmitri Moisseev, Raisa Lehtinen, Jani Tyynelä, and Ludovic Thobois

Combine lidar and radar - winds

Elevation angles closer to horizontal

Vaisala X-Band weather radar
Vaisala Windcube 400s

Clear air, aerosol and lots of insects



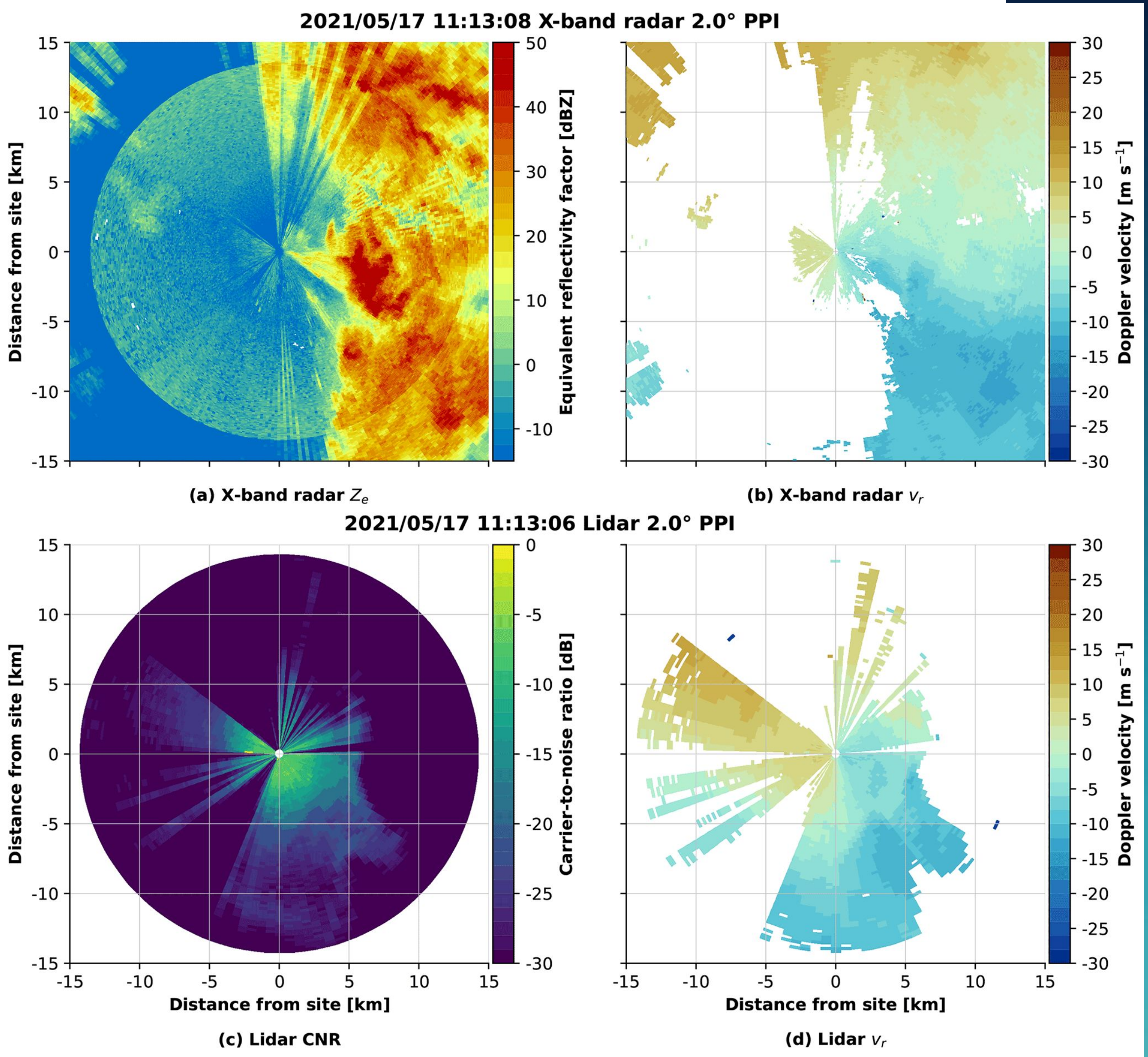
Combine lidar and radar - winds

Elevation angles closer to horizontal

Vaisala X-Band weather radar
Vaisala Windcube 400s

Rain showers

Complementary!



Combine lidar and radar - winds

Elevation angles closer to horizontal

Vaisala X-Band weather radar
Vaisala Windcube 400s

Measurements agree

Articles / Volume 15, issue 21 / AMT, 15, 6507–6519, 2022

https://doi.org/10.5194/amt-15-6507-2022

Article | Assets | Peer review

Research article |

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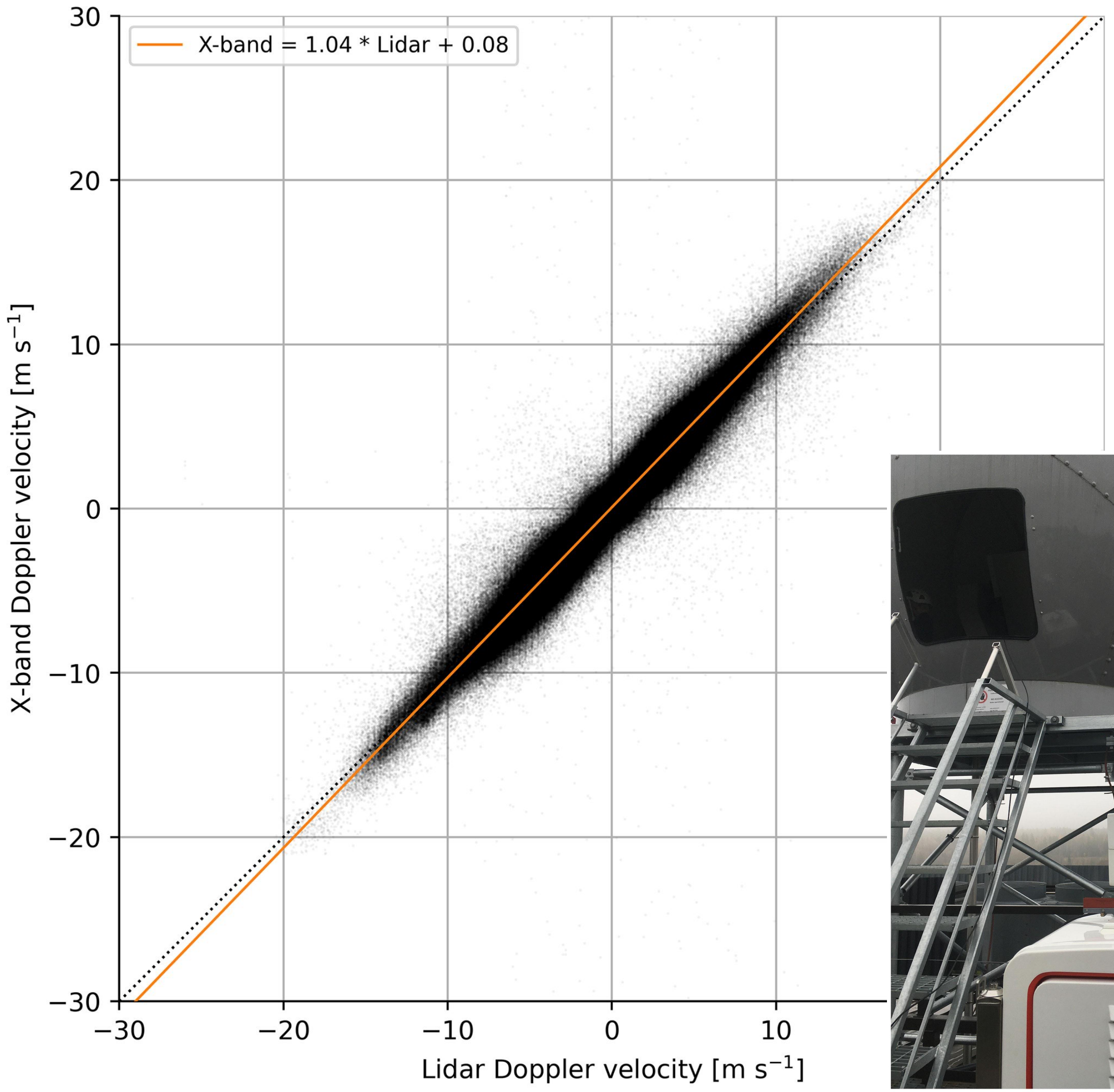

Combine lidar and radar - winds

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Elevation angles closer to vertical

Articles / Volume 15, issue 2 / ESSD, 15, 769–789, 2023

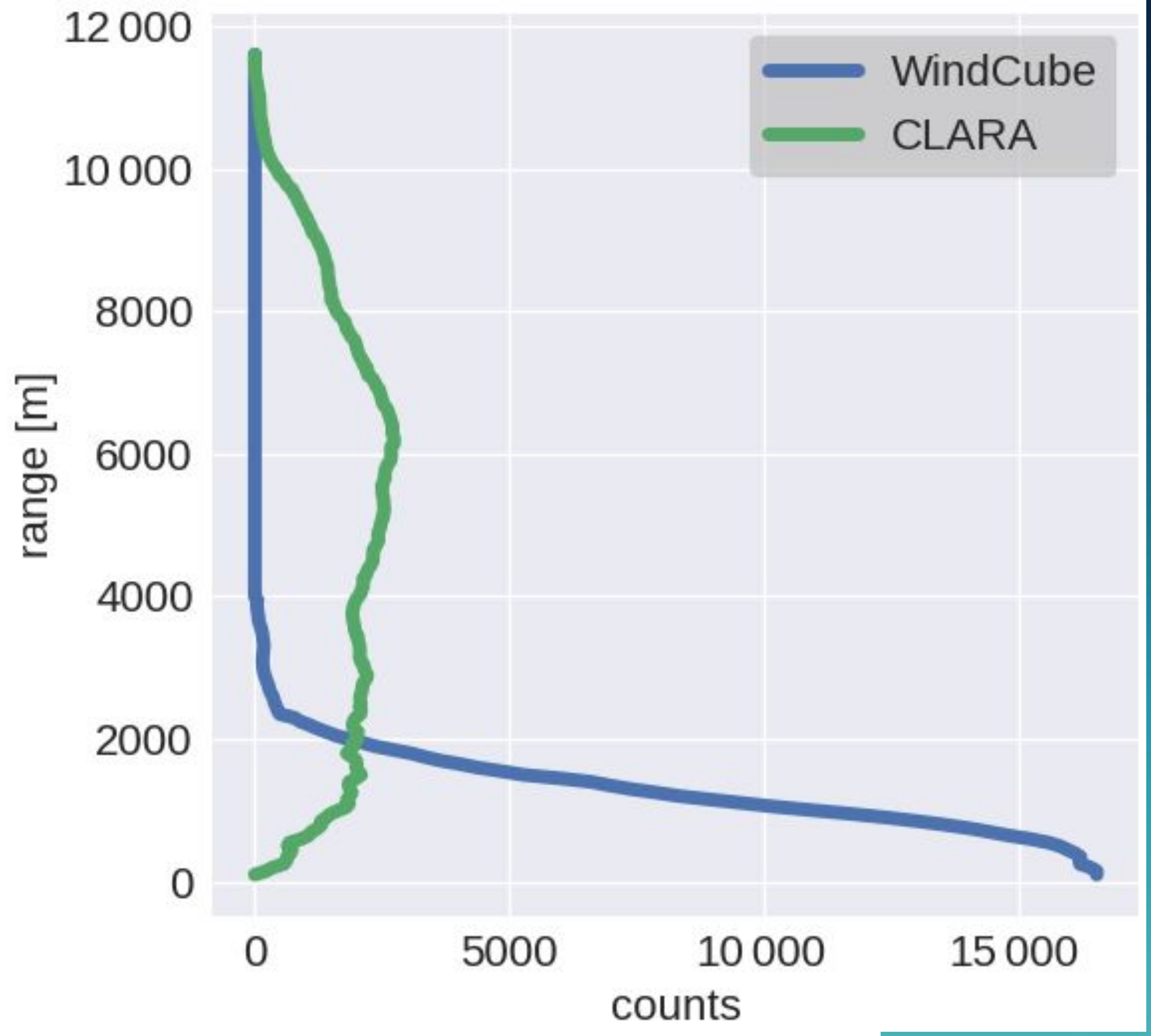
https://doi.org/10.5194/essd-15-769-2023

Article | Assets | Peer review

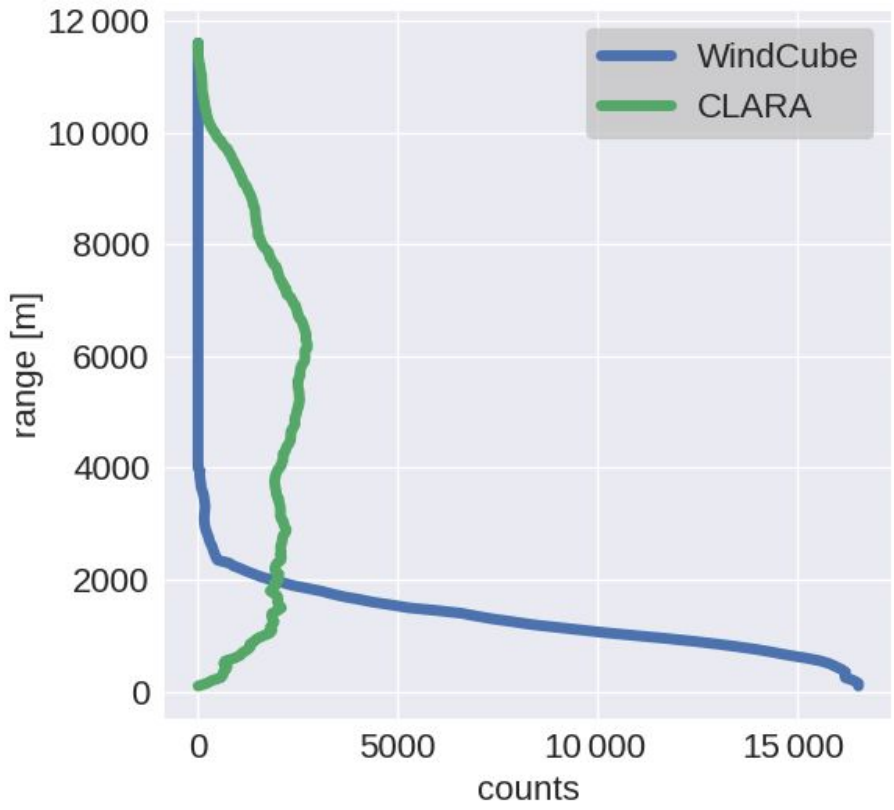
Data description paper |

Combined wind lidar and cloud radar for high-resolution wind profiling

José Dias Neto, Louise Nuijens, Christine Unal, and Steven Knoop



Combine lidar and radar - winds



Articles / Volume 15, issue 2 / ESSD, 15, 769–789, 2023

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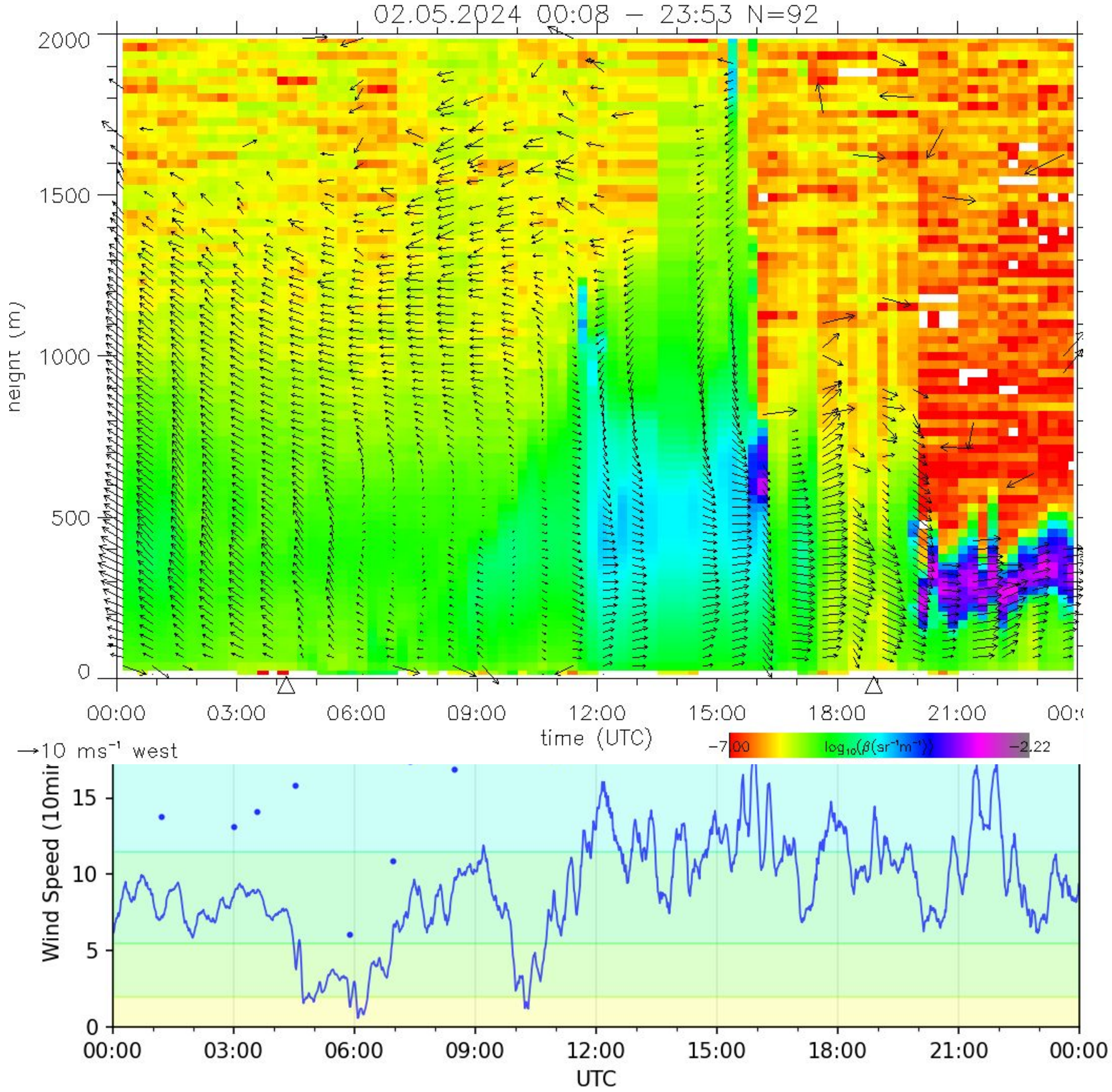
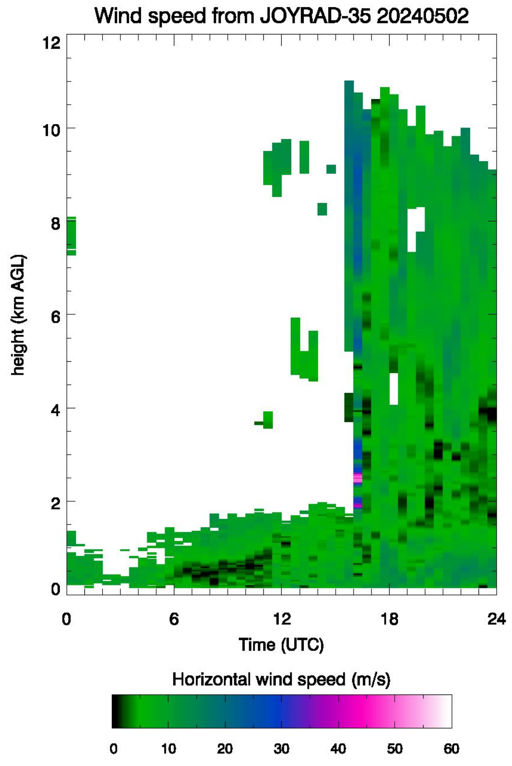
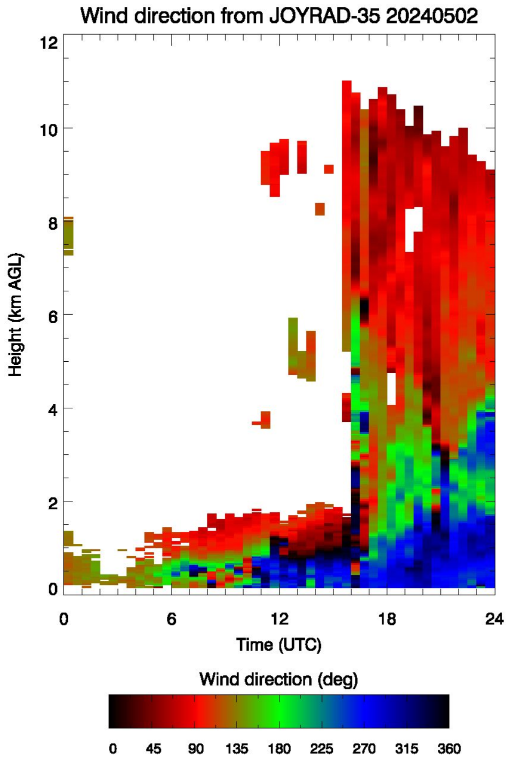
Complementary!

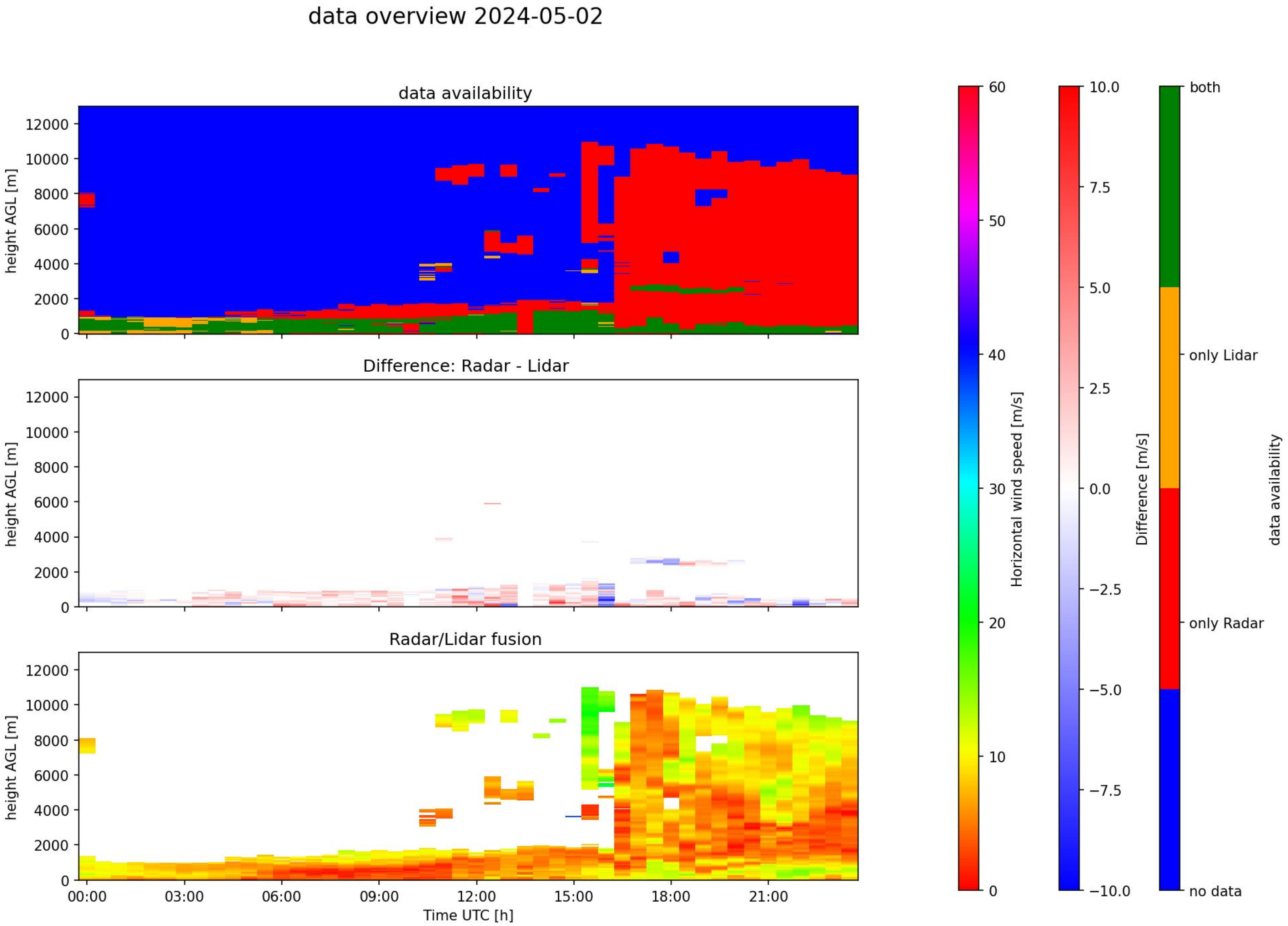
ACTRIS stations: JOYCE (Juelich)







ACTRIS stations: JOYCE (Juelich)

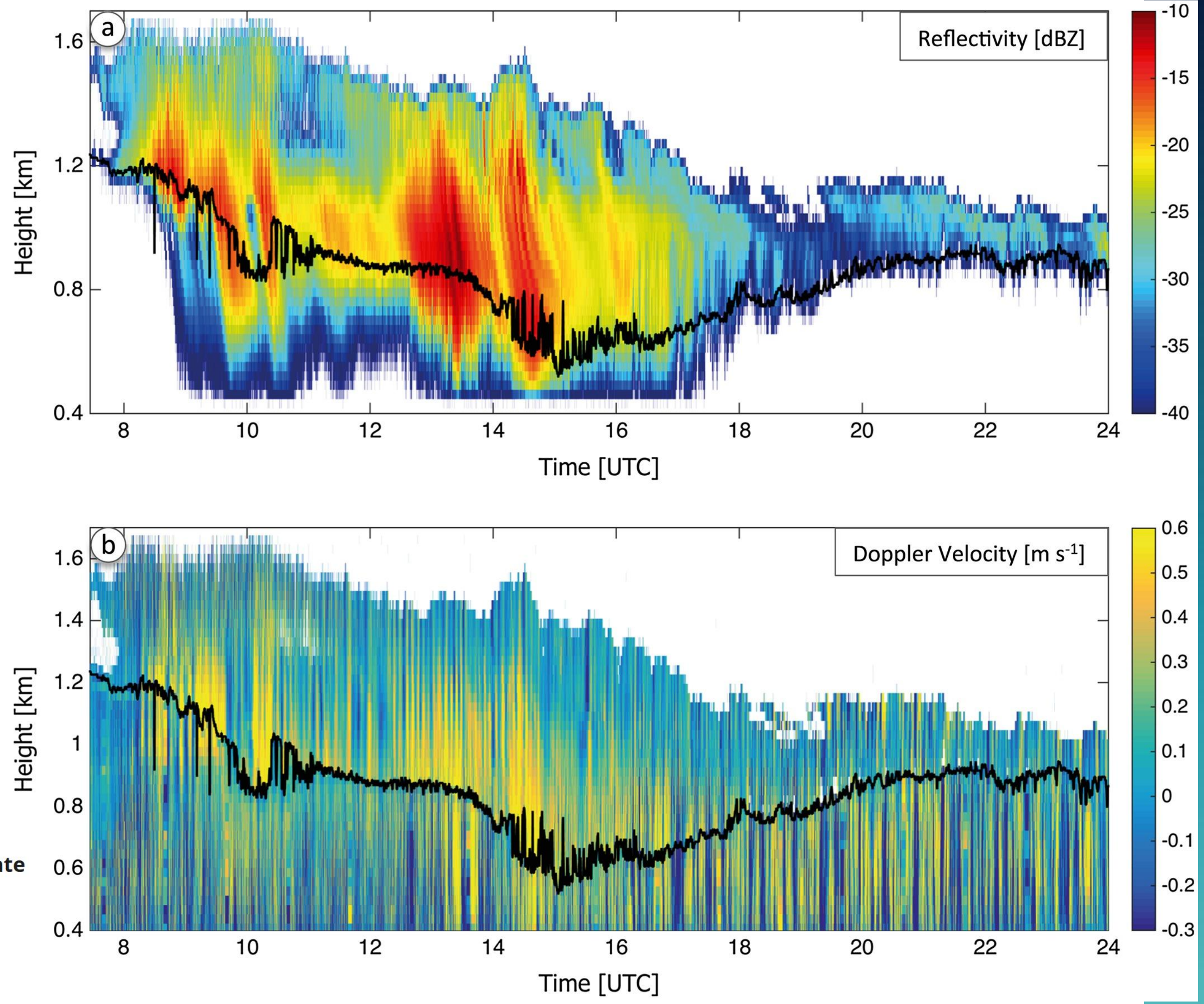


Combine lidar and radar - turbulence

Vertically-pointing

35 GHz KAZR
Halo Streamline

Velocities agree?



On the unified estimation of turbulence eddy dissipation rate using Doppler cloud radars and lidars

Paloma Borque, Edward Luke, Pavlos Kollias

First published: 12 May 2016 | https://doi.org/10.1002/2015JD024543 | Citations: 53

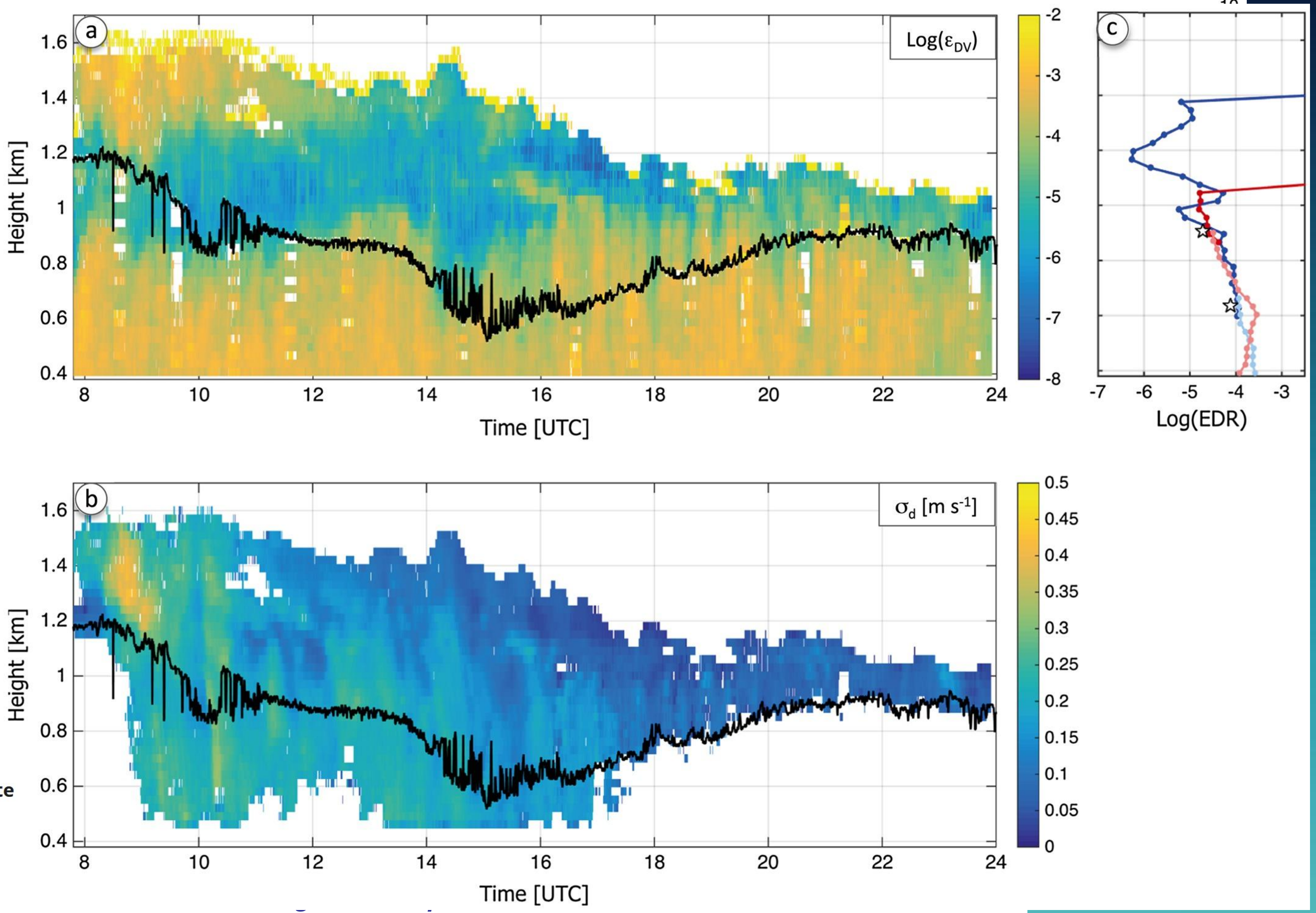
ACTRIS
CCRES

Combine lidar and radar - turbulence

Vertically-pointing

35 GHz KAZR
Halo Streamline

Turbulence does!



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WIVERN Satellite

A WInd VElocity Radar Nephoscope for observing global winds, clouds and precipitation

94 GHz Doppler cloud radar
Launch date: 203?