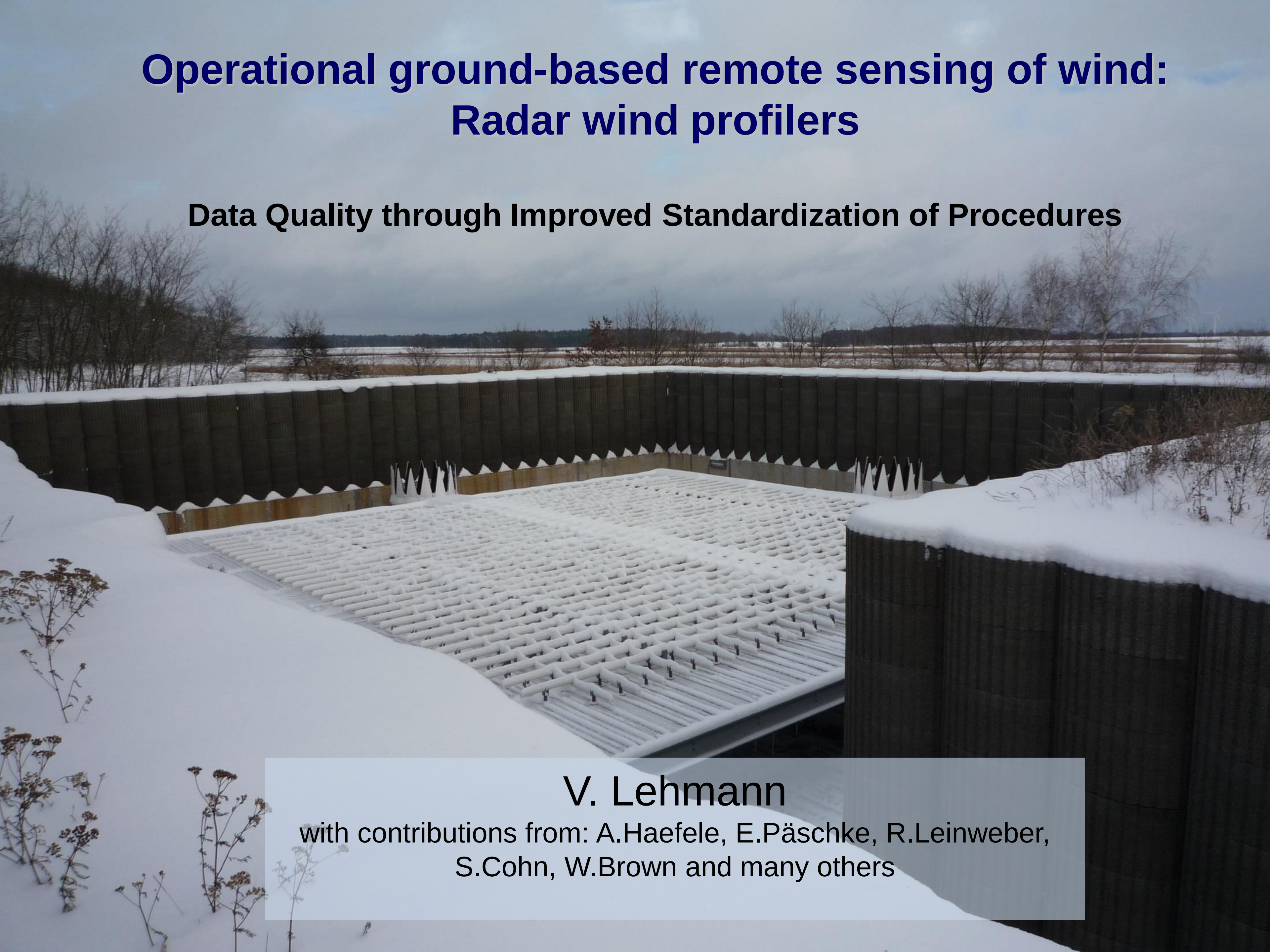
# Operational ground-based remote sensing of wind: Radar wind profilers

## Data Quality through Improved Standardization of Procedures



V. Lehmann

with contributions from: A.Haefele, E.Päschke, R.Leinweber, S.Cohn, W.Brown and many others

# Outline of talk

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

1. RWP networks and data impact in NWP

2. RWP – some fundamentals

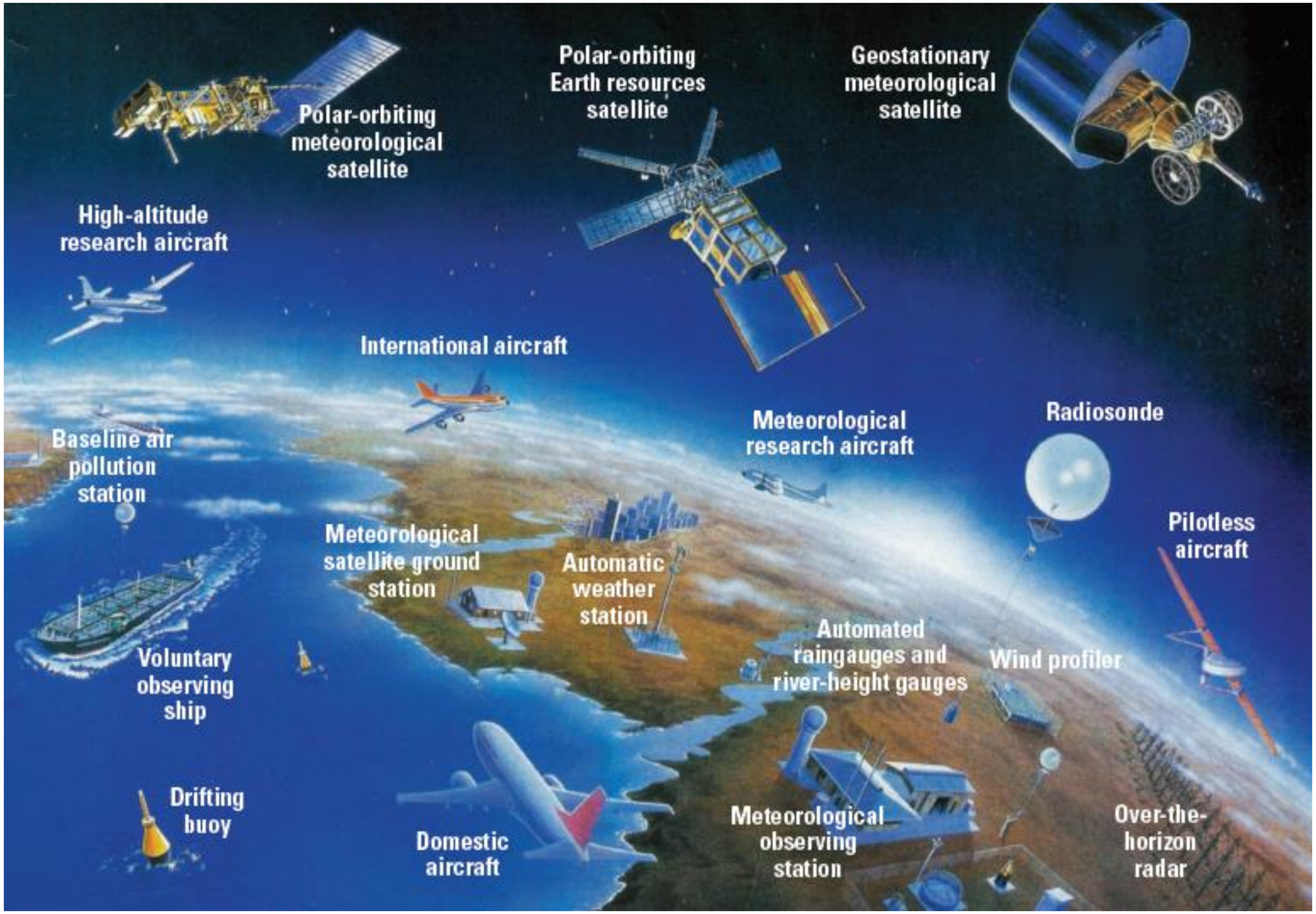
3. Accuracy assessment and possibilities for standardisation

1. **RWP networks and data impact in NWP**

2. RWP – some fundamentals

3. Accuracy assessment and possibilities for standardisation

# The WMO Integrated Global Observing System (WIGOS)




***Vertical profiles of wind vector:***

*Ground based:*

- *Radiosondes*
- *Pilot-Balloons*
- *Aircraft*
- *Wind profilers*
- *(Weather radars)*

*Space based:*

- *AMV's*
- *Indirect (through mass field)*

From WMO WIGOS-Flyer: http://www.wmo.int/pages/prog/www/wigos/index_en.html

# RWP networks in WIGOS (as of 2013)

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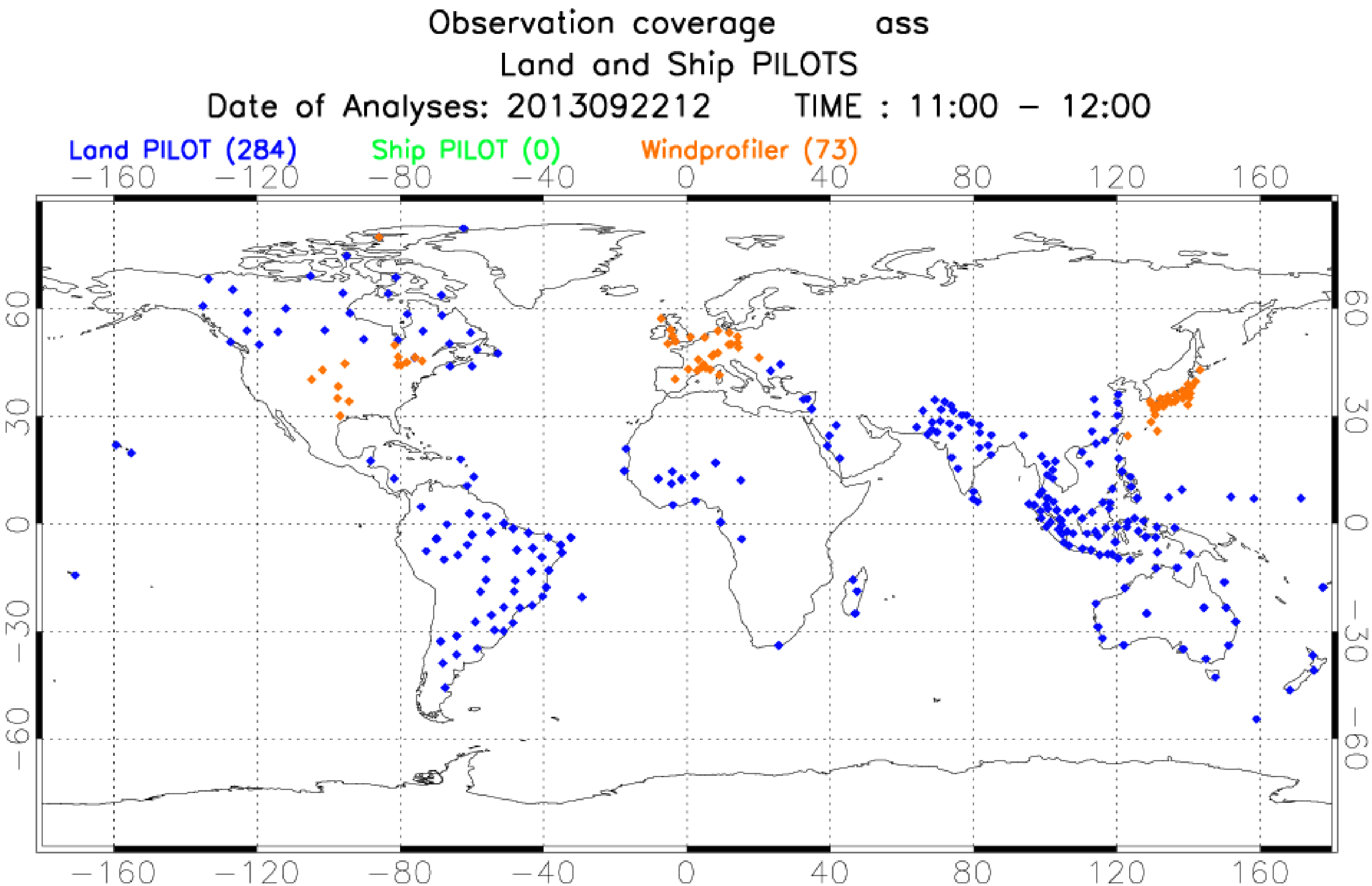


Courtesy: Alexander Cress (DWD)

# ECMWF FSO estimate of observation impact

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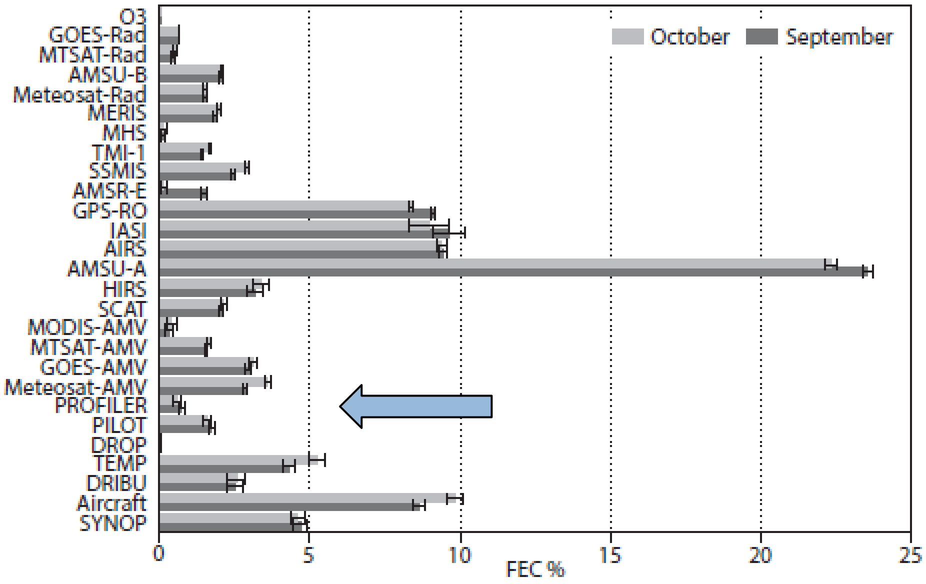
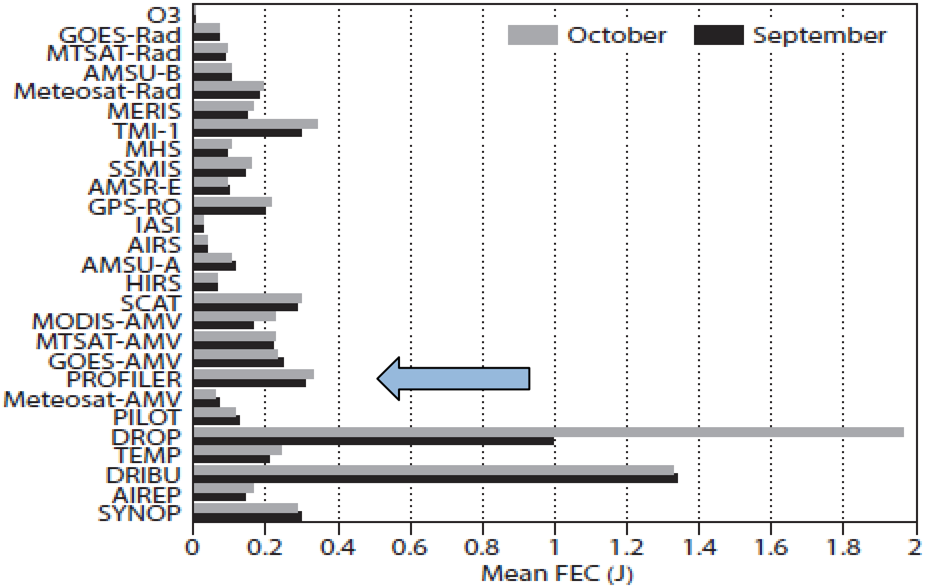
Total FEC.




Mean FEC
(normalized by # of observations)




*Observation contribution to the global forecast error reduction (FEC) in the ECMWF IFS, grouped by observation type in percent, for September and October 2011.*

*Courtesy of C. Cardinali, ECMWF.*

# UK MetOffice FSO estimate of RWP impact

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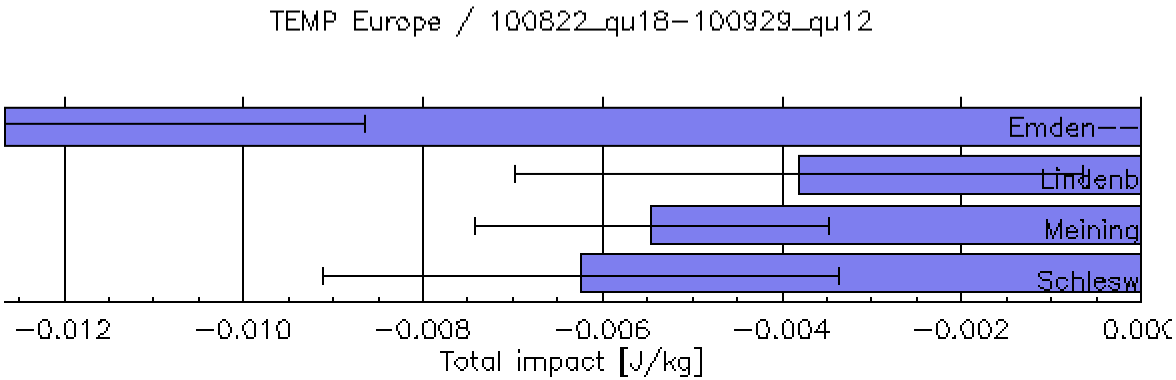
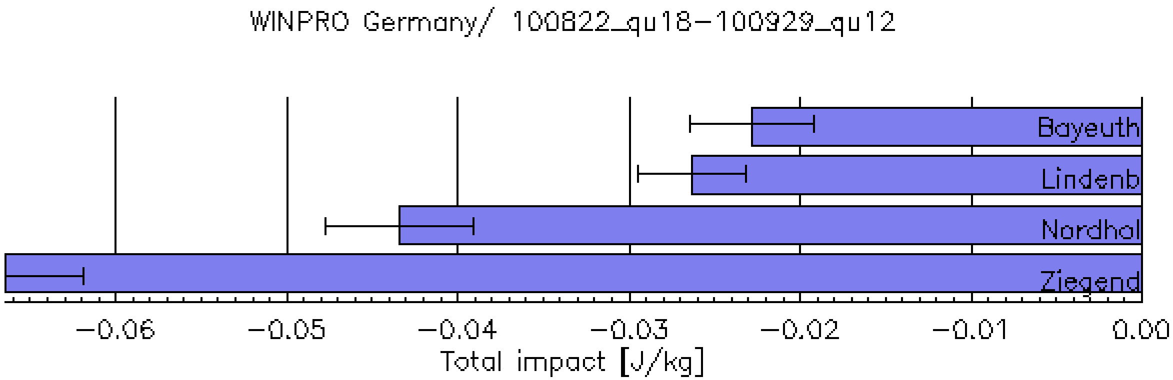



Reduction of forcast error measured by global moist energy norm (u,v,T,p,q)

4 German TEMPs vs.

4 German RWP (482 MHz)

First results from UK MetO FSO-tool for the period

Aug 22 – Sep 29, 2010

**Lindenberg RWP impact is 5 times bigger than the impact of the co-located Radiosonde !**

*Courtesy:*

*Richard Marriott*

*Catherine Gaffard*

*Ronny Leinweber*

Met Office

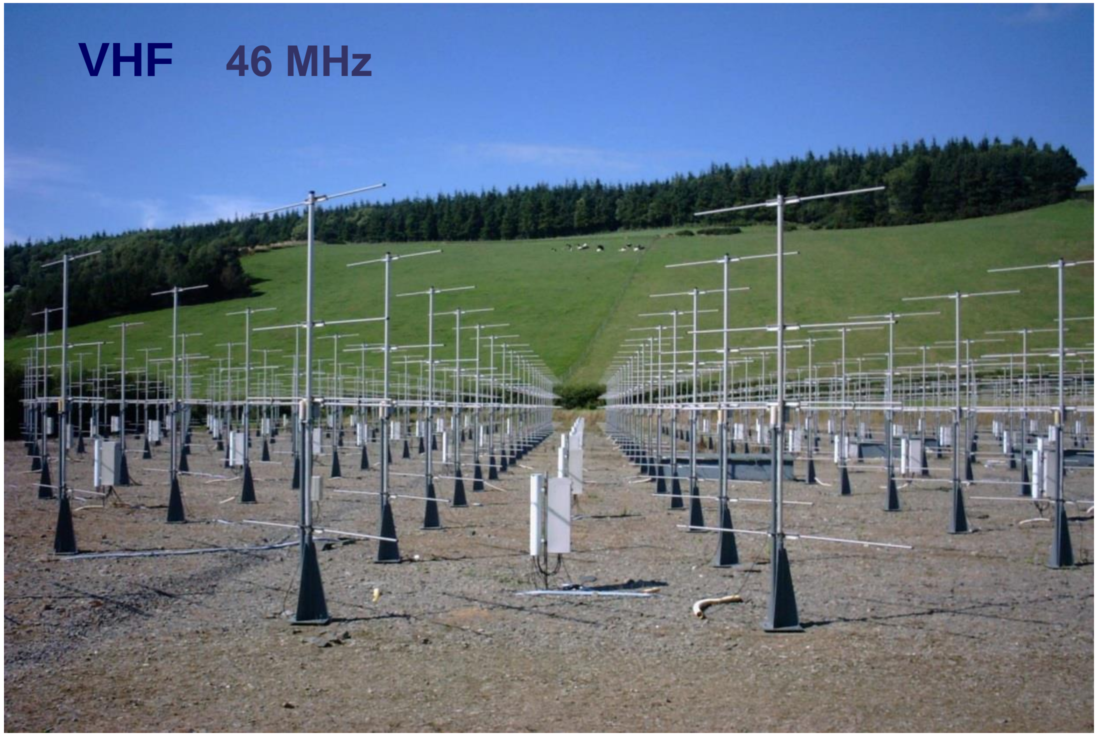
1. RWP networks and data impact in NWP

2. **RWP – some fundamentals**

3. Accuracy assessment and possibilities for standardisation

# RWP - large diversity of instruments
## (2 out of 28 CWINDE profiler)

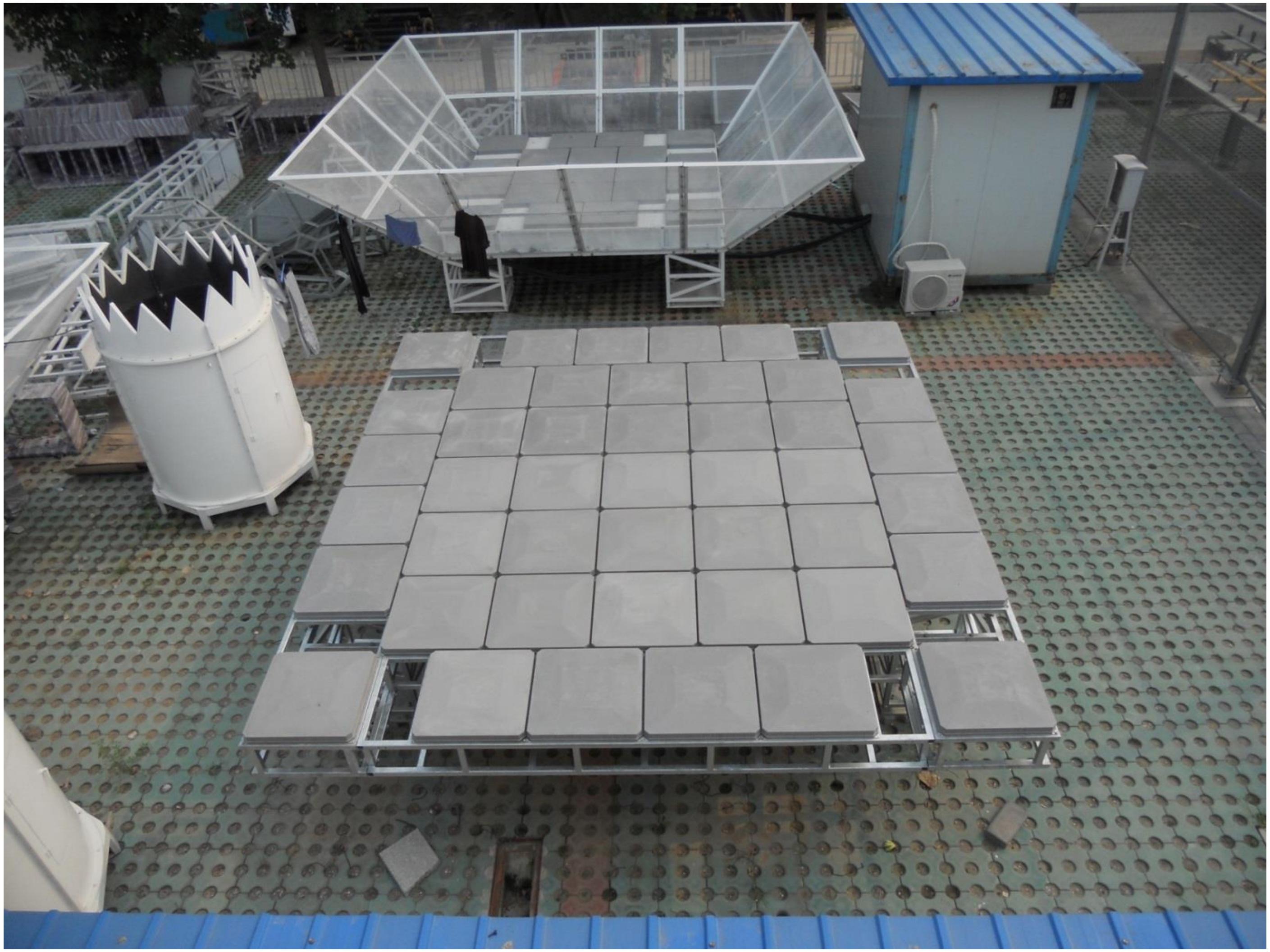





MST Radar Aberystwyth (UK)

RWP Schaffhausen (CH)

# CMA RWP (L-Band)



Courtesy CMA – Li Bai

气象探测中心
**Meteorological Observation Center**

# 449 MHz RWP with full beam steering capability (NOAA)

Courtesy: S. A. McLaughlin

# L-Band RWP (JMA)

Courtesy JMA

# RWP – land- and shipbased operation

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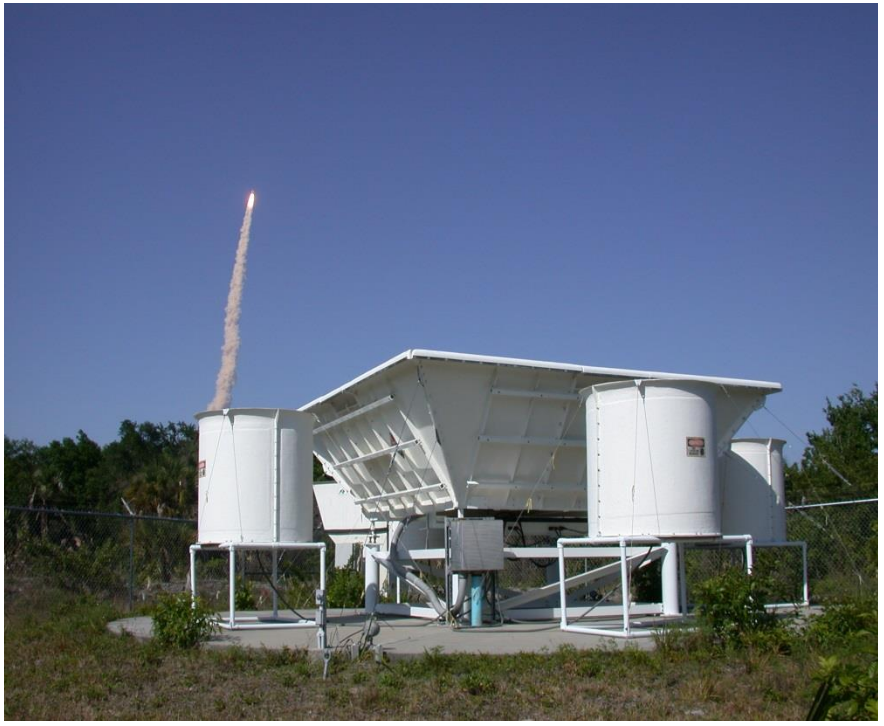
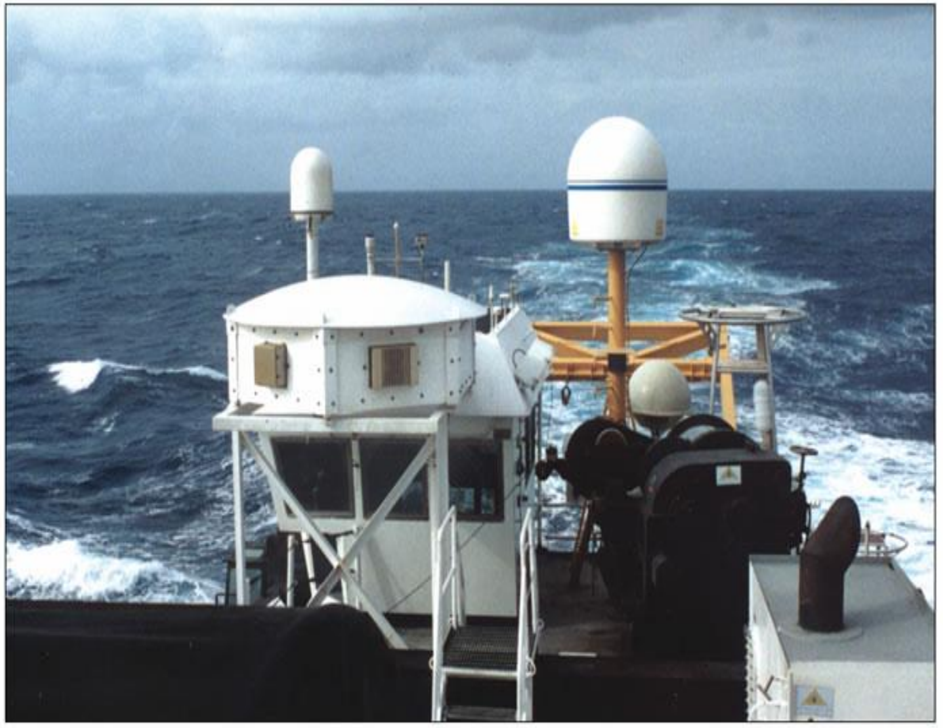
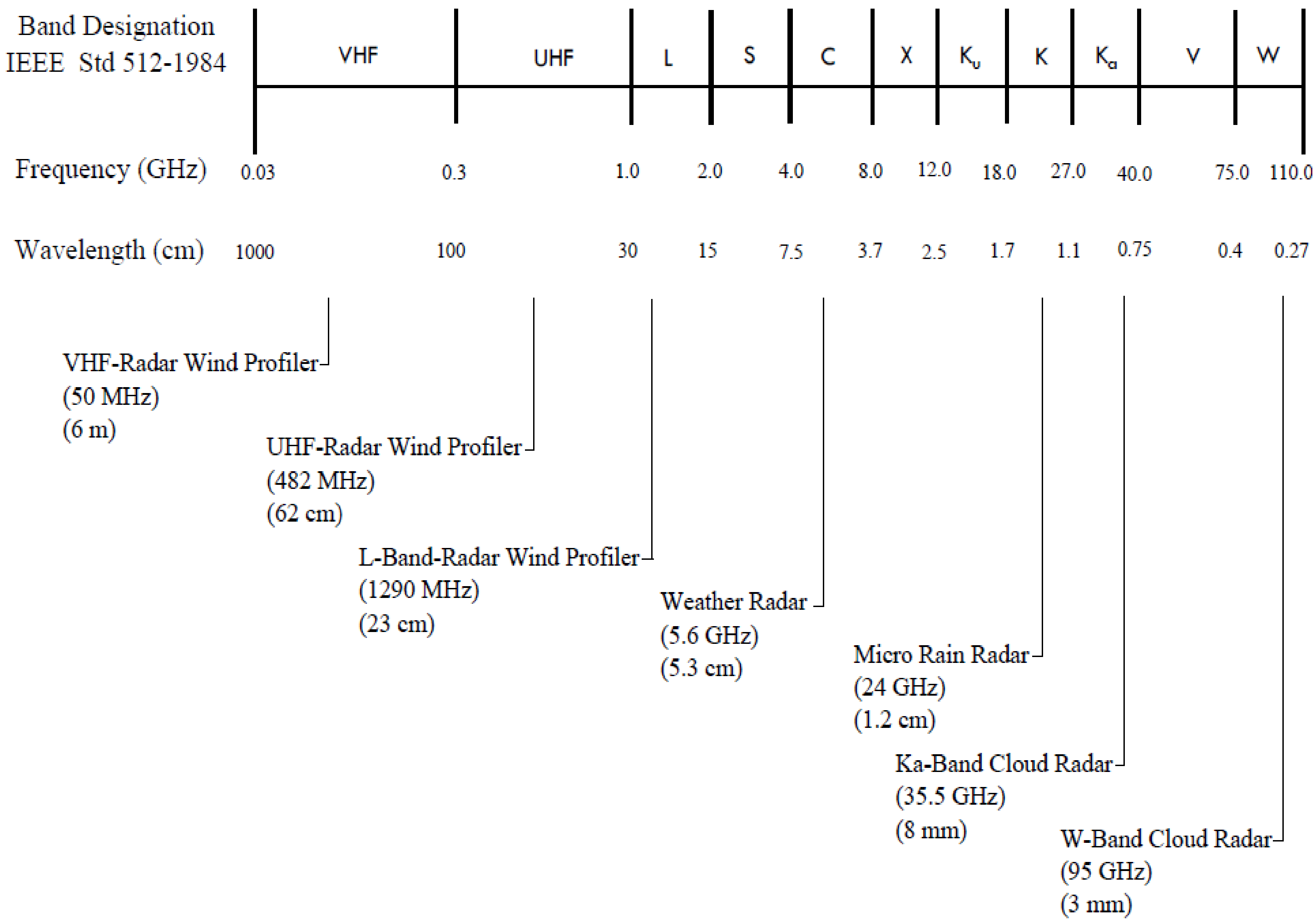


Radar wind profiler at Kennedy Space Center during launch of Space Shuttle Atlantis (2002)



Radar wind profiler on board of NOAA RV „Ronald H. Brown“

# Radar frequencies used in Meteorology



# Physical scattering mechanisms for RWP

- Irregularities of refractive index („clear-air scattering“)
- Particle ensembles (precipitation)
- Clutter:
  - Ground reflections through antenna sidelobes
  - „Flyers“ – birds, bats, aircraft,…
  - Free electric charges (plasma - lighning, ionosphere)

## Dependent on wavelength !

# Refractive index of air

Refractive index descripes microscopic polarization of a dieelectric: $n^2 = \varepsilon.$

For air (mixture of non-polar and polar gases):

$$(n-1)_{Air} = \frac{k_1}{z_a}\frac{p}{T} + \frac{k_2}{z_w}\frac{e}{T} + \frac{k_3}{z_w}\frac{e}{T^2}$$

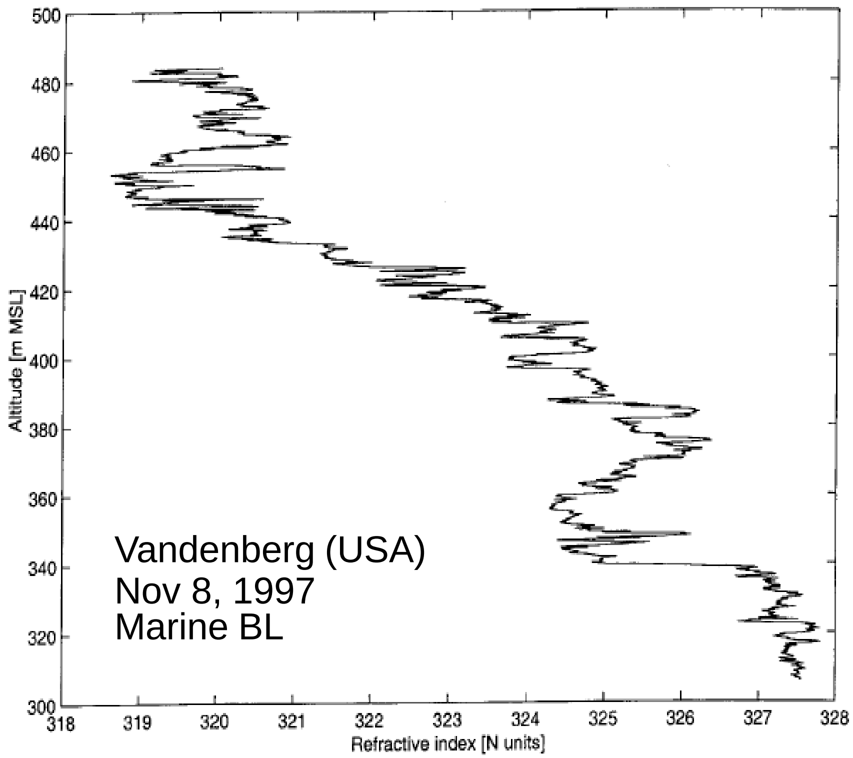
- Polarization ~ density
- $1/T^2$ : Debye relaxation

More conveniently expressed as Refractivity:

$$N = (n-1)\cdot 10^6$$

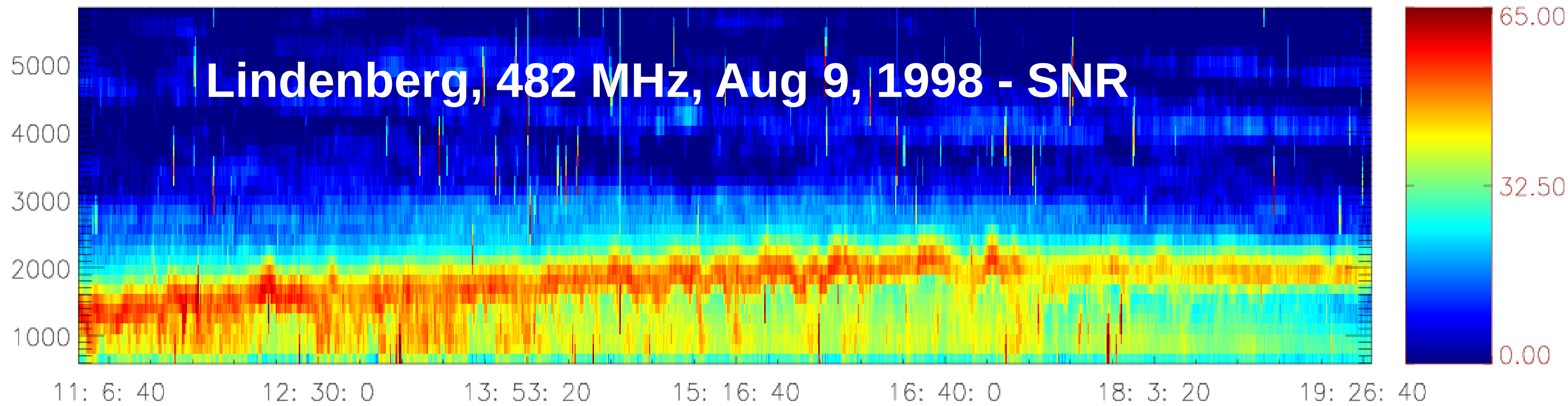
$$N = 77.6\frac{p}{T} + 71.6\frac{e}{T} + 3.7\cdot 10^5\frac{e}{T^2}$$

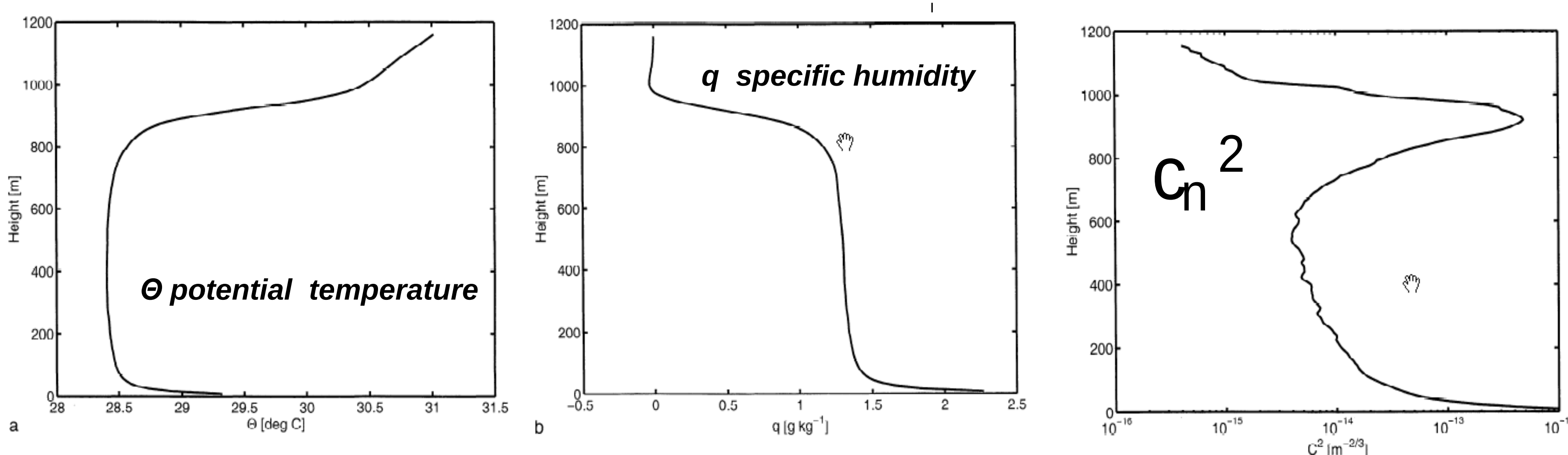
Helipod data from PHELIX 1997:
Tatarskii/ Muschinski (2001)



# Scattering from clear air






LES-Simulation of a CBL (Muschinski et.al 1999)

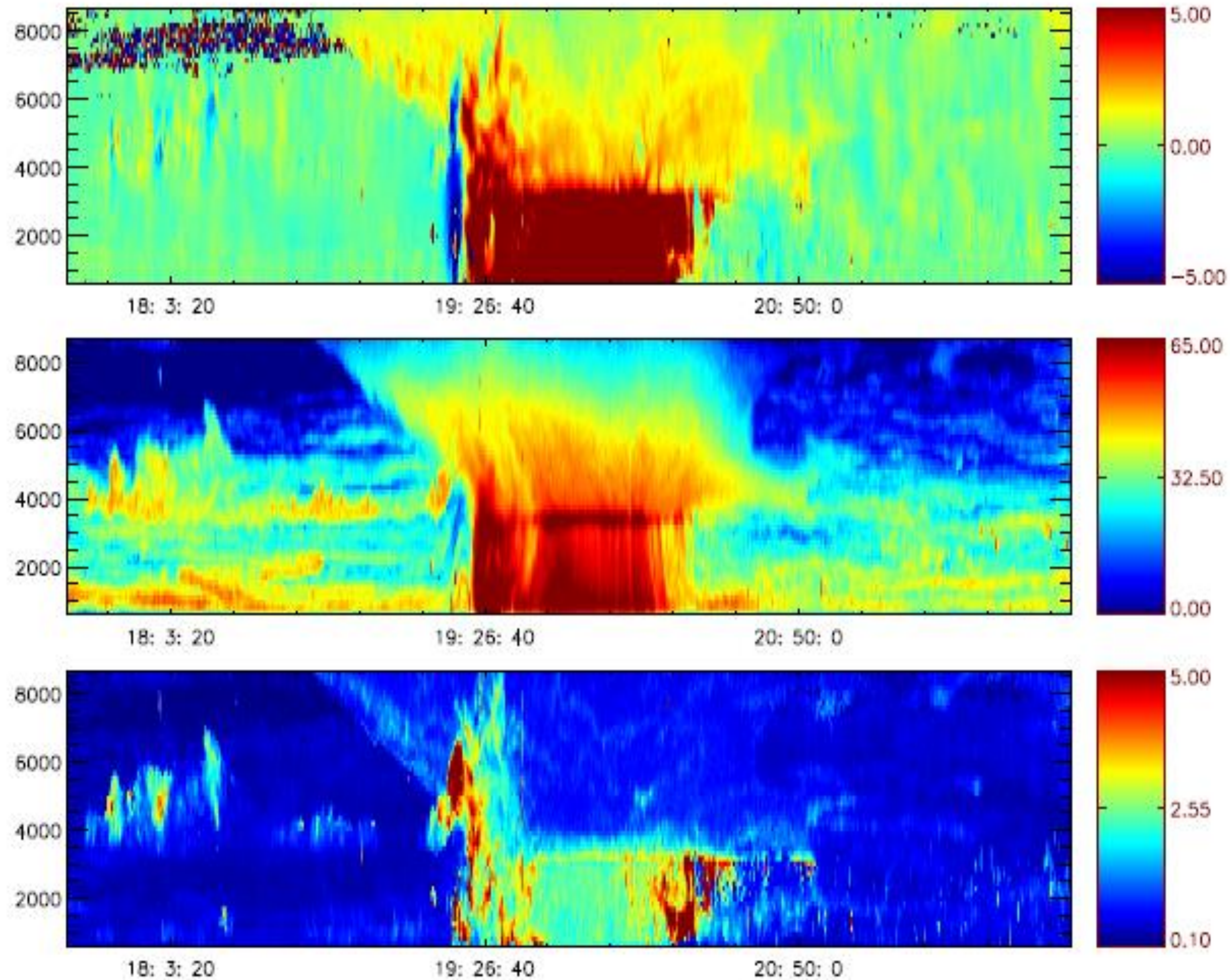
# Scattering from particles



Radial velocity (vertical)

Power

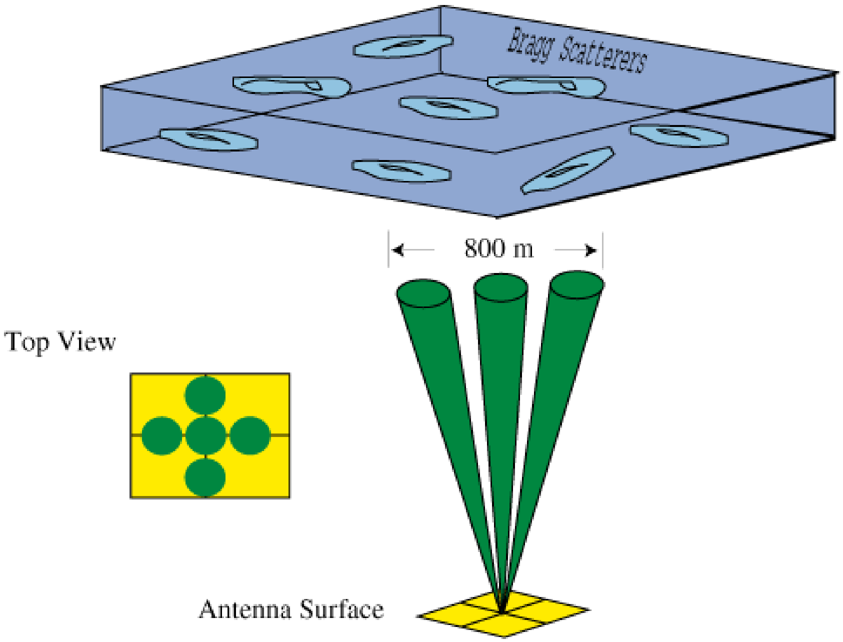
Spectral width



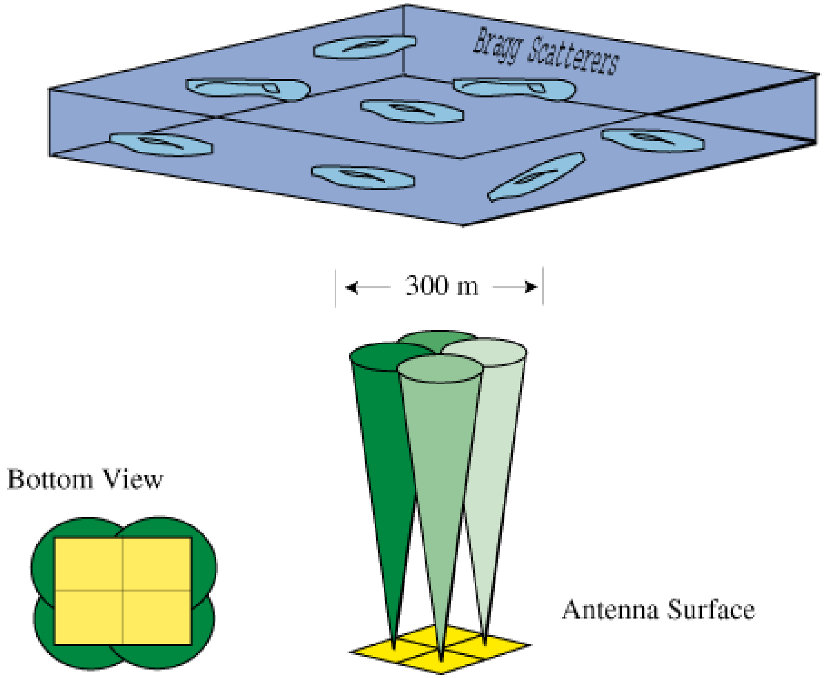

Lindenberg 482 MHz: 12.08.1998: Vertical beam only, PW = 1660 ns (250 m)

# Wind retrieval methods






Doppler method




Spaced antenna drift

Courtesy: Steve Cohn (NCAR)

# Doppler method (DBS)

**Doppler method**:

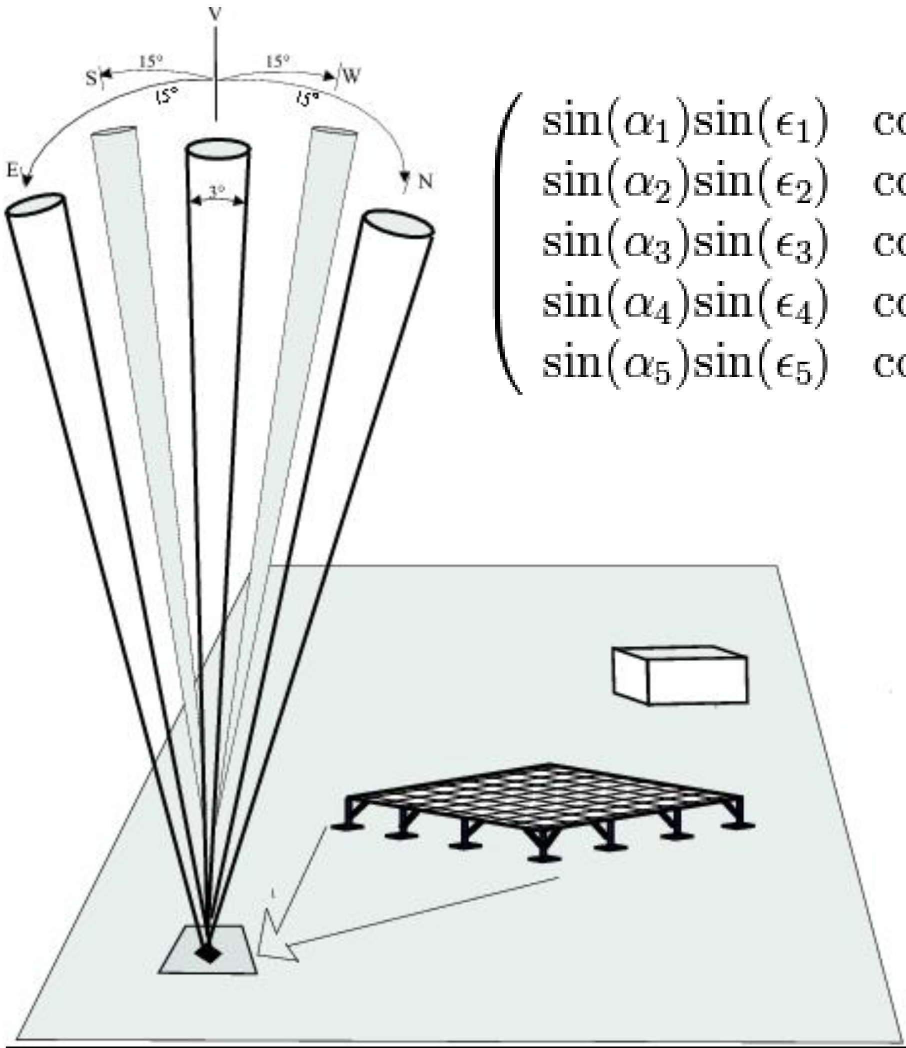
Antenna beam is steered in several directions (min. 3)
Doppler shift is directly estimated
Radial measurements are combined to get wind vector

Pros: Most RWP employ this method
Gives the best height coverage
Method well established

Cons: Assumptions about wind field need to be made
Beam steering required

# Wind retrieval

- Estimation of Doppler shift along 3-5 beams
- Calculation of u, v, w from radial velocities




$$\begin{pmatrix} \sin(\alpha_1)\sin(\epsilon_1) & \cos(\alpha_1)\sin(\epsilon_1) & \cos(\epsilon_1) \\ \sin(\alpha_2)\sin(\epsilon_2) & \cos(\alpha_2)\sin(\epsilon_2) & \cos(\epsilon_2) \\ \sin(\alpha_3)\sin(\epsilon_3) & \cos(\alpha_3)\sin(\epsilon_3) & \cos(\epsilon_3) \\ \sin(\alpha_4)\sin(\epsilon_4) & \cos(\alpha_4)\sin(\epsilon_4) & \cos(\epsilon_4) \\ \sin(\alpha_5)\sin(\epsilon_5) & \cos(\alpha_5)\sin(\epsilon_5) & \cos(\epsilon_5) \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} v_{r1} \\ v_{r2} \\ v_{r3} \\ v_{r4} \\ v_{r5} \end{pmatrix}$$

$$\vec{v} = (A^T A)^{-1} A^T \vec{v_r}$$

Assumptions:

- Uniform wind field across sampled volume (2.5 km @ z=5 km)
- Stationary wind field over measurement time (~ 30 min)

# Spaced antenna (SA) drift method

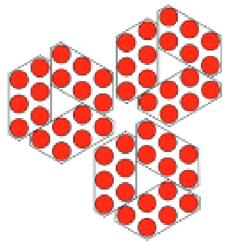
Vertical beam direction, echoes received with multiple (spaced) antennas
Doppler shift is directly estimated for w
Horizontal wind components from cross-correlation of signals

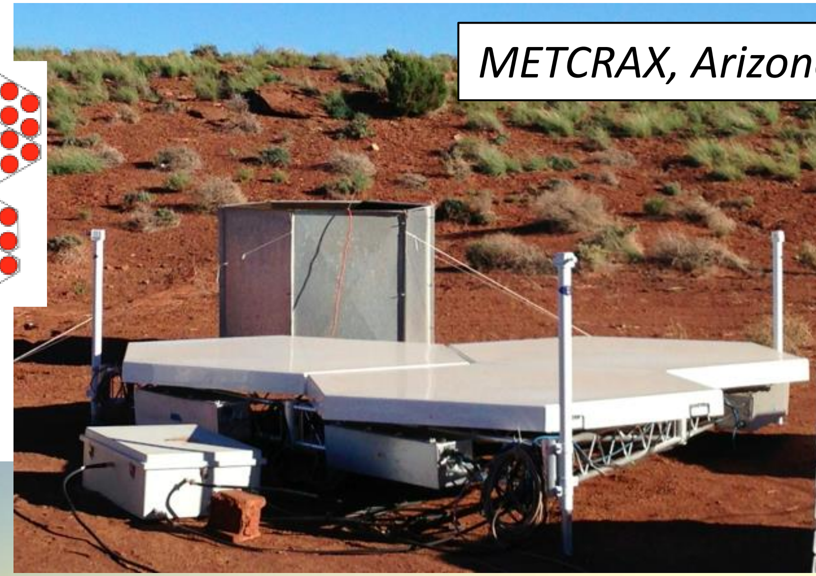
Pros: Single observation volume – almost no assumptions on wind field
No beam steering required - simpler hardware

Cons: Smaller SNR – lower height coverage
Method has still issues (e.g. wind speed bias ~ 10%)

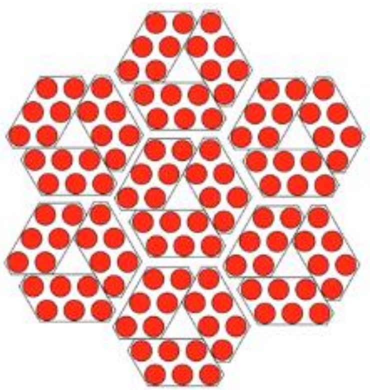
# SA 449 MHz RWP

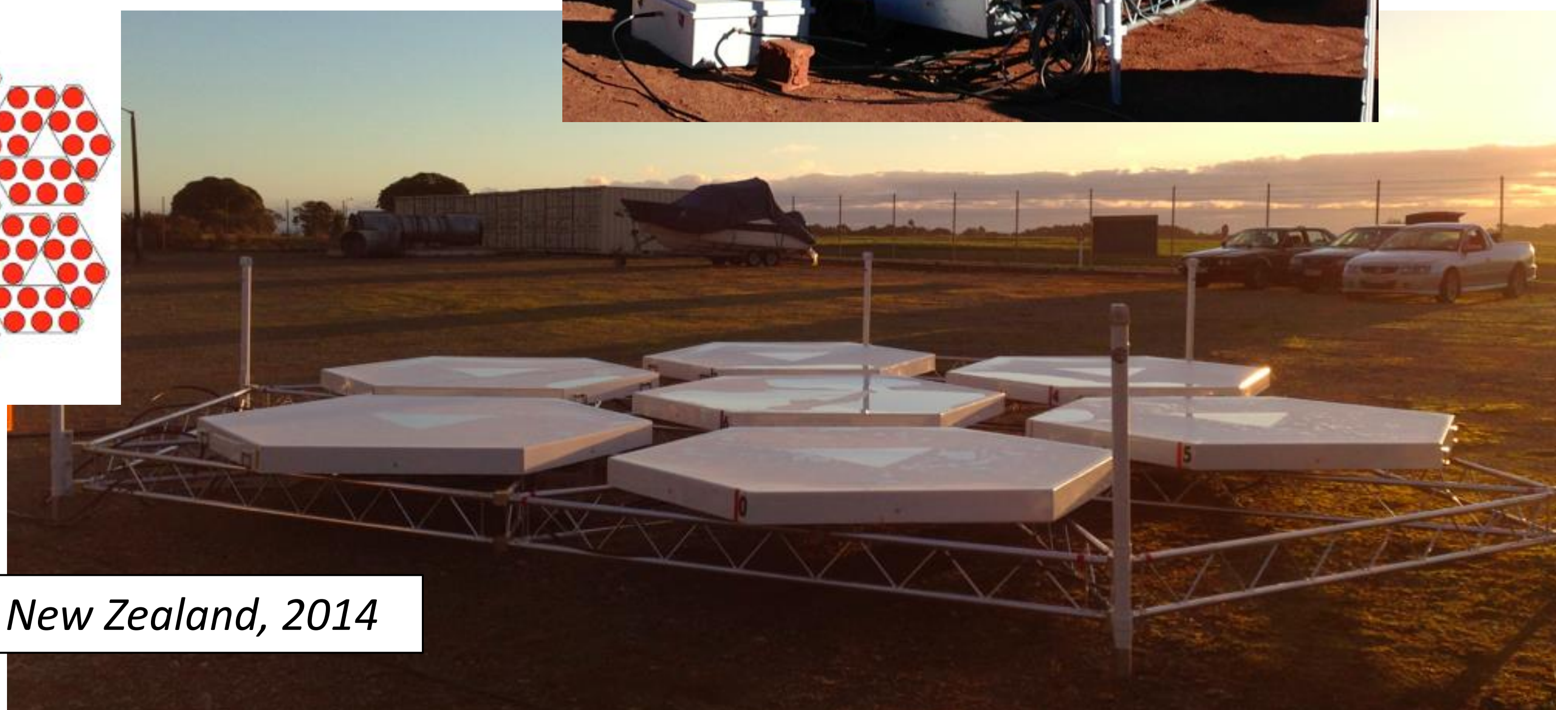
Courtesy:
Bill Brown



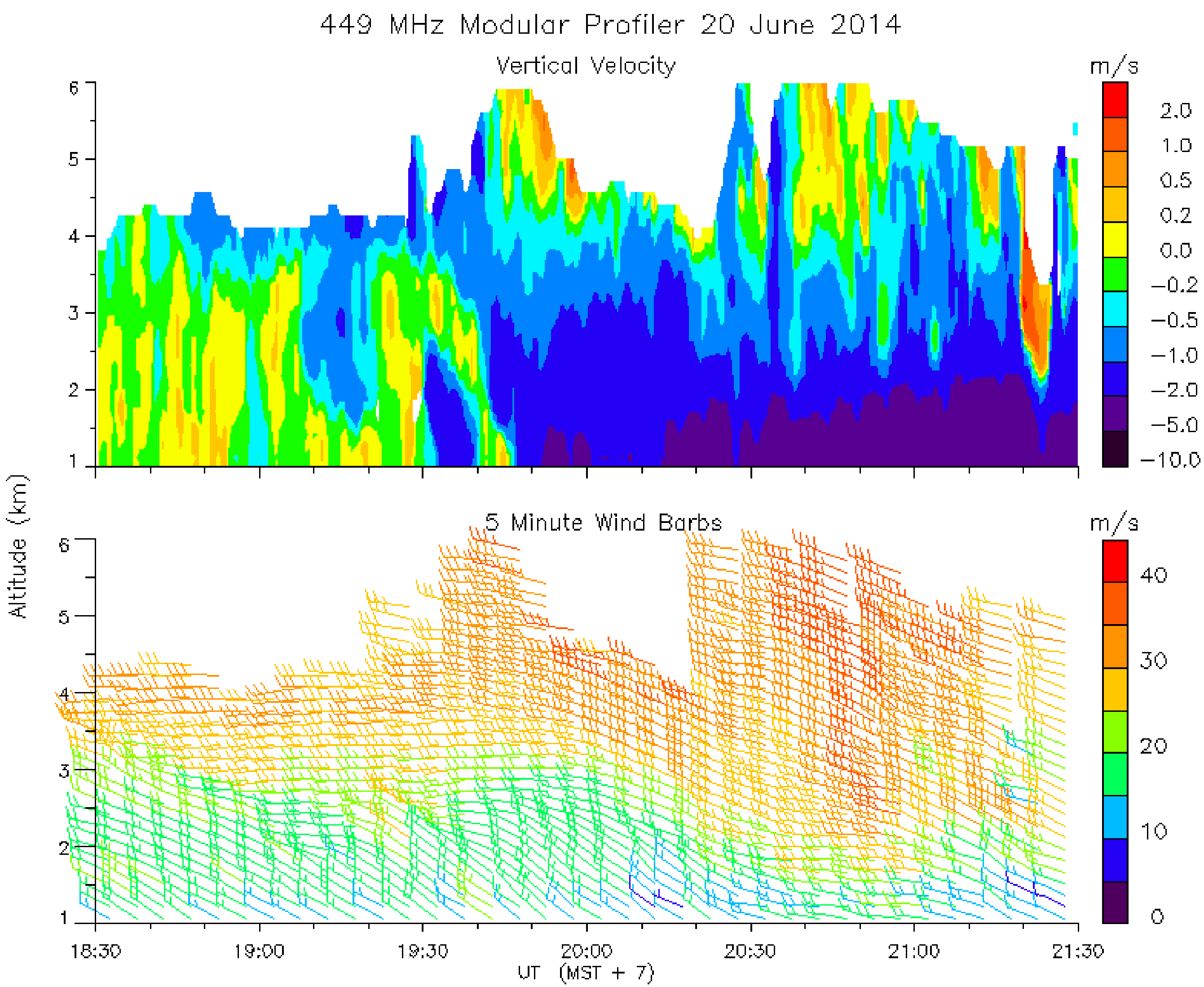


*METCRAX, Arizona, 2013*





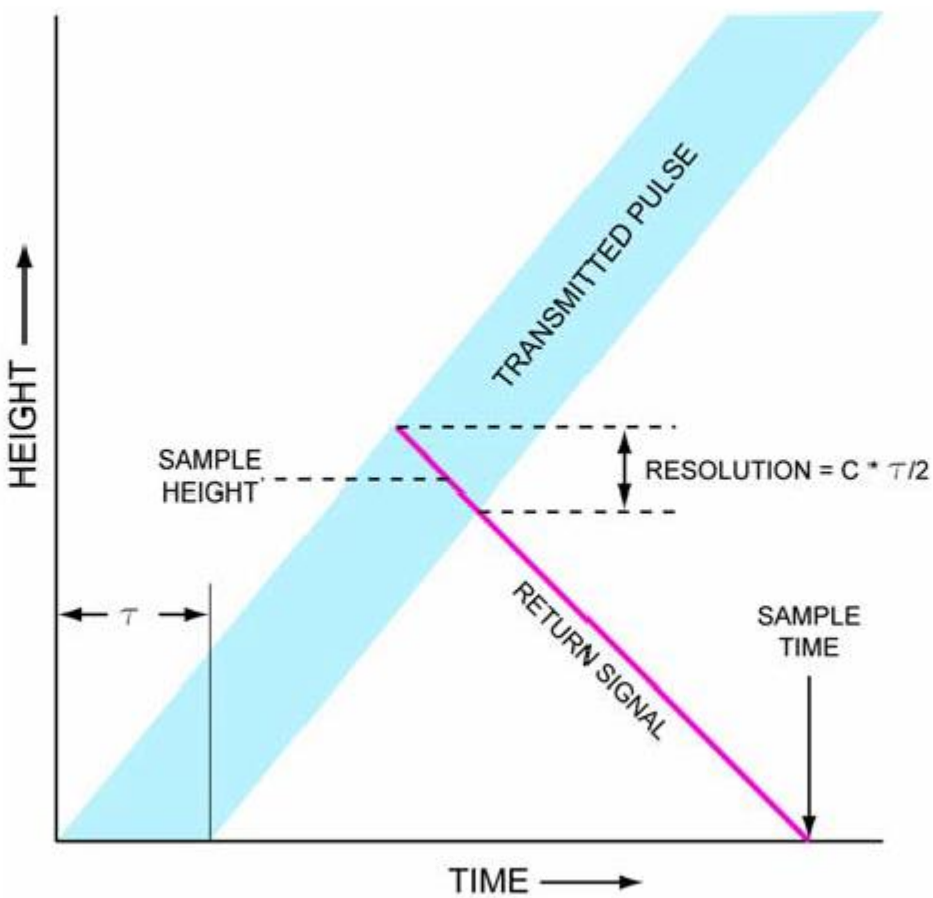
*DEEPWAVE, New Zealand, 2014*

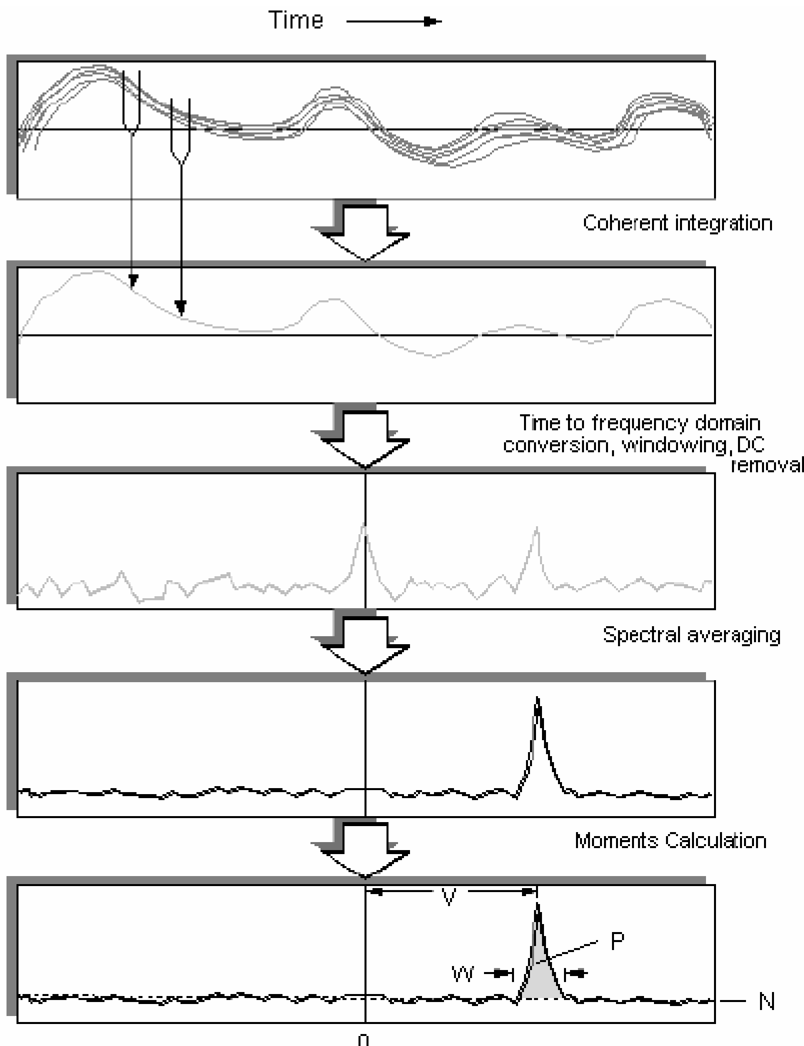



Example from DEEPWAVE-NZ

Courtesy: Bill Brown

# Signal processing
## (in a nutshell)




- P: Backscattered power
- **V: Doppler shift**
- W: Spectral width

# Example: Sampling and processing settings



**DWD Vaisala/Rohde&Schwarz LAP-16000**
f = 482.0078 MHz, λ = 62 cm

**<u>Sampling</u> Parameter (Low mode only)**

Pulse width: 1000 ns: 150 m radial resolution
IPP 81 µs, PRF = 12,346 kHz: Unambigious range: 12150 m
# of range gates: 96 (450 m – 9380 m)

# of coherent integrations: 60
# of points in FFT: 512
# of spectral averages: 16

Beam dwell time: 39,81 seconds (491.520 pulses)

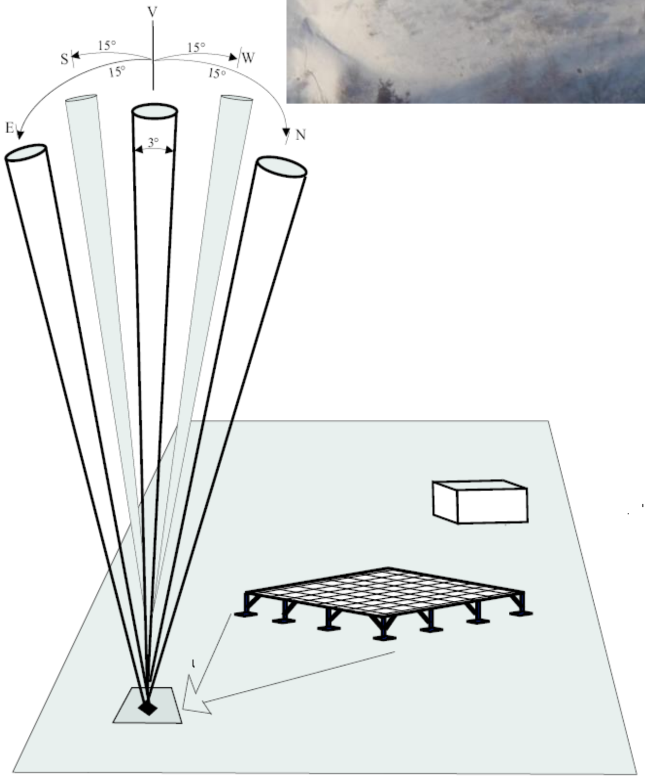
4 oblique beams @ 74.8° elevation, 5 full cycles for 30 minutes

**Signal <u>processing</u> and QC (Low mode)**

•Gabor frame I/Q-timeseries filtering (birds, aircraft, intermittent precip)

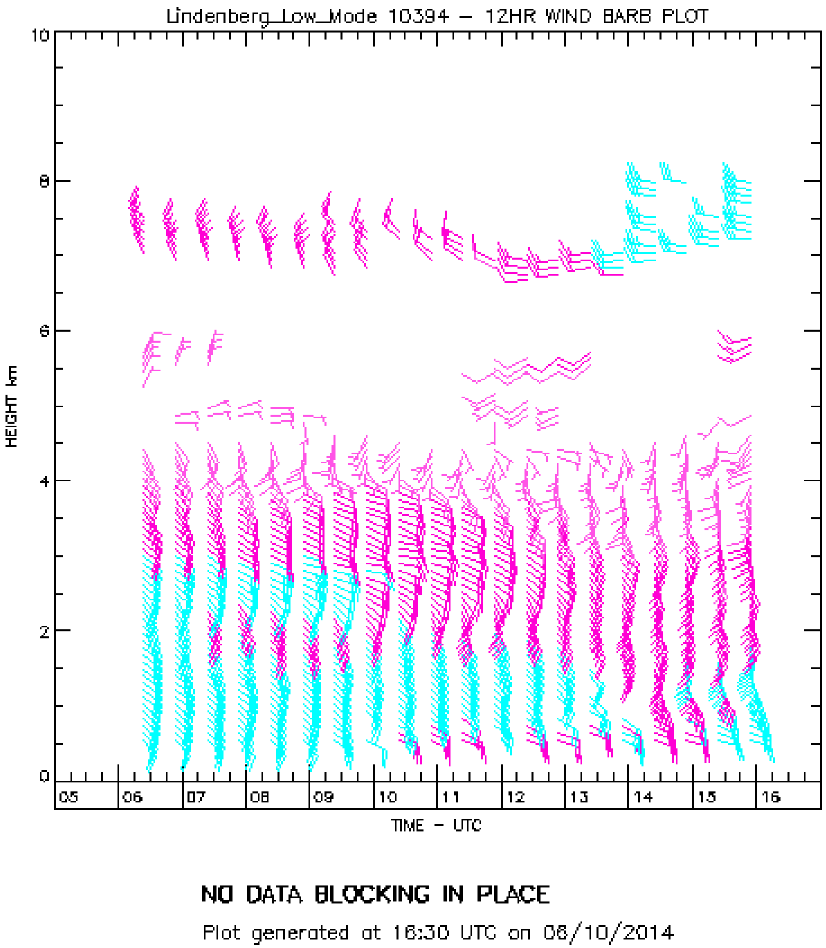
•Doppler spectrum estimation
•Riddle-Algorithm (Groundclutter)
•Minimum spectral width thresholding (RFI)
•4-beam homogeneity check (beam pair comparison)
•Consensus filtering (for signal detection)

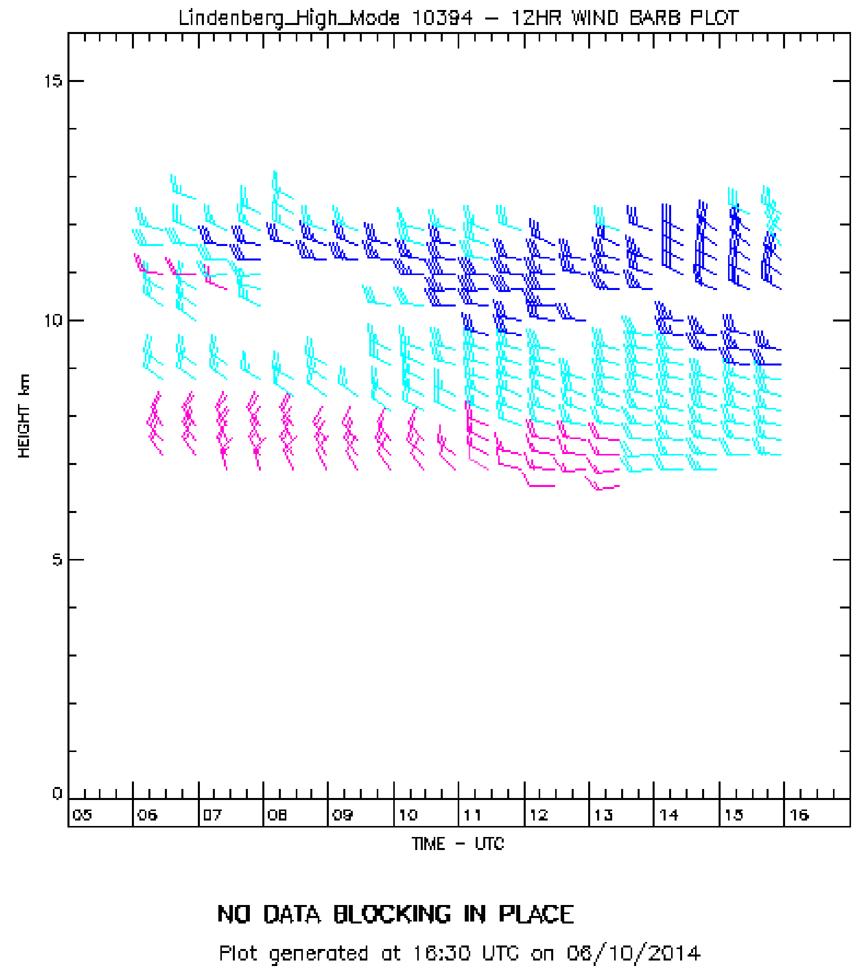
•(Weber-Wuertz continuity check for gross error elimination)



# Low mode and high mode






Low mode: PW = 1000 ns (150 m)

High mode: PW = 2166 ns (330 m)

# Mandatory requirements for the use of (remote sensing) observing systems in operational networks

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Wetter und Klima aus einer Hand

1. **Theoretical and practical understanding – „Maturity of method“**
   - Sufficient knowledge of the „real-world“ measurement process
   - Known error statistics
   - Well-tested algorithms

2. **24/7 all weather operation  - not necessarily all-weather data availability**
   - Fully automated operation
   - Rugged design

3. **Availability**
   - Commercially available
   - Sustainable operation over 10+ years (spare parts, software support)

4. **Practicality**
   - Radars: Available RF spectrum, compliance with regulations
   - Lidars: Eye-saefty
   - Proven systems – be careful with prototypes in networks (!)
   - Reliable and robust calibration methods
   - „Acceptable“ cost / benefit relation

# Radar wind profiler (Doppler method) (L-Band to VHF)

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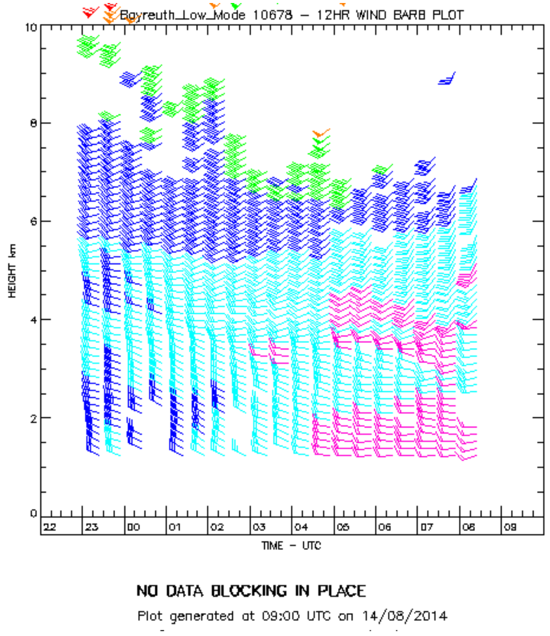


„Clear air“ radars – wavelengths 0.2 – 6 m

→ **Horizontal wind vector (u,v), virtual temperature $T_v$**

1.) Mature technology:
- First demonstration in early 1970‘ies
- Operationally used since mid 1990‘ies
- (Most) operationally relevant problems solved

2.) All-weather 24/7 operation
data in both clear and cloudy atmosphere (!)

3.) Availability
- Commercial vendors existing

4.) Practicality
- RF Spectrum assigned by WRC
- Interference issues must be considered

1. RWP networks and data impact in NWP

2. RWP – some fundamentals

3. Accuracy assessment and possibilities for standardisation

# NWP monitoring statistics

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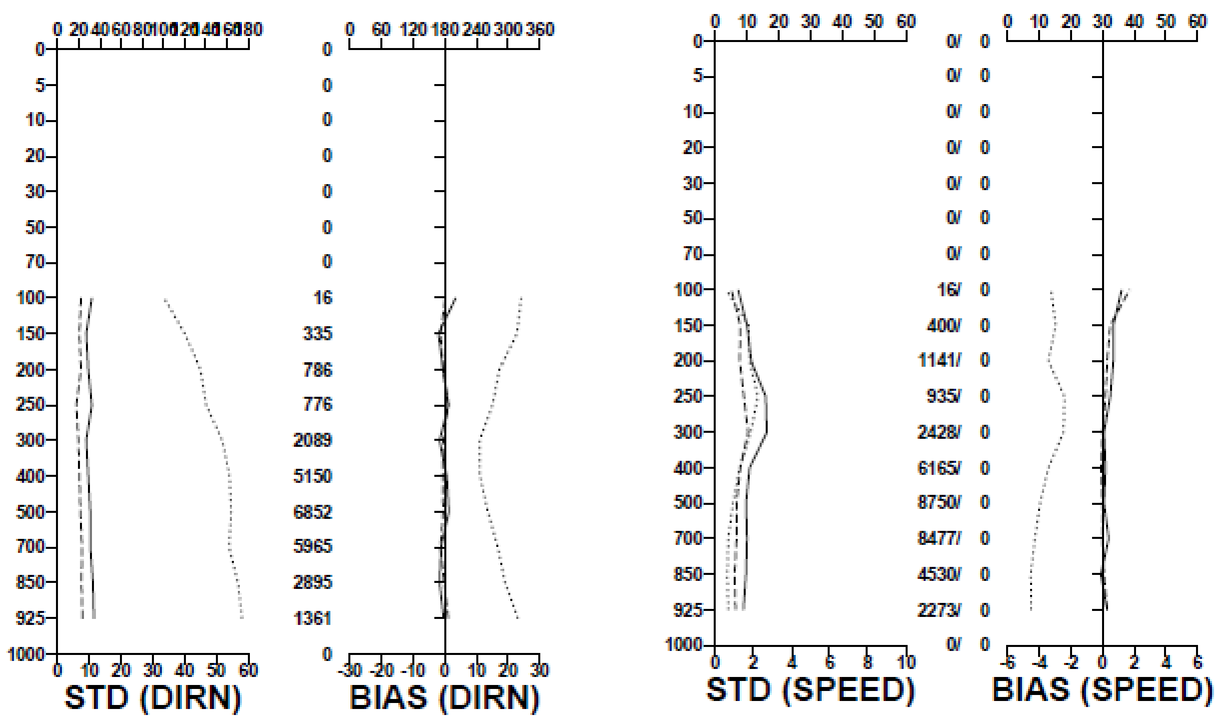
**FEDERAL REPUBLIC OF GERMANY**
**PROFILER 10394**
**SEP 2014**
POSITION: 52.21N 14.13E HEIGHT: 0M




Results from the following NWP centres are also available:

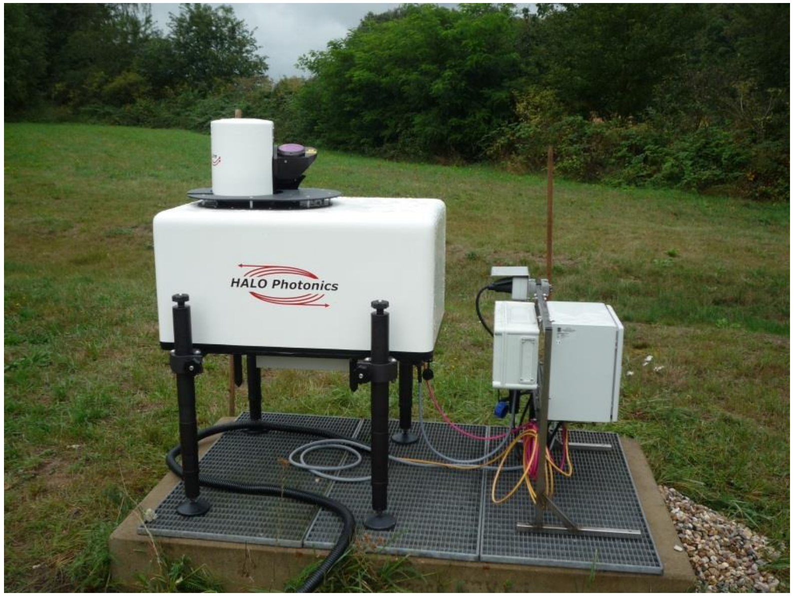
- DWD
- UK MetO
- MeteoFrance

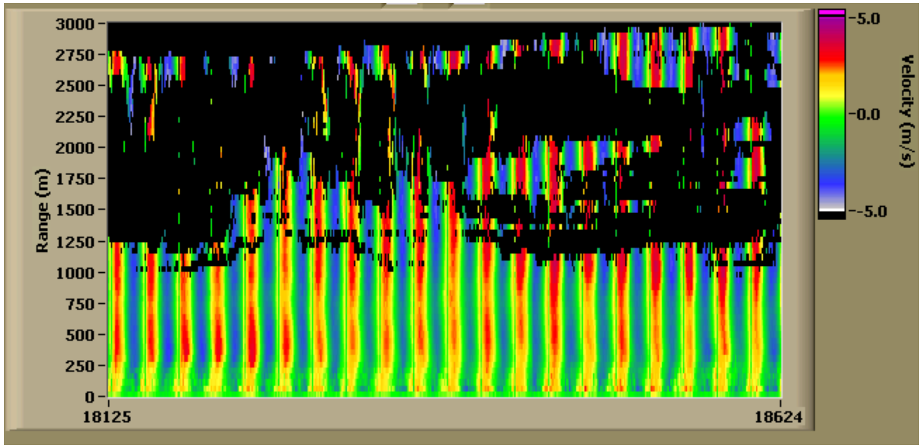
Full line : OBS-FG
Dashed line: OBS-AN

Dotted line: Mean observation (scale at the top of each plot)

# Lidar wind profiler (IR)






**Radial wind data from a 24 beam VAD-scan, Oct 03, 2012 08:20 -09:20 UTC**

→ **Horizontal wind vector (u,v)**

1.) Maturity:
- First demonstration in mid 1960'ies ($CO_2$ laser)
- Wind shear warning systems since mid 2000
- Testing in operational setting under way

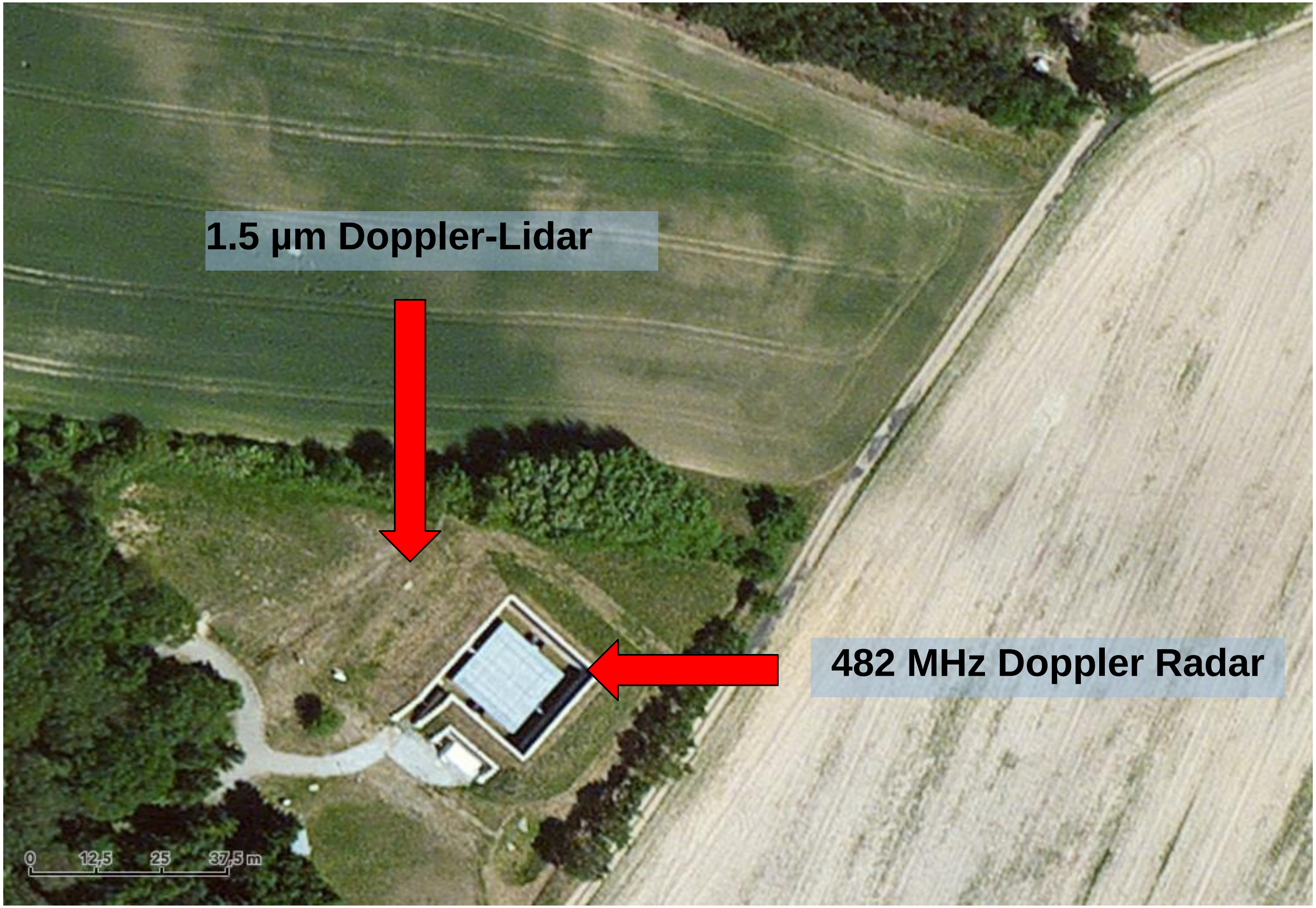
2.) All-weather 24/7 operation: Yes, limited availability
- in and above optically thick clouds
- in particle-free atmosphere (no targets)

3.) Availability
- Commercial vendors existing
- Market currently very active (mainly wind energy)

4.) Practicality
- Easy to deploy, fully autonomous operation
- All-fiber optics: Mechanically very stable
- Eye safe (Laser class 1M)

# Lidar and Radar collocation





# Data availability: Radar vs. Lidar wind profiler

(quality controlled data only)

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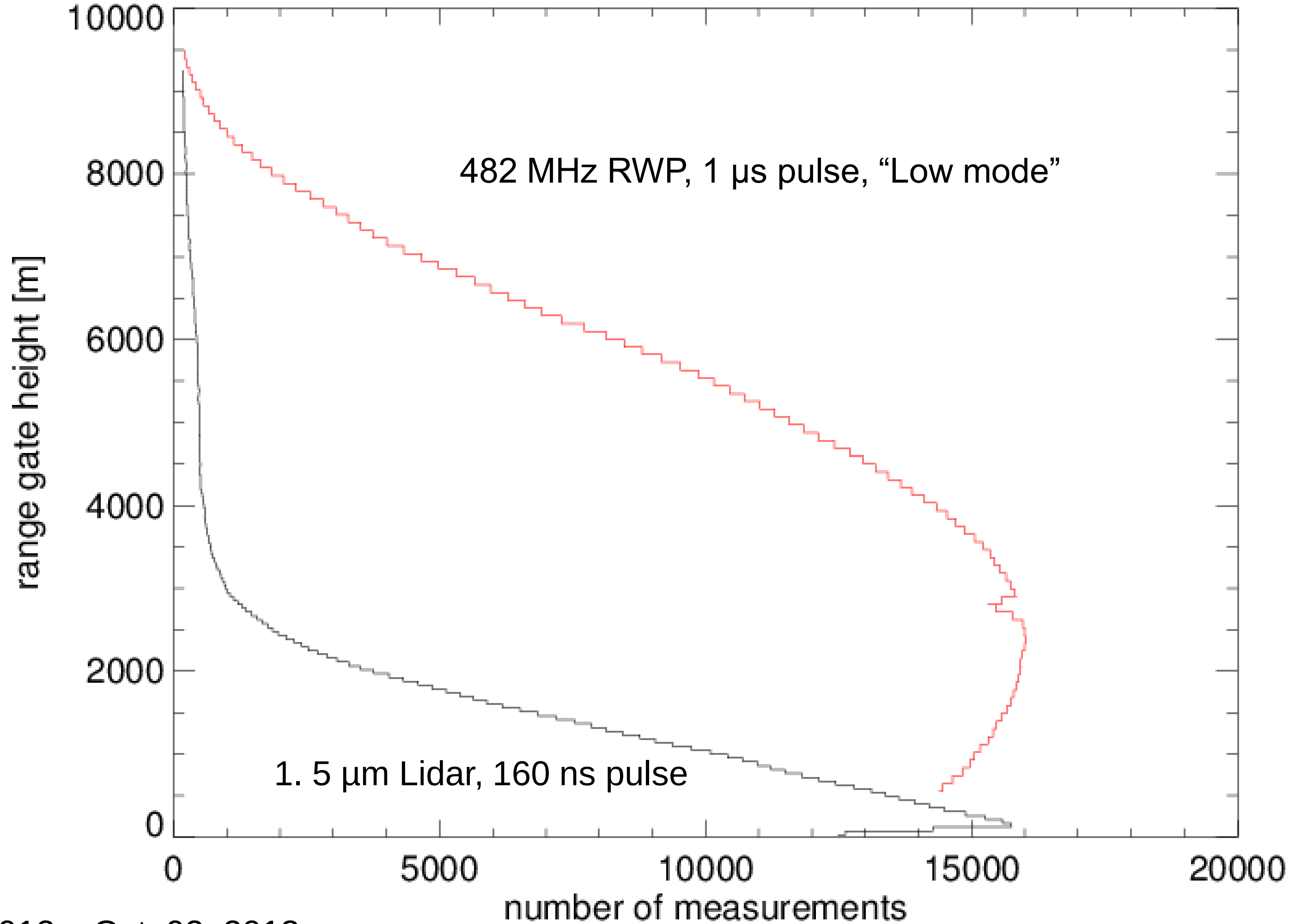
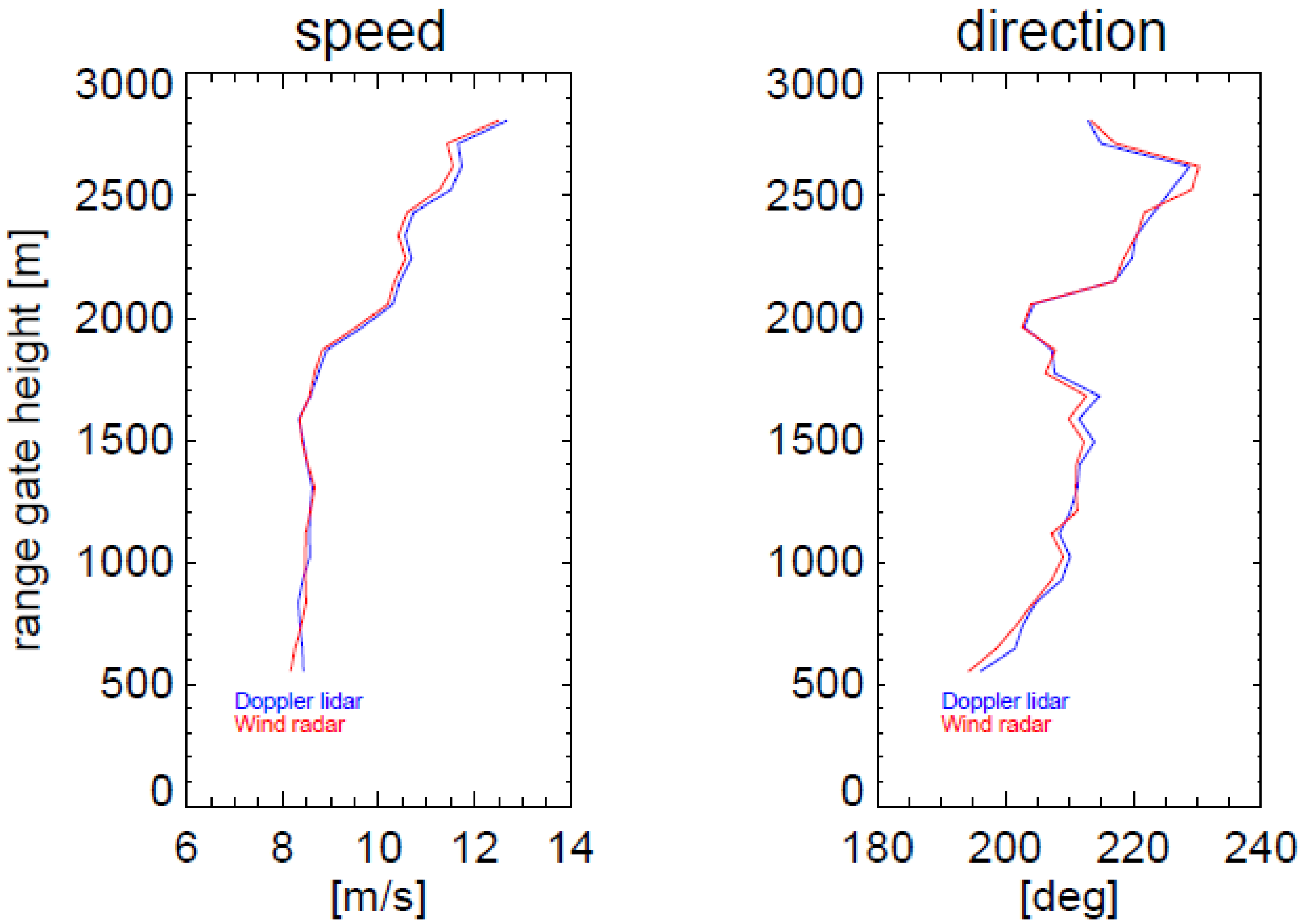



Oct. 02, 2012 – Oct. 02, 2013

max # : 17568

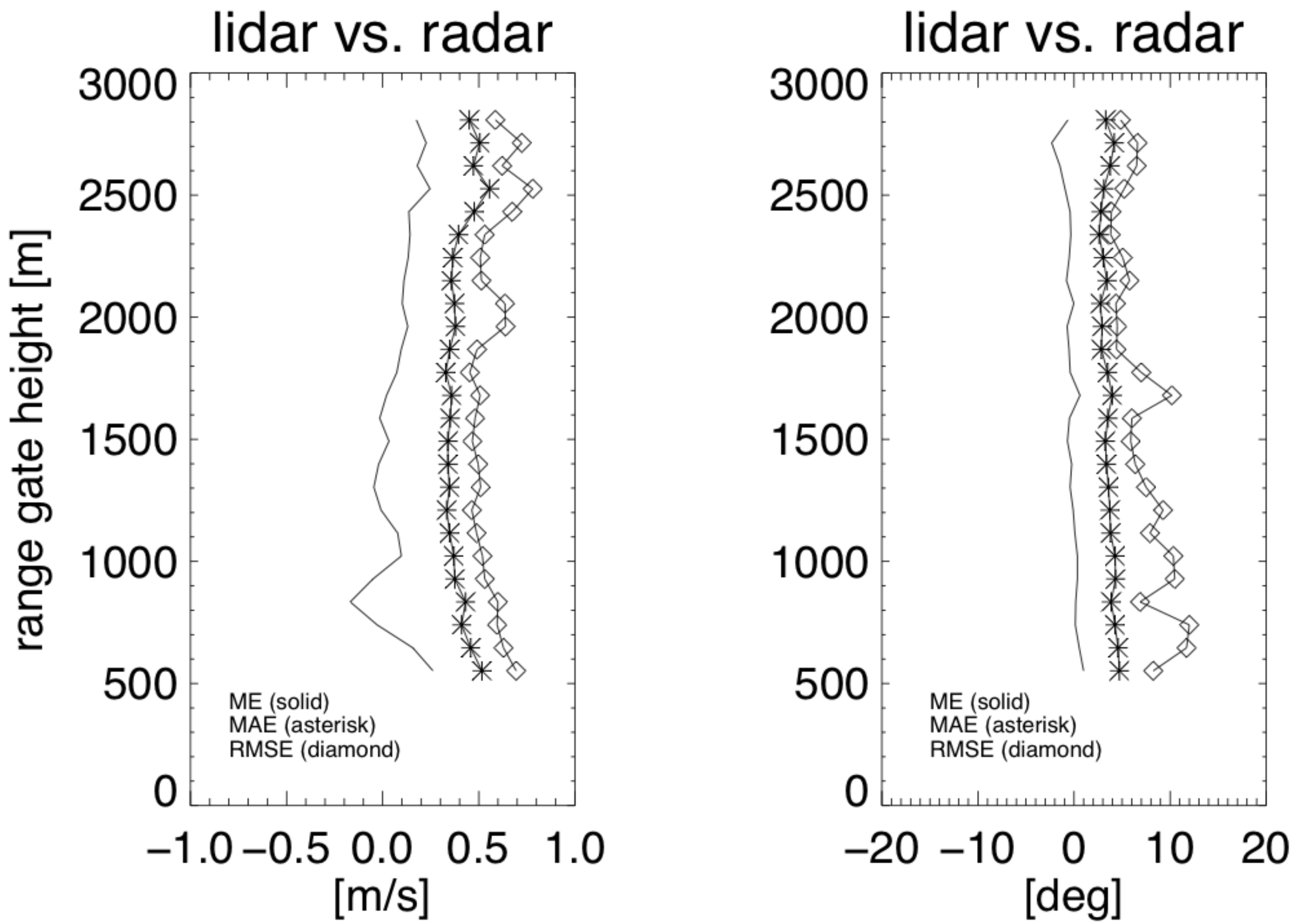
# Comparison statistics: Mean profiles





# 482 MHz radar vs 1.5 µm lidar: 1-year intercomparison statistics





# Comparison statistics: Scatter plots

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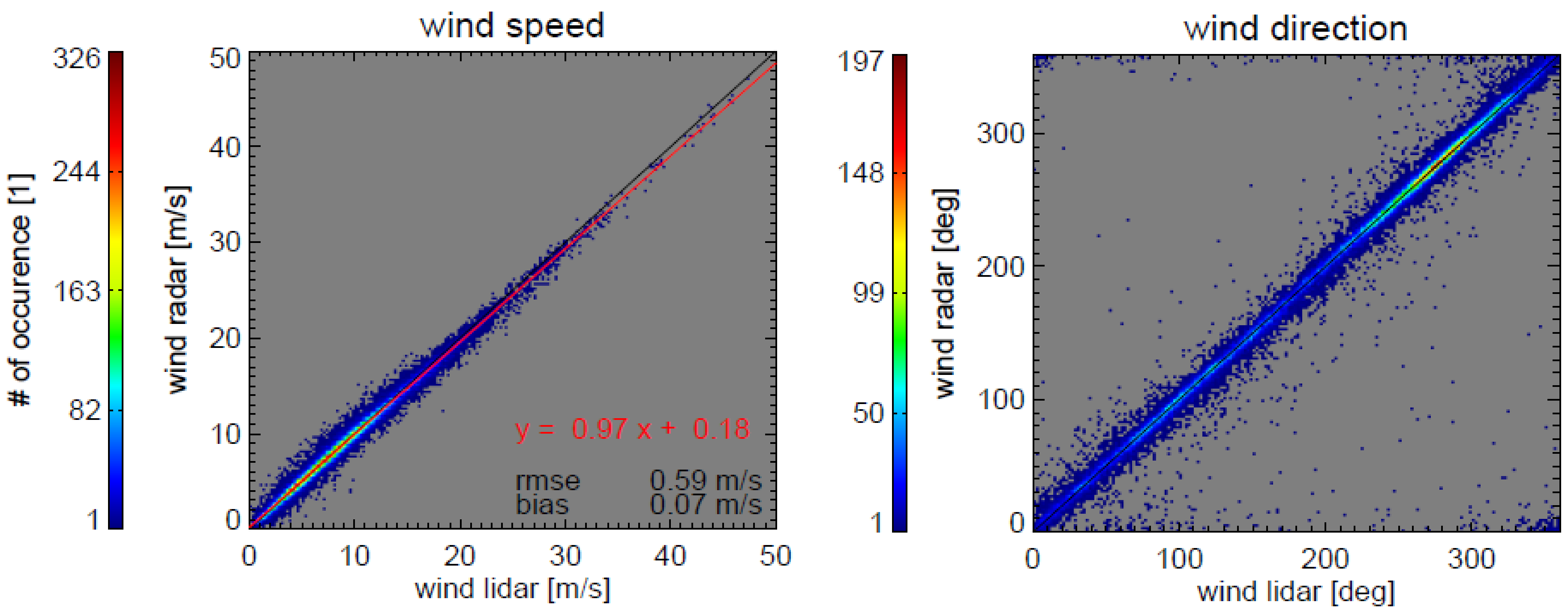

# Wind measurement uncertainty considerations

| Total uncertainty | = | Instrument uncertainty | + | Retrieval uncertainty | + | Representativity |
|---|---|---|---|---|---|---|

Pulse and beam forming, temporal sampling/ranging

Estimation of Doppler shift over large dynamic range (SNR)

Removal of clutter (ground & bird echoes) and radio frequency interference

Wind vector retrieval from radial velocities:

- Spatial sampling aspects: # of beams, elevation(s) & azimuths
- Horizontal homogeneity and stationarity of wind field required - averaging

Atmospheric variability & mismatch between observation and model scale

Partly accounted for by temporal integration

# Identified causes for observation errors in CWINDE

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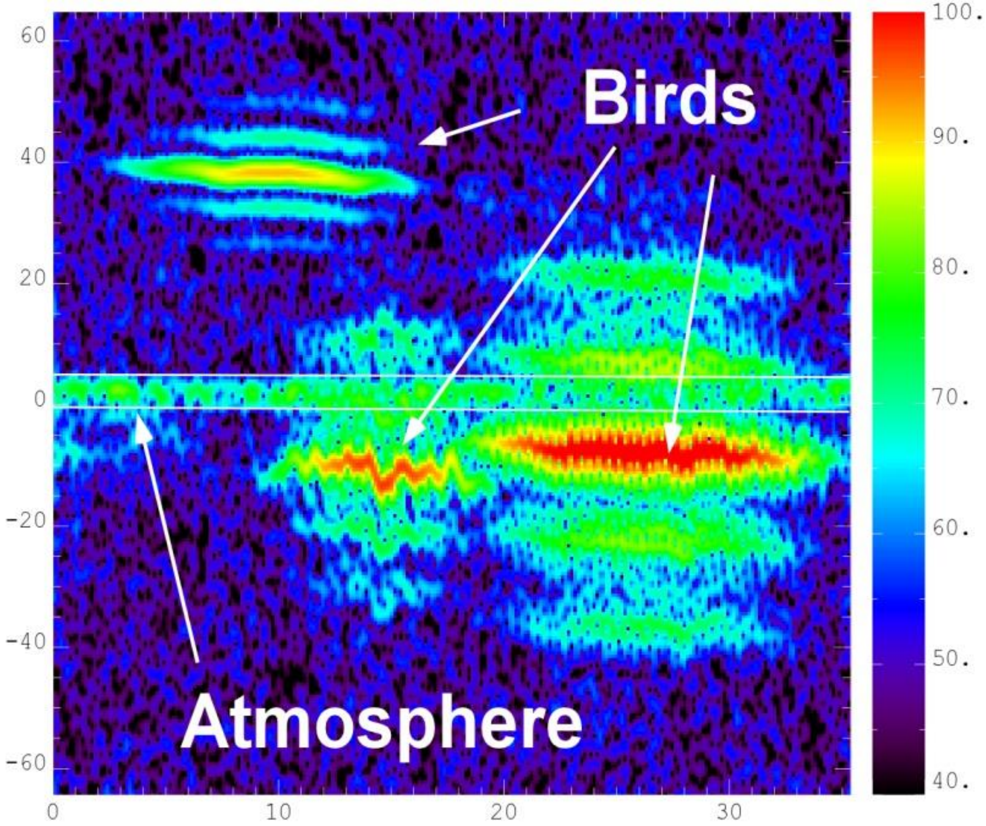
- Incorrect or inappropriate system settings
  - Aliasing effects – with standard manufacturer settings (!)
  - Erroneous range calibration
- Hardware issues
  - internal „self-clutter“ (RF pickup in very sensitive receiver)
  - DBS: failures of beam steering unit (phase shifter relays)
- Clutter (ground echoes, bird migration)
  - Insufficient performance of algorithms
  - Unexpected side effects of more complex algorithms
- External RF interference
  - if RF sources are in-band and not suppressed

# Bird clutter detected in Gabor frame representation of I/Q data

Time-Frequency decomposition of raw signal



# Example of external RFI (suppressed by algorithm)

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LIN TWP 482
Julian: 363
Date: Dec 29, 2010
Local: 14:05:49
UTC: 14:05:49

Mode: WA / 2
Direction: South-East
Azimuth: 133.00 deg
Elevation: 74.80 deg

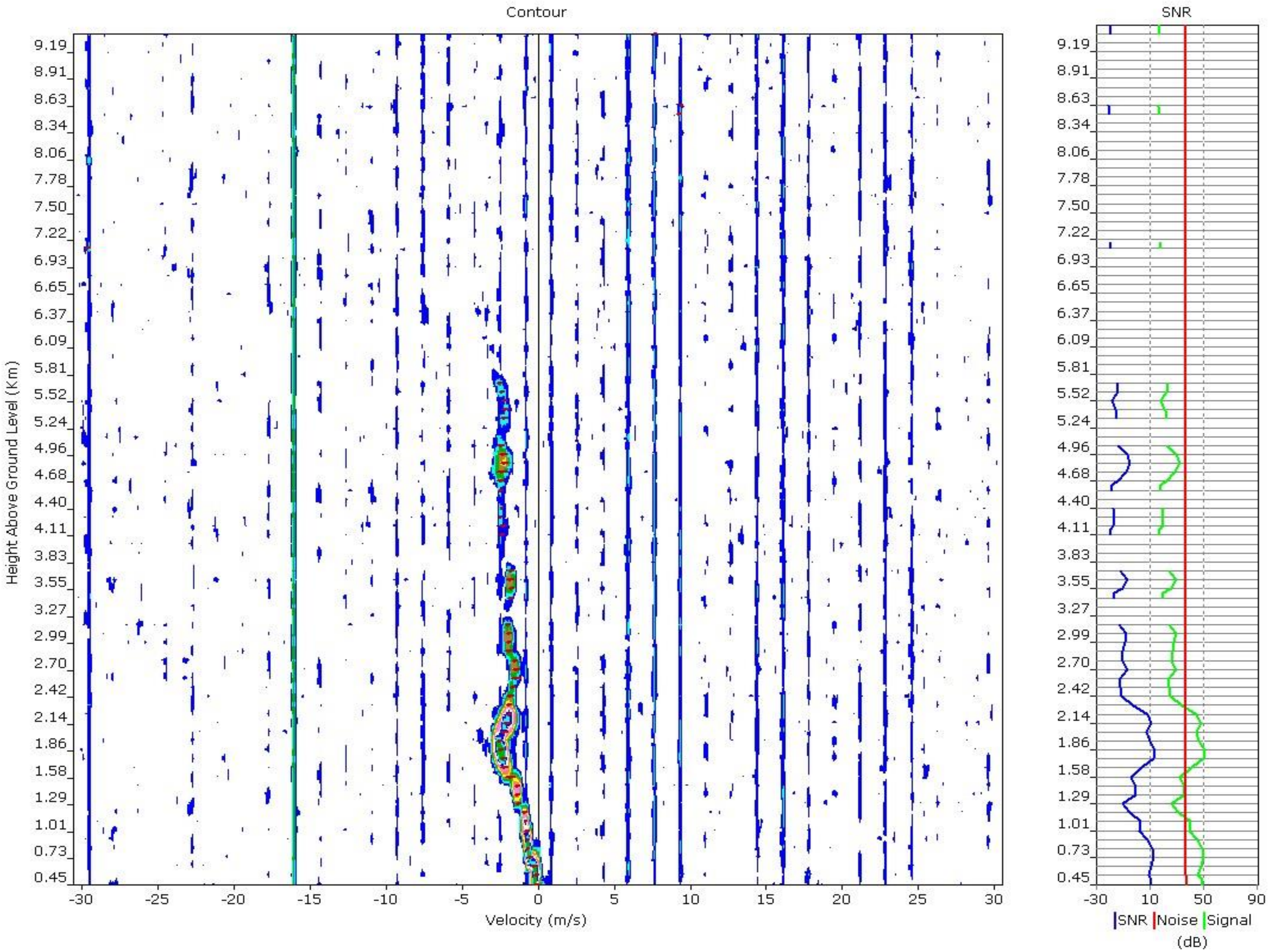
Longitude: 14.13
Latitude: 52.21
Altitude: 104 m

Receiver: 1
NHTS: 96
NPTS: 512
Wind Points: 1 - 512

Pulse Width: 1000 ns
Pulse Coding: 1
IPP: 82000 ns
NCI: 62
NSpec: 16
Flip: 1
Gate Spacing: 650 ns
Delay: 5675 ns

Spectral Average: ICRA
Clutter Removal: 6500 m
Window: Hann
DC Filter: On
iOverlap: On

Frequency: 482.008 MHz
Pre-Blank: 2500 ns
Pre-TR: 2000 ns
Post-Blank: 1500 ns
Post-TR: 400 ns
System Delay: 2575 ns
Fwd Power: 13364 W



# Possibilities for standardisation



Calibration for subsystems:

Antenna - Array excitation
TX/RX: - Group delay, oscillator stability
….

Sampling settings

IPP – to avoid range aliasing
Δt – to avoid velocity aliasing
….

Processing: Algorithms <u>and</u> implementations

Moment estimation for both high and low SNR
Clutter filtering algorithms
Wind retrieval methods – SVD-Pseudoinverse
….

# Thank you !

Lindenberg, Sep 03, 2011:  Aerial view of 482 MHz RWP

# Challenges for RWP



1. Protection of frequencies: Need bands without interfering RF signals

2. Qualified staff crucial – maintain existing knowledge through training and workshops

3. Enforce strict quality control at the sites – "no data is better than bad data"
   - Clutter filtering – many algorithms are existing, bub not always implemented
   - Detection of non-homogeneous wind field conditions – convection, gravity waves,…

4. Hardware and software maintenance:
   - Radars operate over 10+ years – need for renovation or replacement
   - Continuous evolution of operating systems – IT security

5. Development and automation of monitoring
   - System failures must be identified quickly
   - Standardization of RWP "raw data" formats (moments, spectra, I/Q)
   - NWP monitoring statistics – development of unified graphics (results from different models)

6. Exploit potential of new IR Doppler lidars for Boundary-Layer wind profiling
   - Implementation of new WMO BUFR template for wind observations in 2015

# Wind measurement capabilities in WIGOS



- Operational space based wind observing systems in WIGOS
  - Atmospheric motion vectors (AMV)
  - Indirect inference from MW- and IR radiance derived mass field through balance relations
  - No direct wind measurements from space

- Operational ground based wind observing systems in WIGOS:
  - Radiosonde / Pilot ballons
  - Aircraft (AMDAR, TAMDAR, AIREP, ACARS, MODE-S,…)
  - „Weather-radars“ (S, C, X-Band)
  - Dedicated „wind profilers“ – Doppler radars (VHF, UHF or L-Band) – RWP

→ High quality in-situ wind measurements are sparsely distributed in space and time

→ Satellite observations (AMV): good coverage, but comparably poor quality

→ Dominance of mass observations derived from MW/IR-sounders: Global observing system „*heavily skewed towards mass observations over wind measurements*“ (5th WMO Workshop on the impact of various observing systems on NWP, Sedona, AZ, USA, 2012)

→ Ground based remote sensing of wind: Existing technology

# Estimation of RWP observation impact in NWP – Adjoint sensitivity estimates (FSO)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Model state vector, dimension O($10^8$)

$$(\mathbf{x})_i^T = (u_i, v_i, \theta_i, p_i, q_i)$$

Norm of the state vector – „energy measure“:

$$\|\mathbf{x}\|_c^2 = \langle \mathbf{x}, \mathbf{C}\mathbf{x} \rangle = \mathbf{x}^T \mathbf{C}\mathbf{x}$$

$$\|\mathbf{x}\|_c^2 = \frac{1}{M_a} \iiint_V \frac{1}{2} \left[ \rho_r u^2 + \rho_r v^2 + \left(\frac{\rho g^2}{\theta^2 N^2}\right)_r \theta^2 + \left(\frac{\rho}{c}\right)_r p^2 + \epsilon \left(\frac{\rho L^2}{c_p}\right)_r q^2 \right] dV$$

$$e = \|\mathbf{x}_{fcst} - \mathbf{x}_{true}\|^2$$

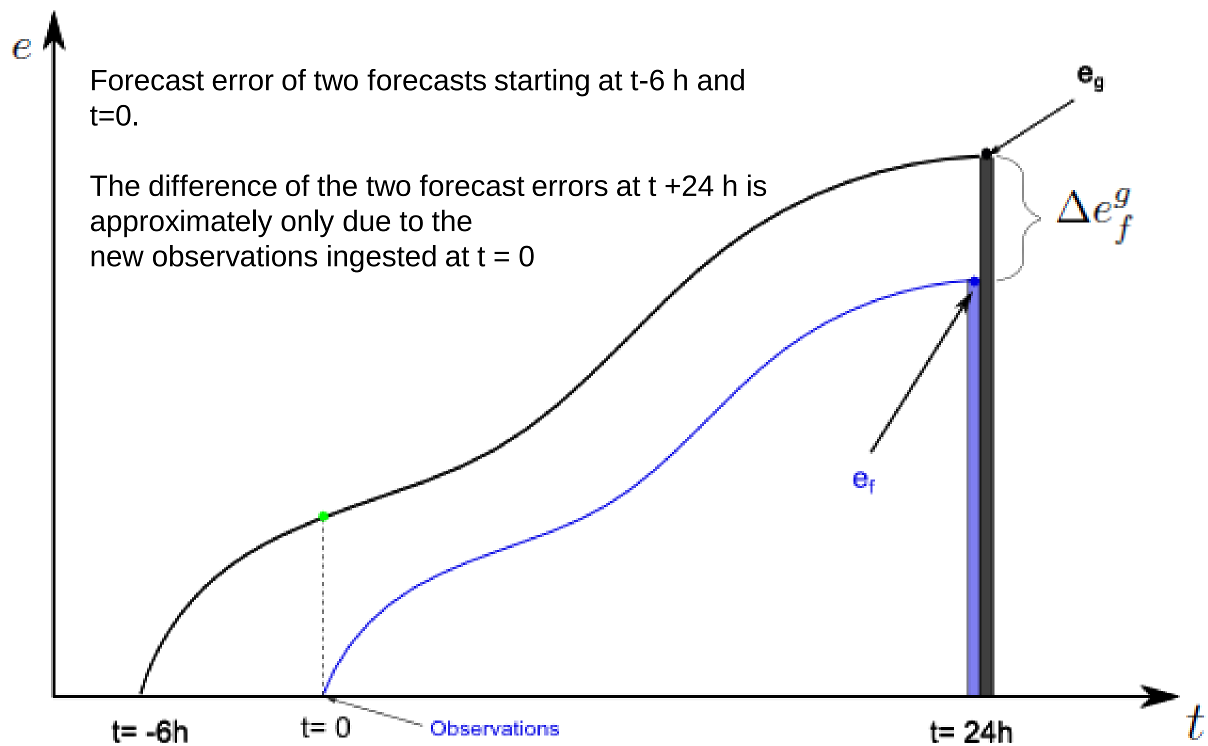
$$\Delta e_f^g = \|\mathbf{x}_f - \mathbf{x}_{true}\|^2 - \|\mathbf{x}_g - \mathbf{x}_{true}\|^2$$

$$\delta e_f^g = \langle \mathbf{y} - \mathbf{H}\mathbf{x}_b, \frac{\partial J_f^g}{\partial \mathbf{y}} \rangle$$

„Innovation x Observation sensitivity“: involves only observation space quantities

Allows partitioning of forecast error reduction for each observation

„Observation sensitivity calculation requires:
(1)Adjoint of forecast model (TL)
(2)Adjoint of data assimilation system




Langland and *Baker (2004) „Estimation of observation impact using the NRL variational data assimilation system“,* Tellus 56A, 189-201

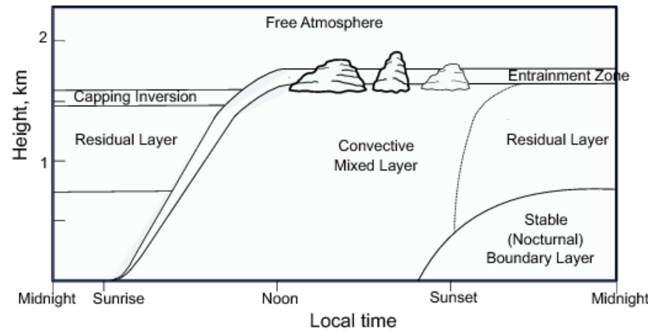
# Example: Noisy wind estimates in CBL

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

482 MHz RWP

Lindenberg, May 06, 2007

4 beam Doppler Beam Swinging, 30 min averaging

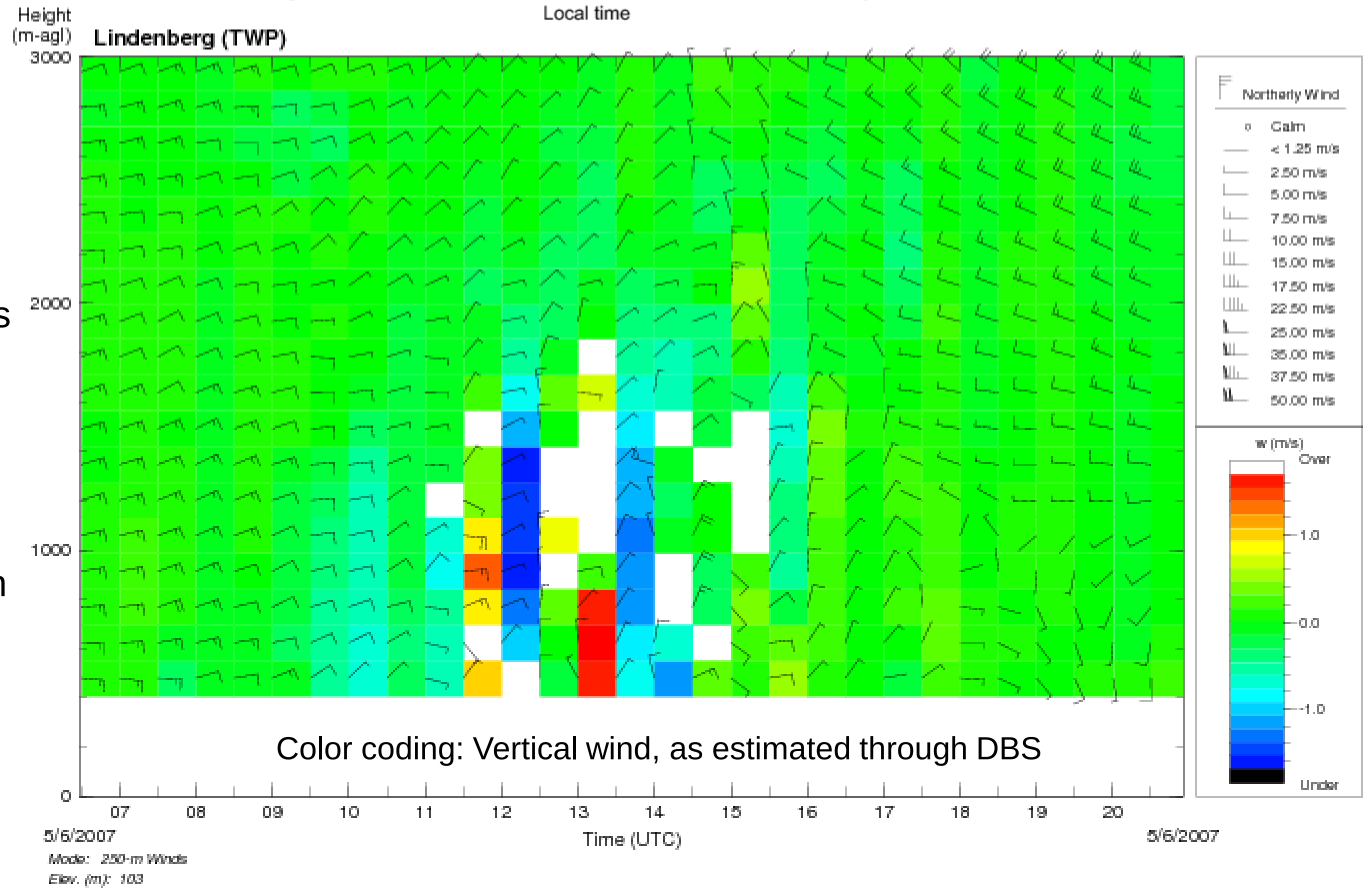



$$\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y} \neq 0$$

strong BL convection leads to violation of DBS assumptions

temporal averaging not always sufficent to restore homogeneity

strongly fluctuating estimates of (u,v,w), depending on beam switching sequence and averaging (dwell) time



**GFS | ECMWF** **January – September 2011**

Proxy for (unknown) wind analysis uncertainty in NWP:

300 hPa Wind Speed, Root Mean Square of Analysis Differences

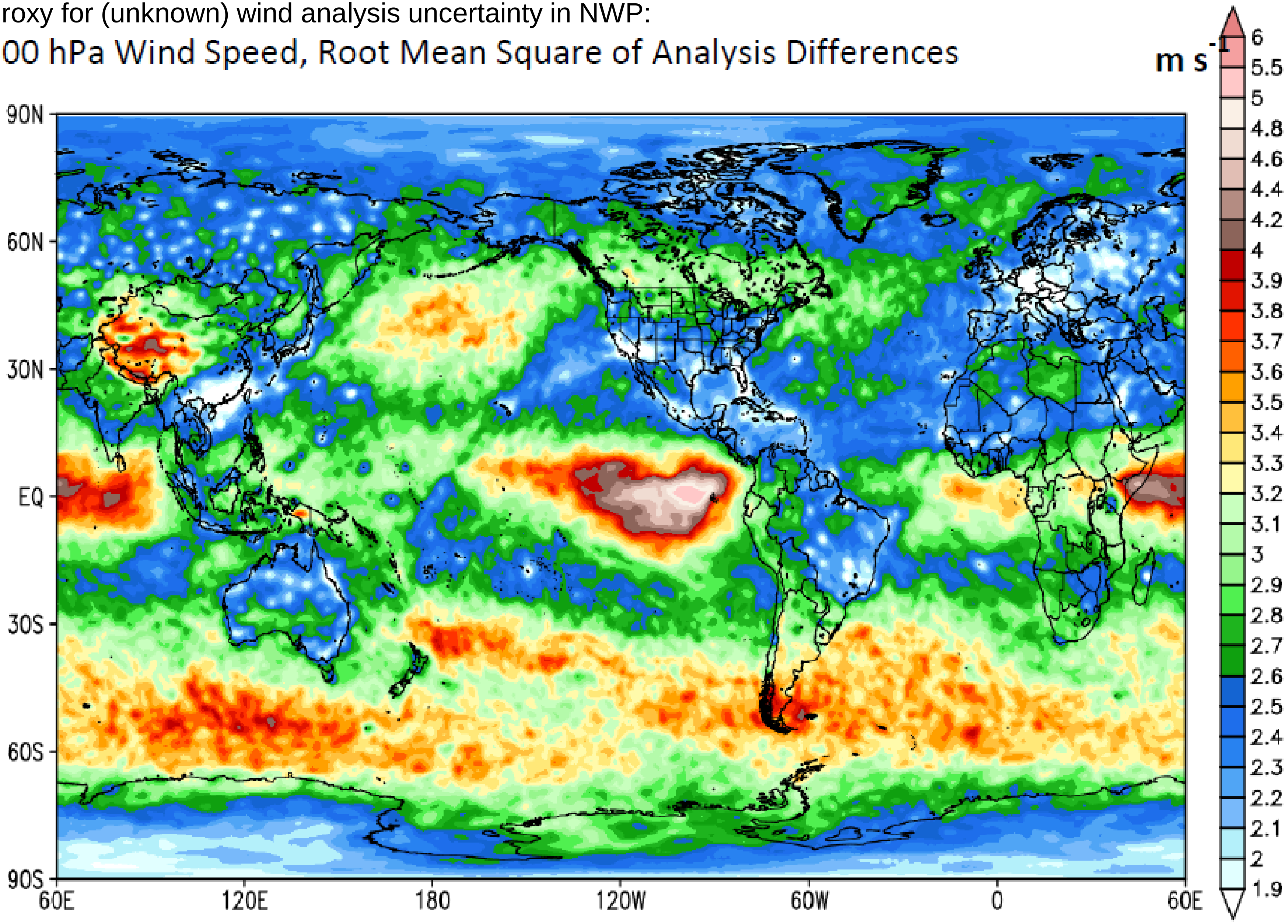



Figure from Langland and Maue (2012). Courtesy of Rolf Langland, NRL-Monterey

# ESA ADM-Aeolus Satellite

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

ESA ‘s Wind-Mission (Demonstrator)

Sun-synchronous orbit, period 90 min

Lidar ALADIN: wavelength 355 nm (UV)

Range-resolved HLOS winds

Launch: Early 2016 (?)

1.) Ground campaigns for A2D

09.10. – 20.10. 2006 Lindenberg

25.06. – 31.07. 2007 Lindenberg

http://www.pa.op.dlr.de/aeolus/

2.) External CAL/VAL after launch

Comparison with RWP data !!