



Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Project WERAN plus

Predicting DVOR Bearing Errors Caused by Wind Turbines – A New Tool

Dr. T. Schrader

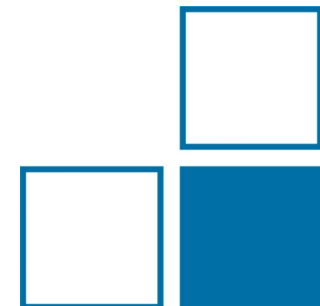
Specialist Meeting on
Electromagnetic Waves and Wind Turbines
ENAC, Toulouse, France, December 5-6, 2019

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Project team WERAN plus



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Overview



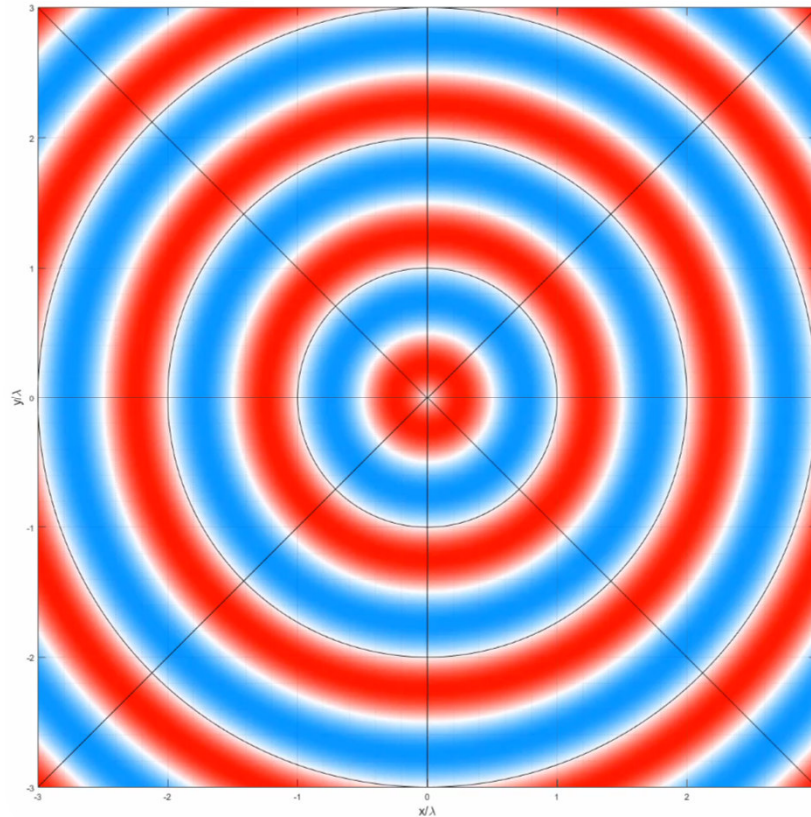
- Introduction
- Status of research
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- Invitation to participate in Round Robin Test (DVOR WT forecast)

Doppler VHF Omnidirectional Radio Range (DVOR)

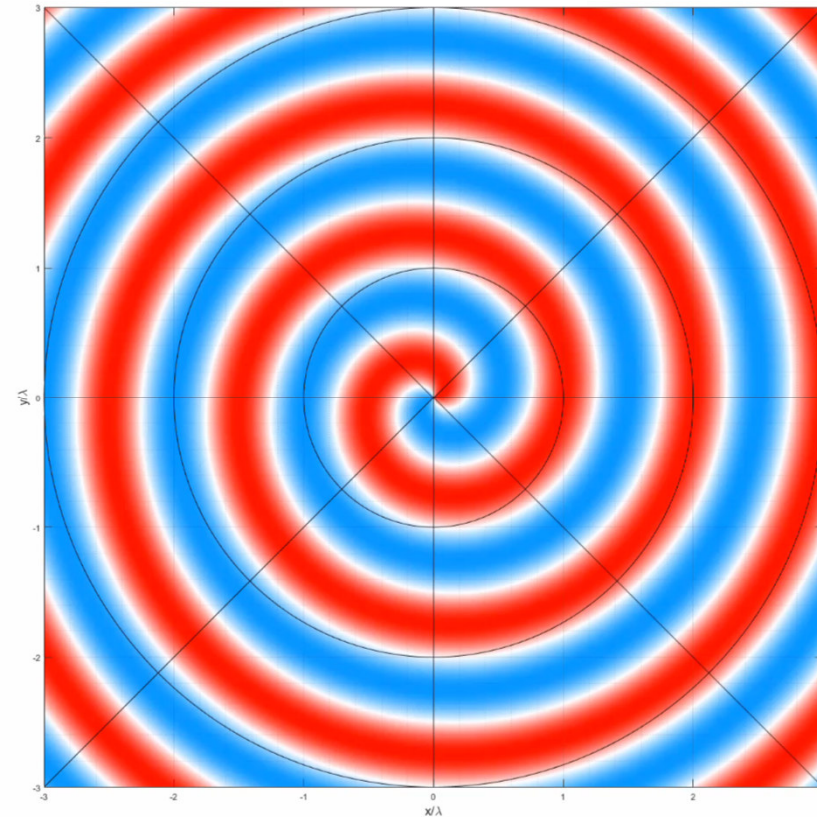


Doppler VHF Omnidirectional Radio Range (DVOR)

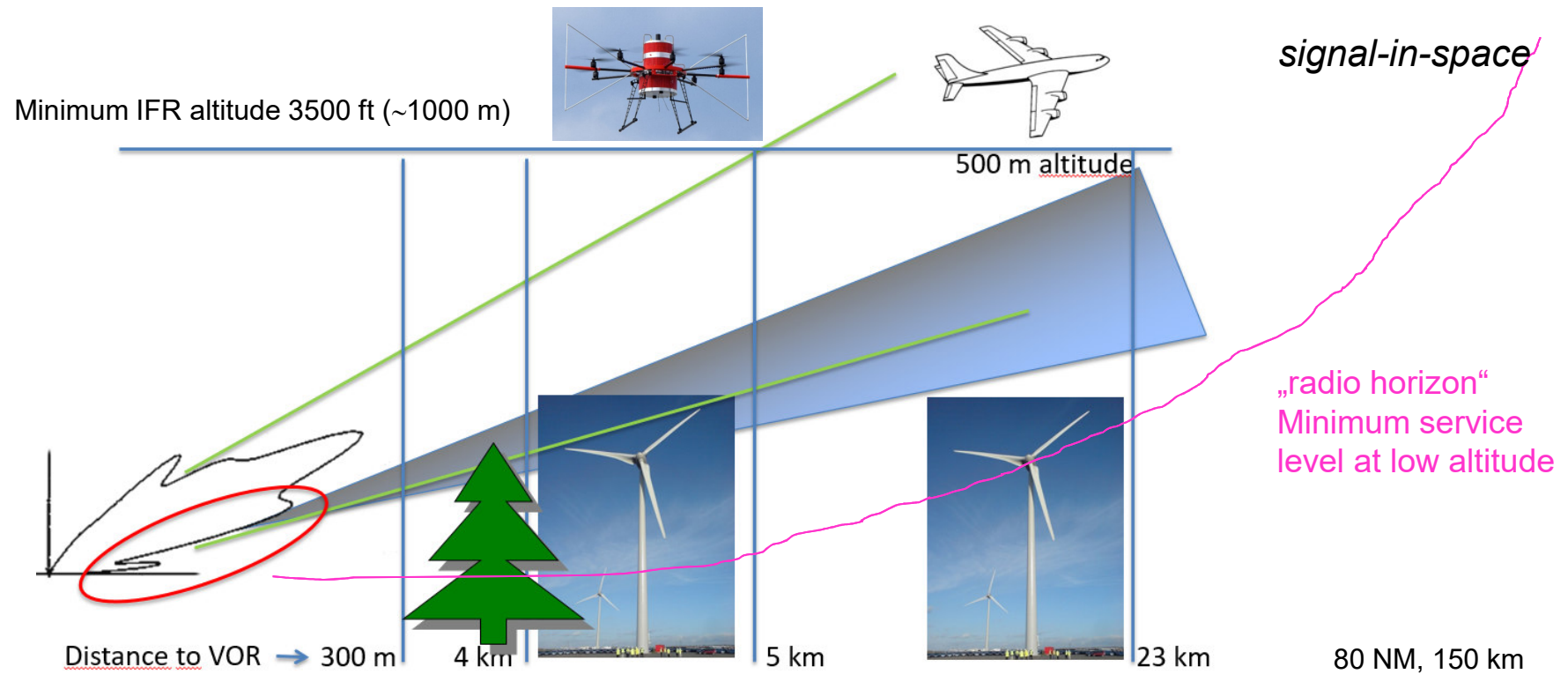
AM reference signal



FM course signal



Geometry of the Problem



Research Focus *arcass*: On-Site Measurements of Navigation and Radar Systems



Non-directional beacons (NDB) and direction finder (ADF)	500 kHz
Instrument Landing Systems Localizer (ILS-LLZ)	110 MHz
VHF Omnidirectional Radio Ranges (CVOR DVOR)	113 MHz
Marine radio Service	160 MHz
Instrument Landing Systems Glide Path (ILS-GP)	330 MHz
DWD UHF-Windprofiler	482 MHz
Airport surveillance radar (ASR)	2.7 GHz
Military surveillance radar (LVR)	some GHz
DWD precipitation radar (C-Band)	5.6 GHz
X-Band Marine radar	9.375 GHz

arcass: Advanced remote-controlled airborne sensor systems

On-Site Measurement Platforms



VTOL
„Vertical take-off and landing“

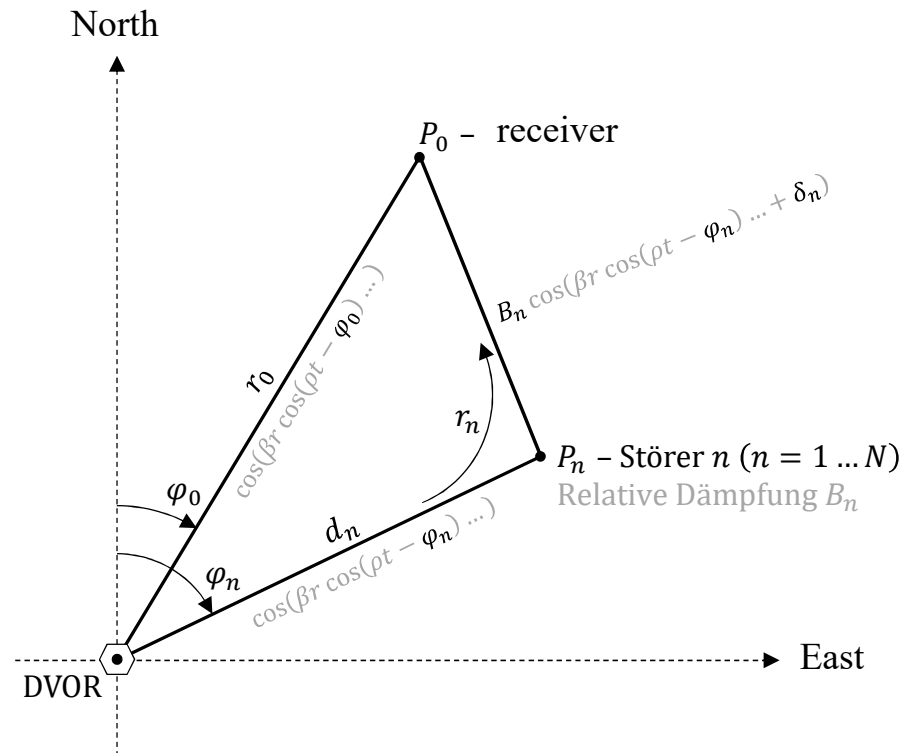


2-Path Error Model (Anderson and Flint)/Forecast



Overview

- Original DFS formula (DFS)
- Modified DFS formula (DFSM)
- Anderson-Flint based integral solution (AFIS)



Anderson-Flint based Error Models



The original DFS formula (DFS)

$$\varepsilon_{DFS}(\varphi_0, r_0) = \sum_{n=1}^N \left| C_n \cdot J_1 \left[2\beta r \sin \left(\frac{\varphi_n - \varphi_0}{2} \right) \right] \cdot \cos \left(\frac{\varphi_n - \varphi_0}{2} \right) \cdot \underbrace{\cos(\beta(r_n - r_0) + \delta_n)}_{-1} \right|$$

$$C_n = \frac{\varepsilon_{ref} \cdot \frac{h_n - \frac{d_n^2}{4100^2}}{h_{ref}} \cdot \left(\frac{d_{ref}}{d_n} \right)^u \cdot \frac{2A_n}{\beta r}}{\max_{0^\circ \leq \varphi_0 \leq 360^\circ} \left| \frac{2A_n}{\beta r} \cdot J_1 \left[2\beta r \sin \left(\frac{\varphi_n - \varphi_0}{2} \right) \right] \cdot \cos \left(\frac{\varphi_n - \varphi_0}{2} \right) \cdot \underbrace{\cos(\beta(r_n - r_0) + \delta_n)}_{-1} \right|}$$

C. Morlaas, ENAC, 2008

$$\varepsilon_{ref} = 0.08^\circ \quad h_{ref} = 95 \text{ m} \quad d_{ref} = 4000 \text{ m} \quad u = \frac{\ln(1.60)}{\ln(1.36)}$$

$$A_n = 0.1 \quad \delta_n = 180^\circ \quad \beta = \frac{2\pi f}{c} \quad r = 6.75 \text{ m}$$

Anderson-Flint based Error Models



The modified DFS formula (DFSM)

$$\varepsilon_{DFSM}(\varphi_0, r_0) = \sum_{n=1}^N \left\{ C_n \cdot J_1 \left[2\beta r \sin \left(\frac{\varphi_n - \varphi_0}{2} \right) \right] \cdot \cos \left(\frac{\varphi_n - \varphi_0}{2} \right) \cdot \cos(\beta(r_n - r_0) + \delta_n) \right\}$$

$$C_n = \varepsilon_{ref} \cdot \frac{h_n - \frac{d_n^2}{d_{ref}^2} \cdot d_M}{h_{ref} \cdot m_B} \cdot \left(\frac{d_{ref}}{d_n} \right)^u$$

$$\varepsilon_{ref} = 0.08^\circ \quad h_{ref} = 95 \text{ m} \quad d_{ref} = 4000 \text{ m} \quad d_M = 0,95 \text{ m} \quad u = \frac{\ln(1.60)}{\ln(1.36)}$$

$$A_n = 0.1 \quad \delta_n = 180^\circ \quad \beta = \frac{2\pi f}{c} \quad m_B = 0.58 \dots \quad r = 6.75 \text{ m}$$

Anderson-Flint based Error Models



The Anderson-Flint Integral Solution (AFIS, Prof. Harald Löwe)

$$U(t) = e^{j[\beta r \cos(\rho t - \varphi_0) - \beta r_0]} + \sum_{n=1}^N B_n e^{j[\beta r \cos(\rho t - \varphi_n) - \beta r_n - \delta_n]}$$

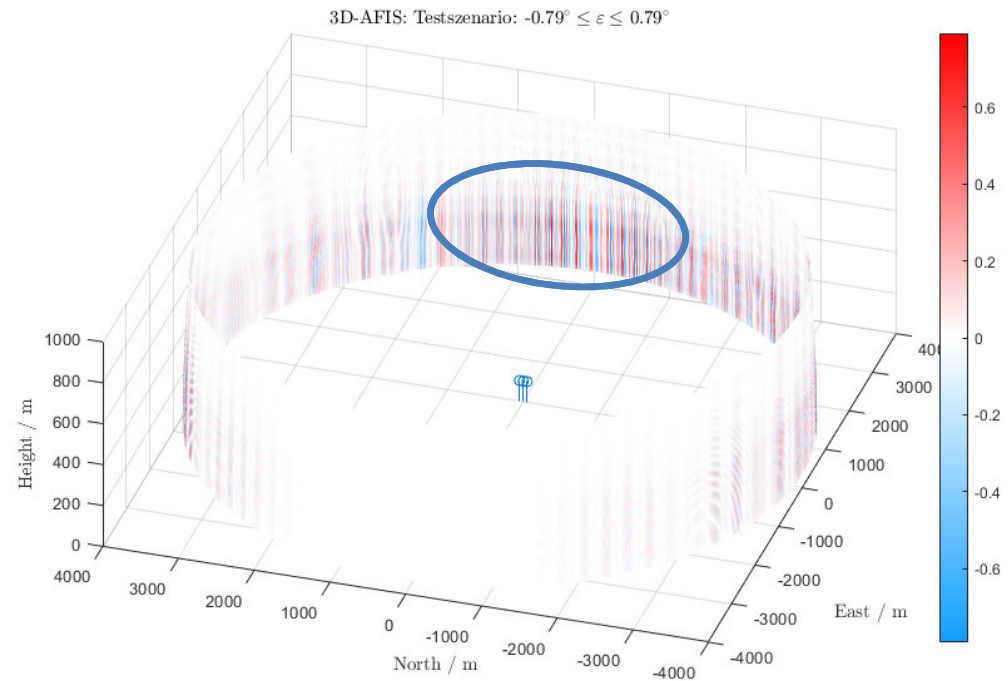
$$B_n(d_n, h_n, f) = \frac{\beta r}{2} C_n \quad \sum_{n=1}^N B_n < 1 \quad \text{all scatterers}$$

$$\varepsilon_{AFIS}(\varphi_0, r_0) = \arg \left(j \cdot \int_0^{2\pi/\rho} \underbrace{\text{Im} \left(\frac{\dot{U}(t)}{U(t)} \right)}_{\psi(t)} \cdot e^{j(\rho t - \varphi_0)} dt \right)$$

3D AFIS Error Model



- three WT with 100 m height east of DVOR (1 km)
- Frequency of DVOR 115 MHz (wavelength ca. 2.6 m)
- Weighted integration with equidistant steps
- „Fitted“ to DFSM factor
- Calculated error on the surface of a sphere with 4 km radius



Now state-of-the-art



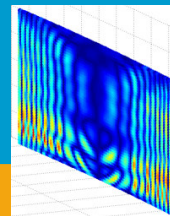
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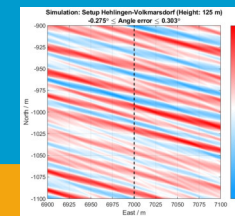
On-Site-
Measurements
(time stamp,
location, data)



Full-wave-
simulation in
time- and
frequency-
domain



New
forecast
tools:
DFSM
AFIS

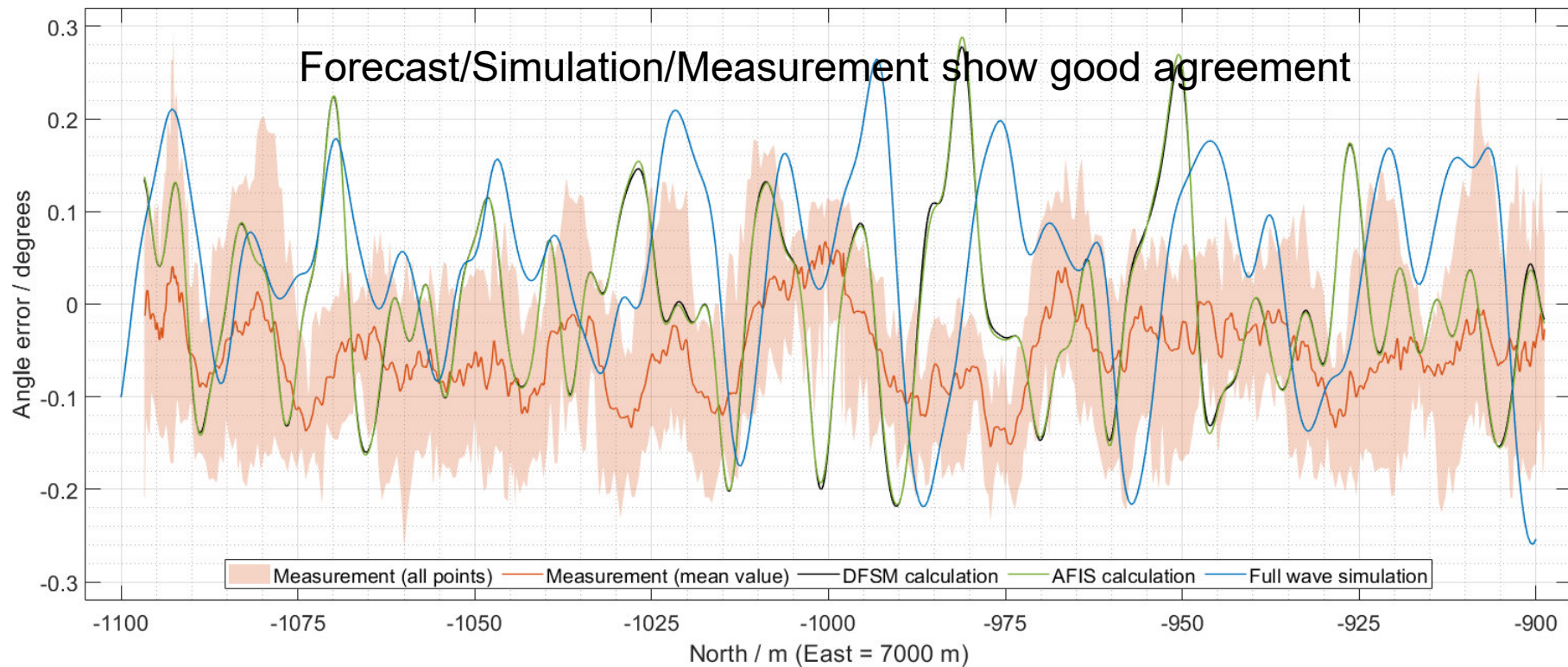


Three independent methods yield the same results ?

DVOR Hehlingen



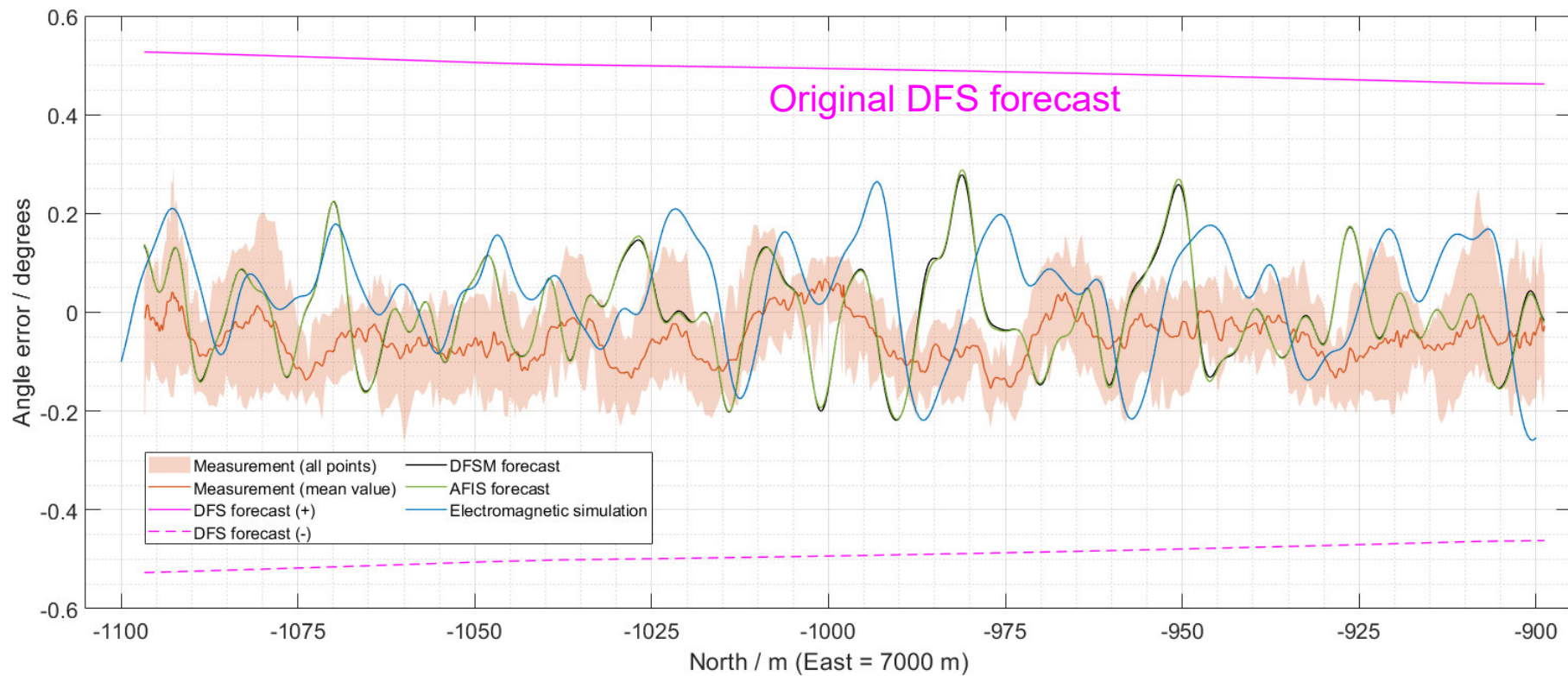
Comparison: **DFSM** / **AFIS** / **EM Simulation** / **Measurements**



DVOR Hehlingen



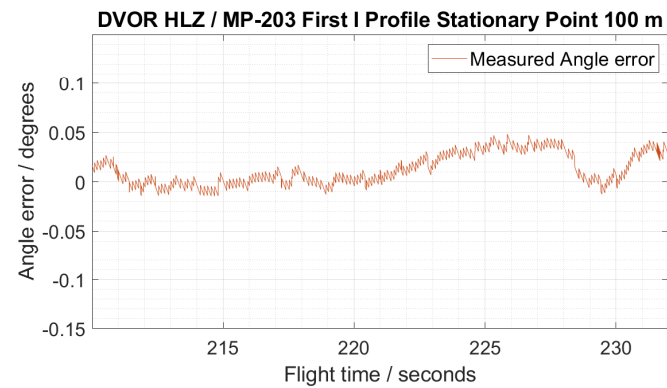
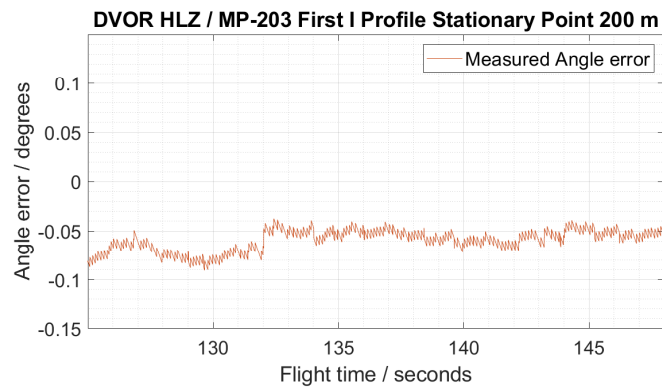
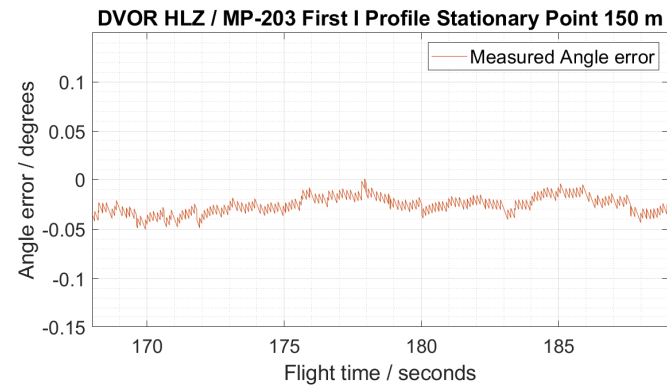
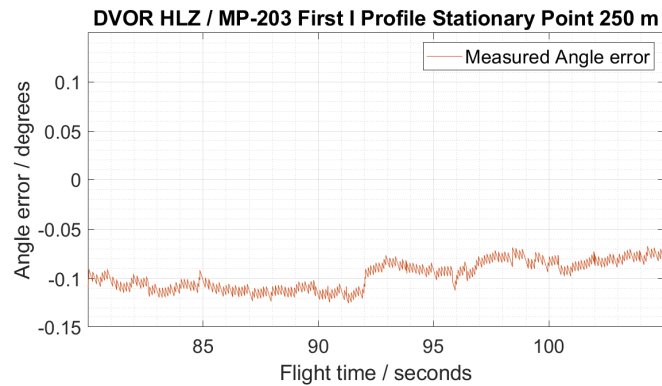
Comparison: DFS / DFSM / AFIS / EM Simulation / Measurements



DVOR Hehlingen – Test for low bearing error



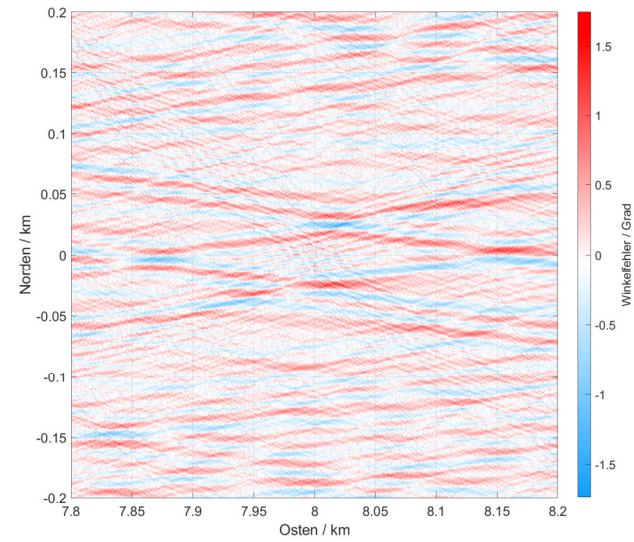
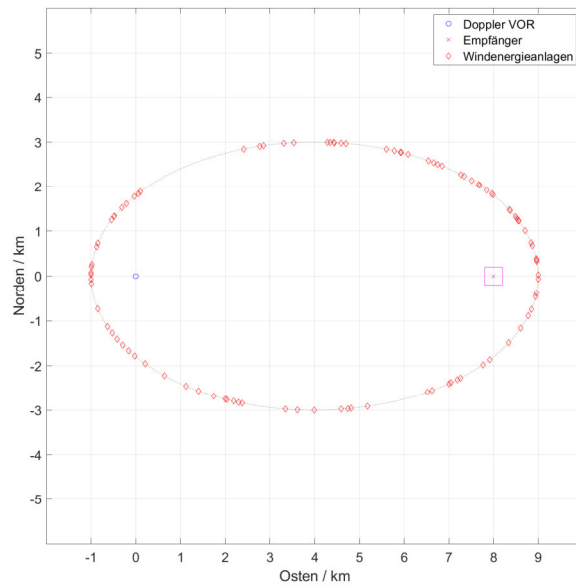
DVOR Hehlingen – Test for low bearing error



Test for Worst-Case – Part 1



Two focal points of elliptical setup

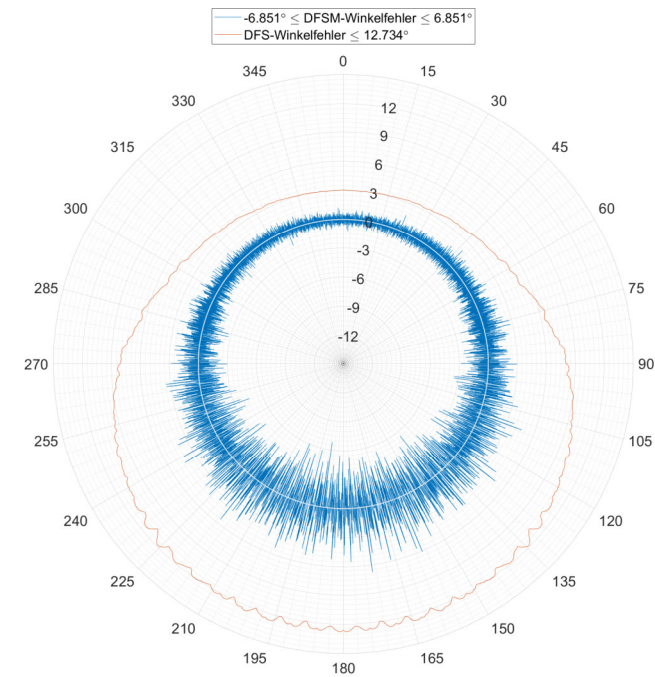
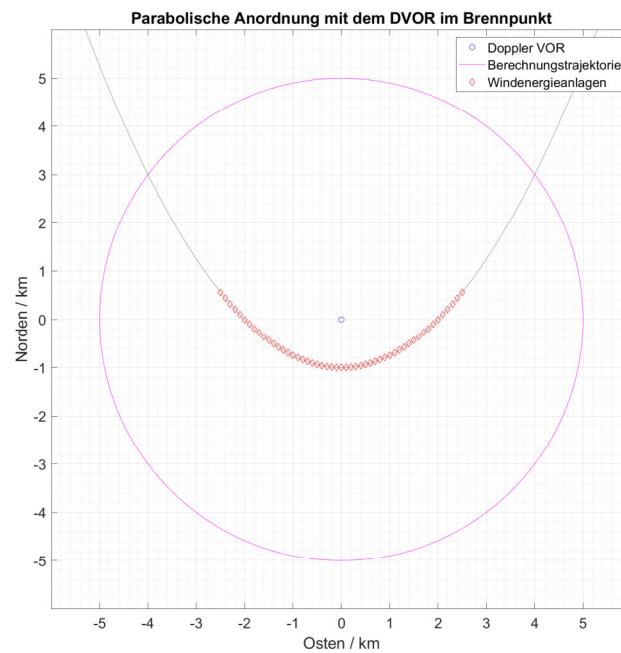


Test for Worst-Case – Part 2



Focal point of concave mirror

Setup: 51 Windenergieanlagen, 200 m Höhe



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Flight Inspection according to ICAO



- The flight calibration of terrestrial radio navigation systems is carried out in accordance with ICAO Doc 8071 Vol. I
- According to ICAO Doc 8071 measurements shall be performed deploying an aircraft typical system (receiver, antenna, etc.), Doc 8071 Vol. I 5th edition 2.3.41
- The calibration of the measuring system onboard the flight inspection aircraft takes place at regular intervals under stationary laboratory conditions
- The measurement uncertainty MU of the receiving system is determined by using traceably calibrated transmitters
- According to Doc 8071 (Vol. I 5th edition 2.3.9 and 2.3.10), the periodic orbit flight shall take place in the main lobe at an appropriate distance and service volume

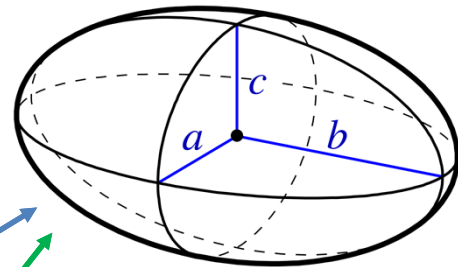
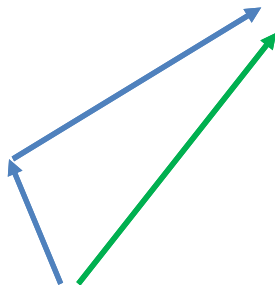
Using results of flight inspection as pre-load of VOR



- Single, linear measuring antennas on-board the aircraft do not allow to determine the 3D electric field vector in space and are not required by ICAO Doc 8071
- **Dependent on the movement of the aircraft additional bearing error contributions occur: Fullwave simulations of a generic aircraft shows 0.5°, up to 1° additional error**
- **This is different for every combination aircraft/antenna**
- Periodic orbit flights acc to ICAO Doc 8071 are not performed at the radio horizon (Elevation 1°)
→ no worst-case
(Worst-Case is checked using radial flights of published flight procedures)
- Determination of bends ($\pm 3,5^\circ$) should be done in radial flights acc to ICAO 8071:2018 2.3.12 (which are periodically performed in Germany)

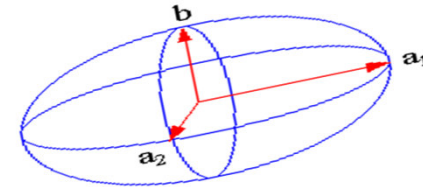
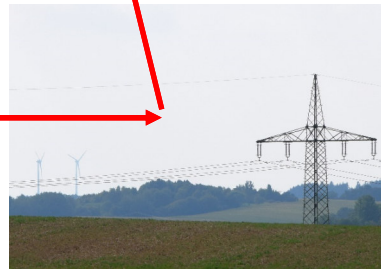
Flight Inspection acc. ICAO and *signal-in-space*

WT lead to additional deformation of ellipsoid in space:
 → *signal-in-space*
 → No bearing error yet



3D ellipsoid
 Ideal: $a, c = 0, b = b_0$

Real: with area
 $a, c > 0, b \neq b_0$



Vectorial 3D receiving structure:

- Yield scalar value
 antenna voltage = $f(t)$
- Demodulation / Filtering
- Bearing error

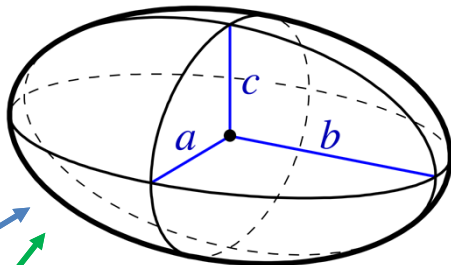
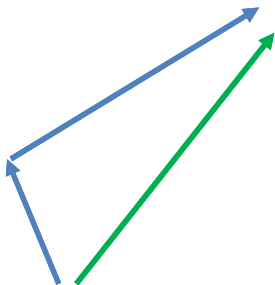
Antenna pattern:

- Measuring aircraft: type dependent
- drone: dipole-like, well-known

Flight Inspection acc. ICAO and *signal-in-space*

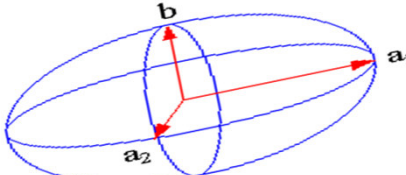


WT lead to additional deformation of ellipsoid in space:
 → *signal-in-space*
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3D ellipsoid
 Ideal: $a, c = 0, b = b_0$

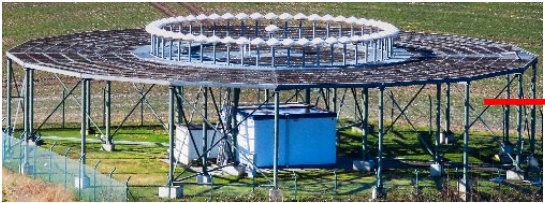
Real: with area
 $a, c > 0, b \neq b_0$



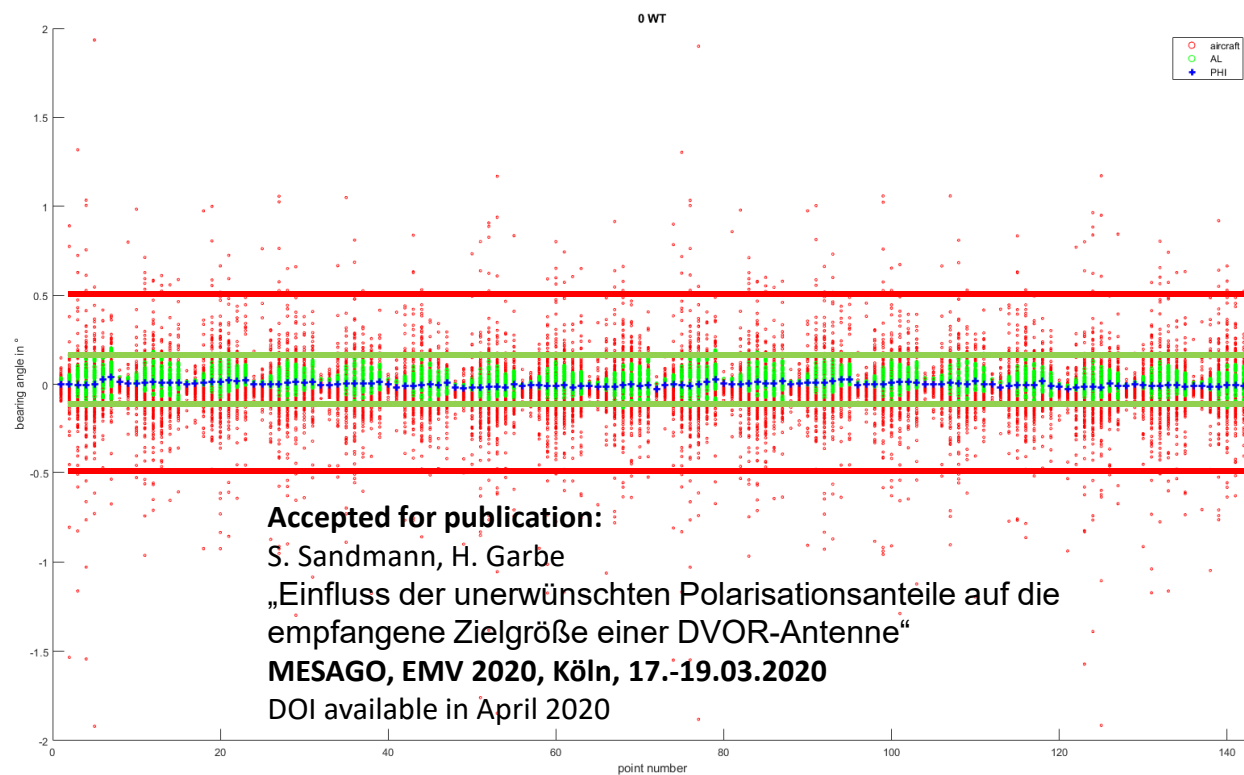
Vectorial 3D receiving structure:
 → Yield scalar value
 antenna voltage = $f(t)$
 → Demodulation / Filtering

FI orbit flights show rather high uncertainties when used to determine the pre-load of VOR

- Measuring aircraft: type dependent
- drone: dipole-like, well-known



Simulation of Orbit flights at $R = 15$ km



„Pre-load“:
Depends on type
of meas antenna

Simulated
uncertainty
about 0.5°

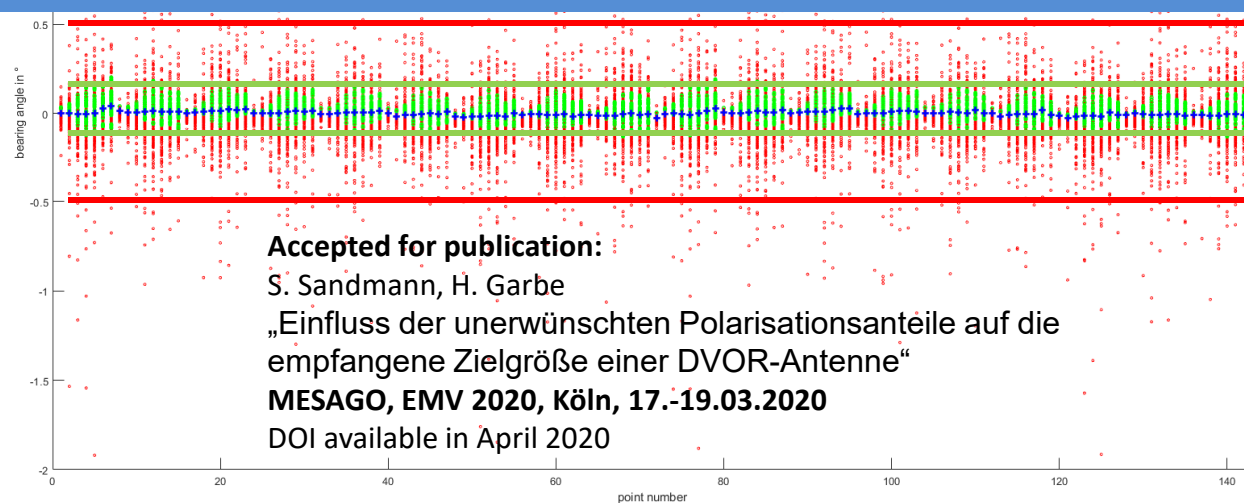
Simulation of Orbit flights at $R = 15$ km



Annex 10, Vol.1: 2006

3.3.3.1 The emission from the VOR shall be horizontally polarized. The vertically polarized component of the radiation shall be as small as possible.

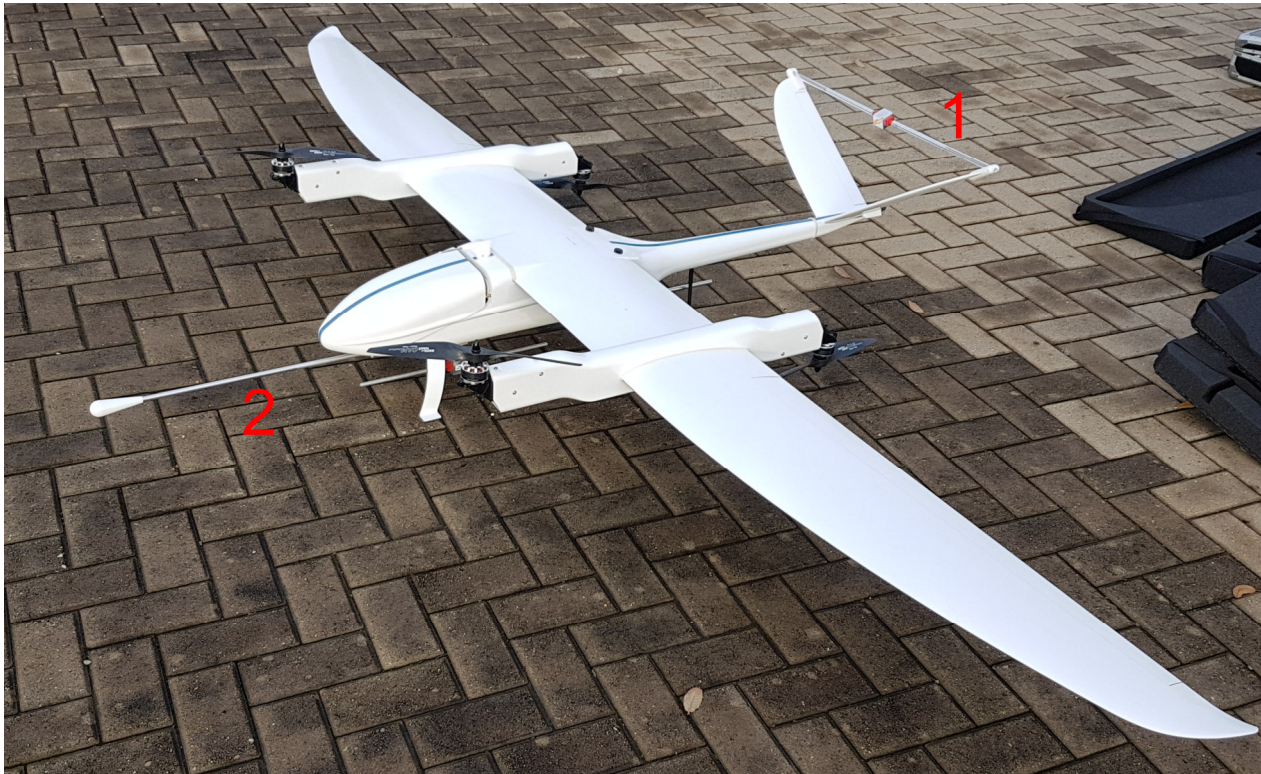
Note. — It is not possible at present to state quantitatively the maximum permissible magnitude of the vertically polarized component of the radiation from the VOR. (Information is provided in the Manual on Testing of Radio Navigation Aids (Doc 8071) as to flight checks that can be carried out to determine the effects of vertical polarization on the bearing accuracy.)



„Pre-load“:
Depends on type
of meas antenna

Simulated
uncertainty
about 0.5°

Measurements of Pre-load using PTB VTOL

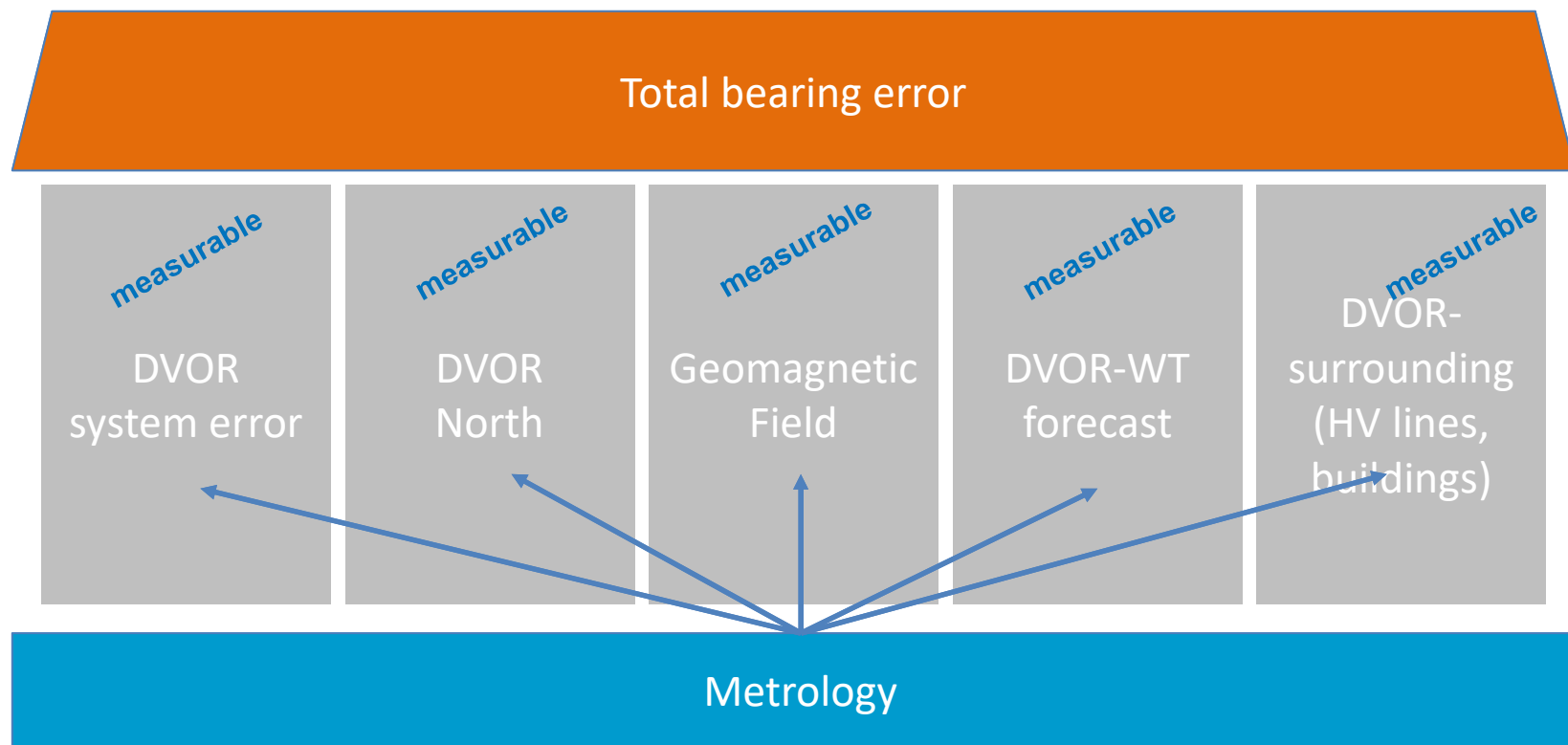


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Signal-in-Space of a DVOR



Total DVOR Bearing Error Budget DVOR (s-i-s)



$\Delta\varphi_{Anl}$	systematic, system error, magnetic north calibration
$\Delta\varphi_{Umg}$	systematic, terrain, HV lines, tall buildings
$\Delta\varphi_{Umg_var}$	statistic, incl. slowly variations, cars, vegetation
$\Delta\varphi_{Erdmagn}$	daytime dependend geomagnetic north
$\Delta\varphi_{Erdmagn_Drift}$	slow, $0.1^\circ/5$ Jahre, negligible
$\Delta\varphi_{WEA}$	statistic process, in particular if many WT, may depend on daytime when nacelle is rotating with wind direction
$\Delta\varphi_{AM}$	statistic process, without correlation to WT, etc.

Total DVOR Bearing Error Budget DVOR (s-i-s)



Größe	Wert	Standardmess- unsicherheit
ϕ_{Anlage}	2.0 Grad	0.0 Grad
ϕ_{FI}	0.700 Grad	0.300 Grad
ϕ_{WEA}	1.500 Grad	0.100 Grad

DFS

$$\Delta\phi = \Delta\phi_{Anlage} + \sqrt{\Delta\phi_{FI}^2 + \Delta\phi_{WEA}^2}$$

Ergebnis:

Wert: ±
 Erw. Messunsicherheit:
 Erweiterungsfaktor:
 Überdeckung:

Größe	Wert	Standardmess- unsicherheit
ϕ_{Anl}	0.500 Grad	0.100 Grad
ϕ_{Umg}	0.700 Grad	0.100 Grad
ϕ_{Umgvar}	0.300 Grad	0.100 Grad
ϕ_{WEA}	1.500 Grad	0.100 Grad
ϕ_{erde}	0.8000 Grad	0.0577 Grad
ϕ_{AM}	0.2000 Grad	0.0577 Grad

PTB

New: Measured

$$\Delta\phi = \Delta\phi_{Anl} + \Delta\phi_{Umg} + \sqrt{\Delta\phi_{Umgvar}^2 + \Delta\phi_{Erdmag}^2 + \Delta\phi_{WEA}^2 + \Delta\phi_{AM}^2}$$

Wert: ±
 Erw. Messunsicherheit:
 Erweiterungsfaktor:

Total DVOR Bearing Error Budget DVOR (s-i-s)



Größe	Wert	Standardmess-unsicherheit
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DFS

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Ergebnis:
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ϕ_{Umgvar}	0.300 Grad	
ϕ_{AM}	1.500 Grad	

PTB

$$\Delta\phi = \Delta\phi_{Anl} + \Delta\phi_{Umg} + \sqrt{\Delta\phi_{Umgvar}^2 + \Delta\phi_{Erdmag}^2 + \Delta\phi_{WEA}^2 + \Delta\phi_{AM}^2}$$

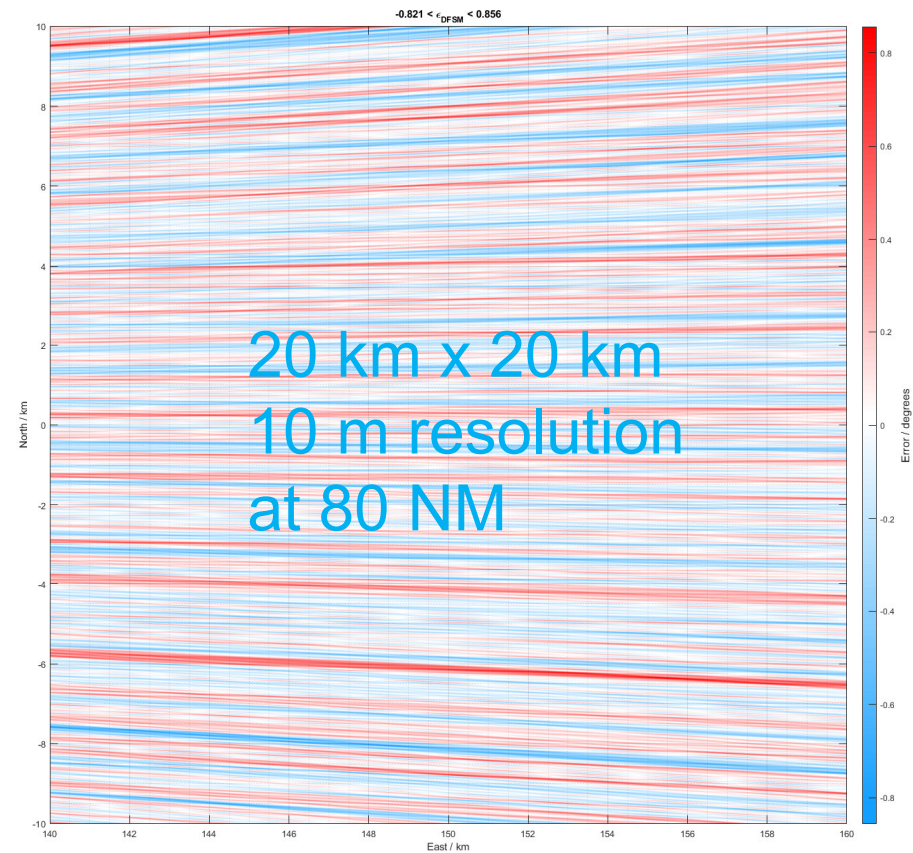
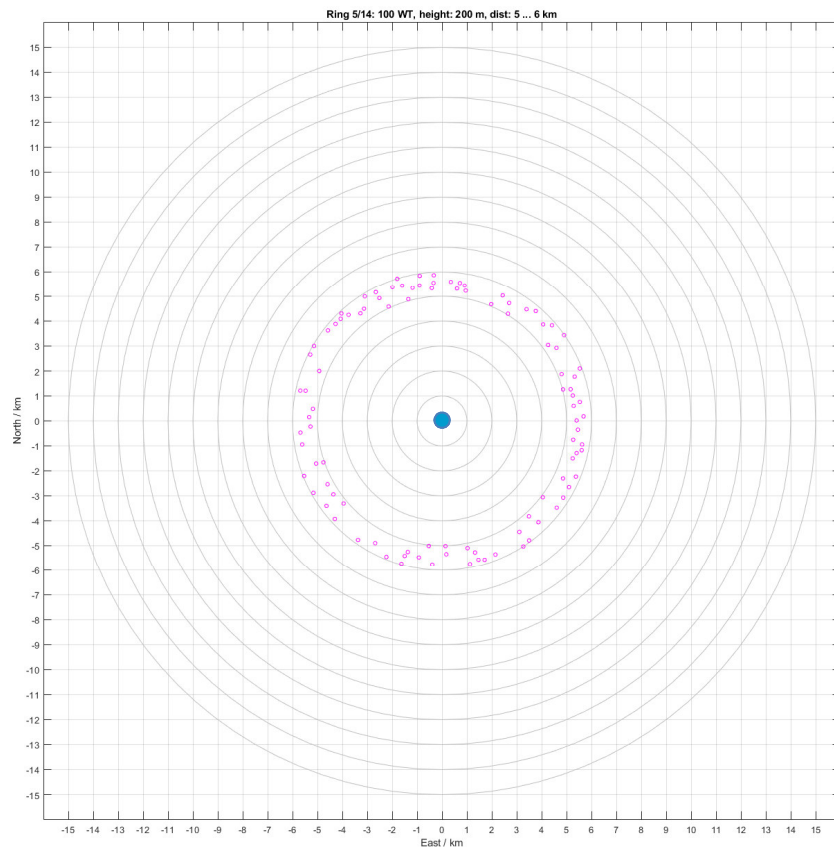
Wert: ±
 Erw. Messunsicherheit:
 Erweiterungsfaktor:

< 2 deg

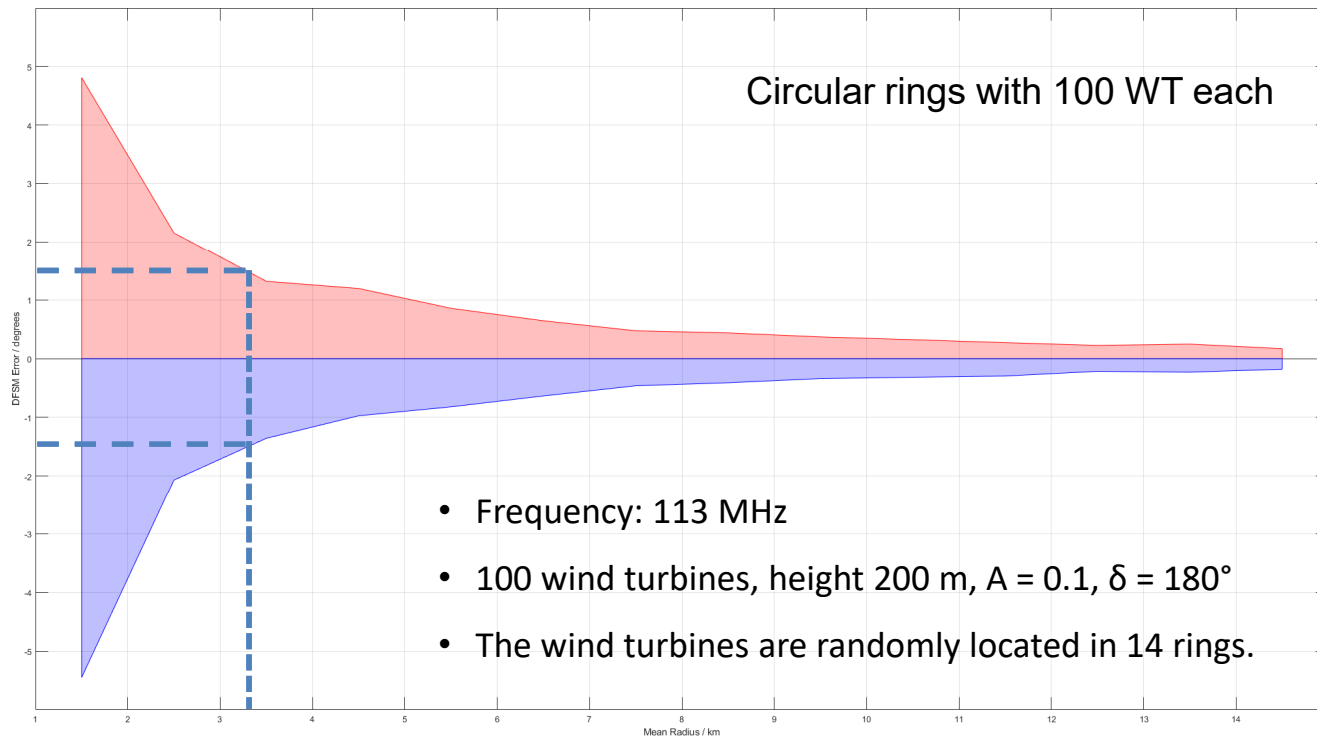
< 3.5 deg

New: Me Conformity assessment: $|\Delta\phi + U| < 3.5 \text{ deg}$

Future impact of 1.5° bearing error budget for WT



Future impact of 1.5° bearing error budget for WT



Executive Summary

- 1) Replace all CVOR with DVOR
- 2) **State-of-the-art_1**: Use new forecast tool DFSM or AFIS
- 3) **State-of-the-art_2**: DVOR system error, surrounding and WT influence now measurable
- 4) Evolution of total error budget

$$\Delta\varphi = \Delta\varphi_{Anlage} + \sqrt{\Delta\varphi_{FI}^2 + \Delta\varphi_{WEA}^2}$$

State-of-the-art_3: $3.5 \geq \Delta\varphi = \Delta\varphi_{Anl} + \Delta\varphi_{Umg} + \sqrt{\Delta\varphi_{Umg_var}^2 + \Delta\varphi_{Erdmag}^2 + \Delta\varphi_{WEA}^2 + \Delta\varphi_{AM}^2}$

Important: Measurements of *s-i-s* contain all error contributions

➡ **New: Conformity assessment**, no further worst-case assumptions necessary

- 5) **State-of-the-art_4**: Do not use pre-load φ_{Umg} from Flight inspection orbit flights due to increased uncertainty

Invitation to participate in Round Robin Test



- Part of the WERAN plus project
- International comparison on the effect of wind turbines on DVOR (forecast)
- Different setups will be available to work on (simple, intermediate, advanced)
- Will be organized in spring 2020
- Check for our website www.ptb.de and search for „WERAN plus intercomparison“
- Or send me an e-mail: thorsten.schrader@ptb.de



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