Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

WERAN:

Interaction of Wind Turbines with VHF Omnidirectional Radio Ranges

T. Schrader, J. Bredemeyer, C. Stupperich, H. Garbe

M. Mihalachi, D. Ulm, S. Sandmann

EMWT 2017
Braunschweig, 6.-7.12.2017

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

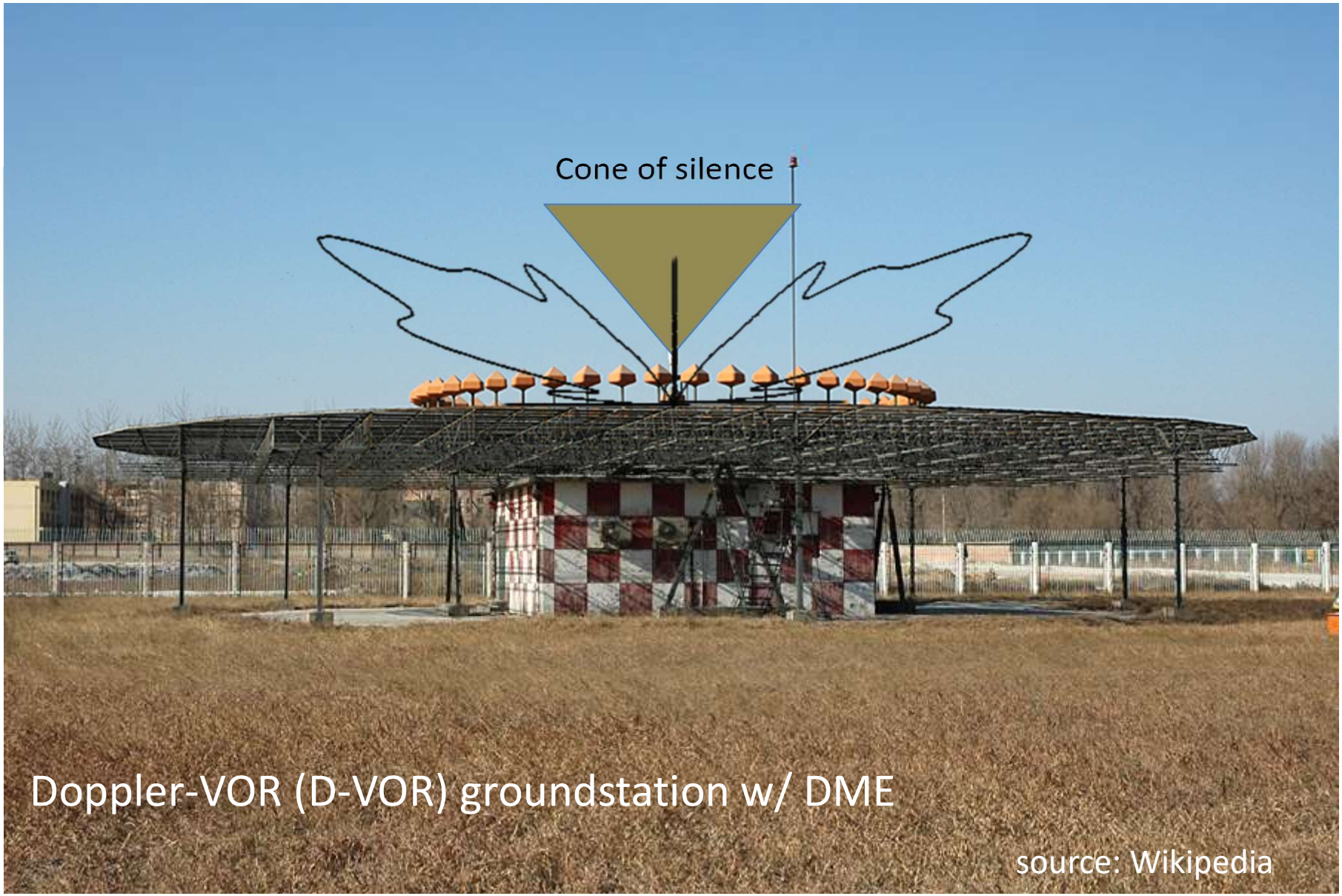
aufgrund eines Beschlusses des Deutschen Bundestages

FKZ: 0325644A-D

Content

- Technical Background of DVOR
- VHF Antenna and instrumentation installed at the UAS
- Measurement results
- Comparison of measurement results and numerical simulations
- Summary

All numerical simulations performed by Leibniz-University, Hannover, Germany, otherwise stated.

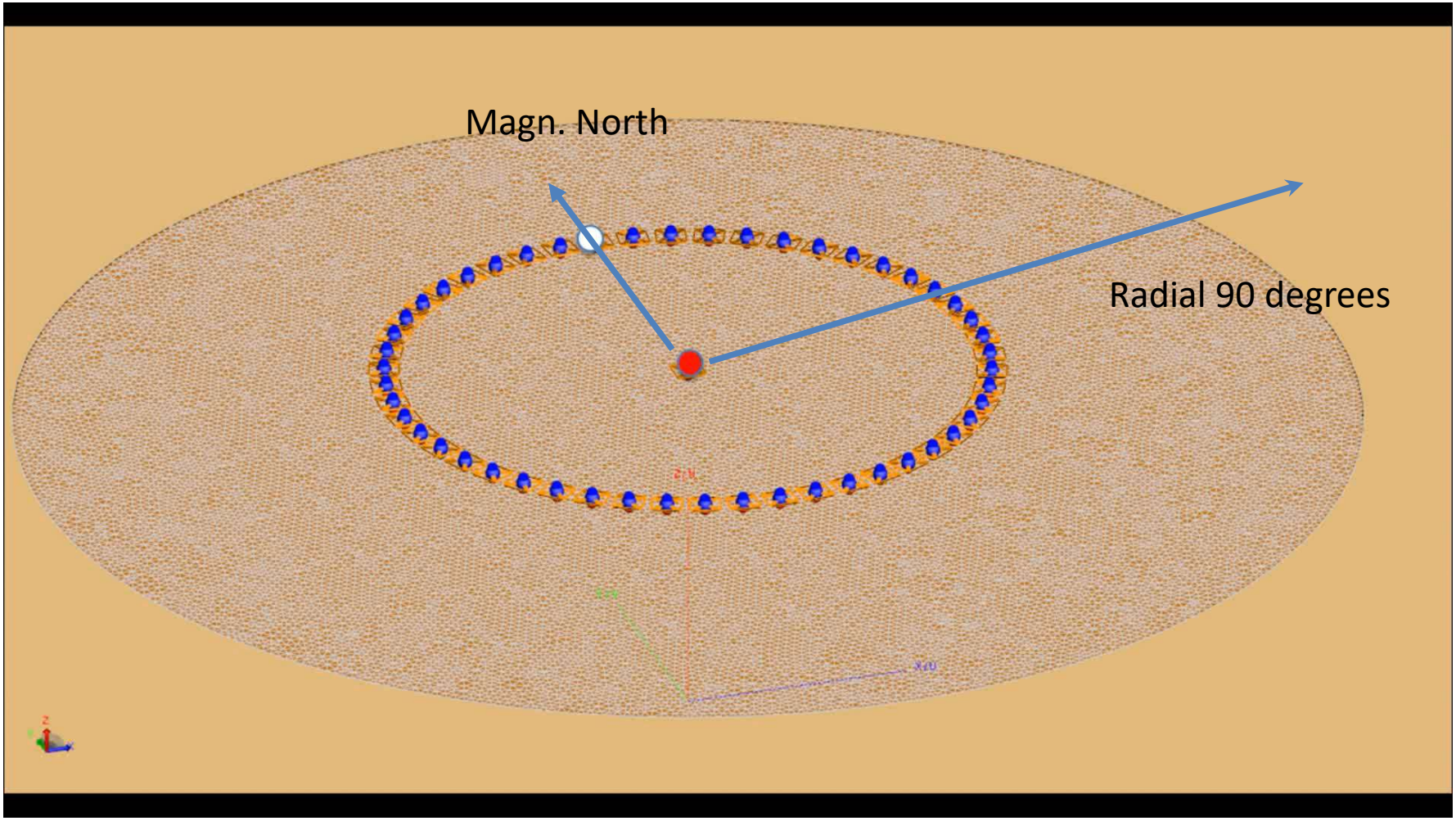


Doppler-VOR (D-VOR) groundstation w/ DME

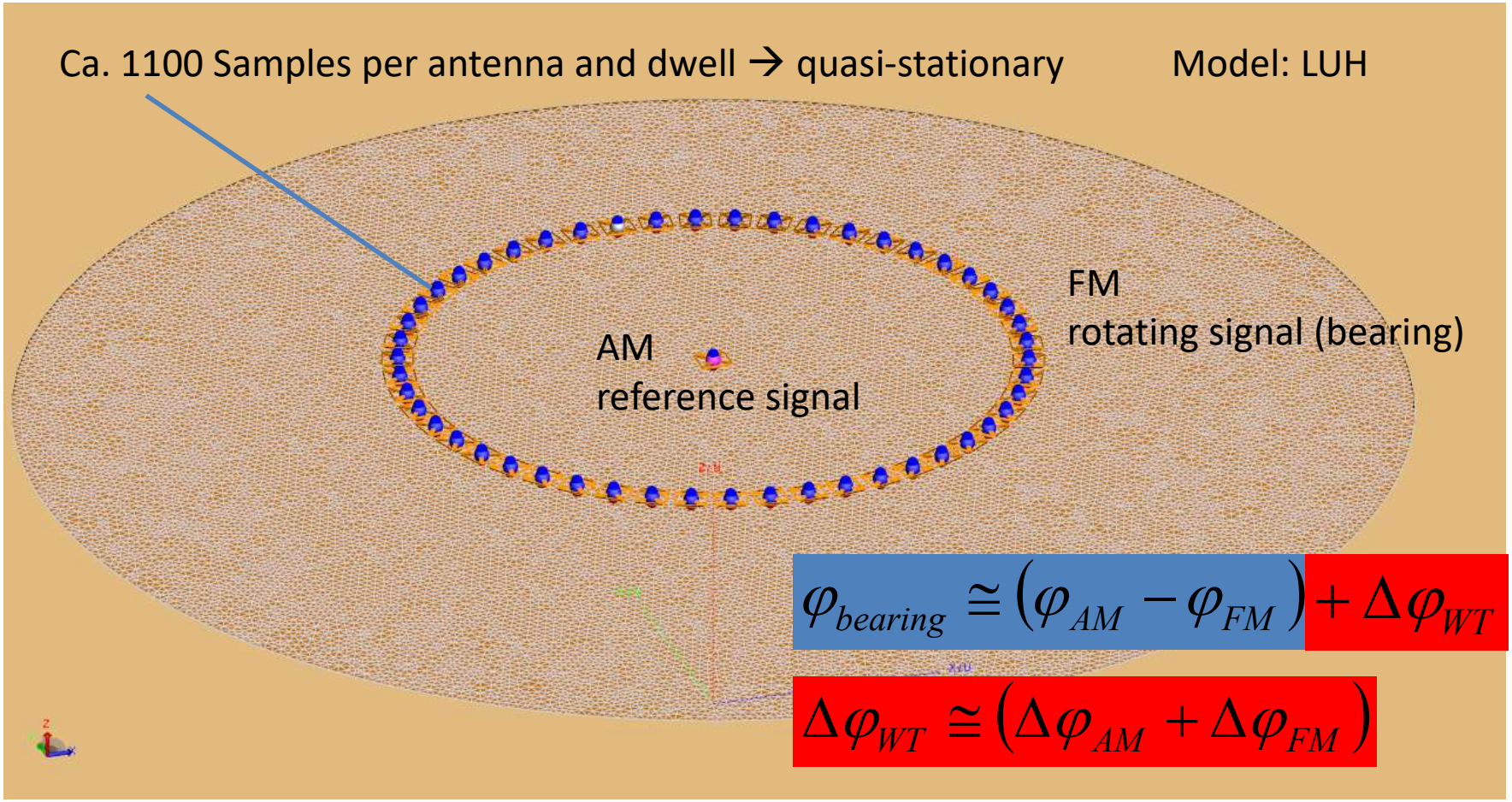
source: Wikipedia

Explanation of DVOR Functionality

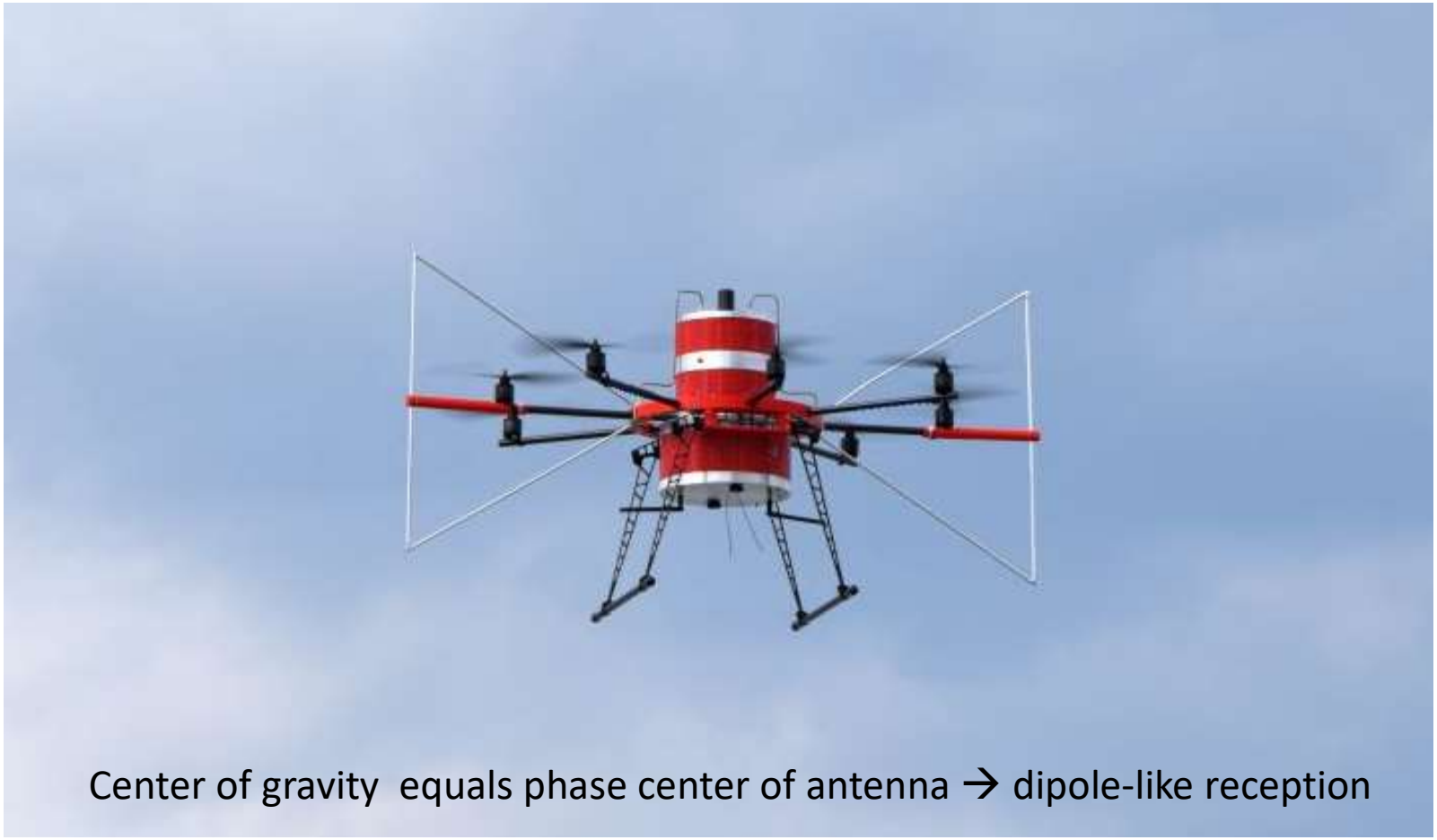
Model: LUH



CAD Model of the DVOR Groundstation:
51 Alford-Loop-Antennas above Groundplane

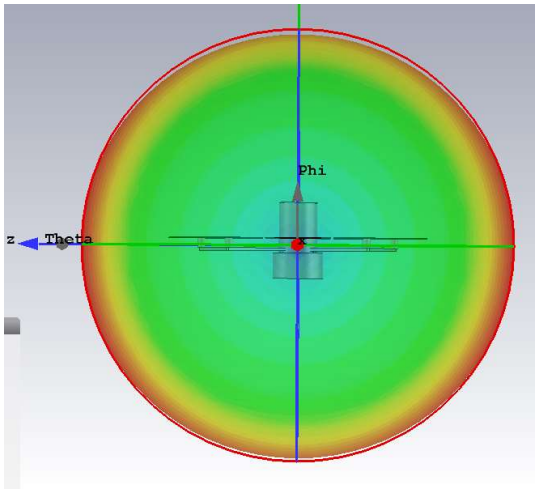


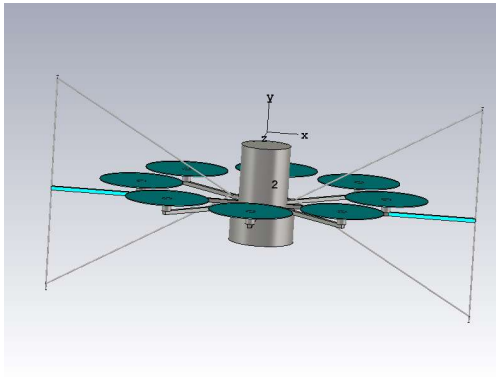
VHF Antenna installed at the UAS

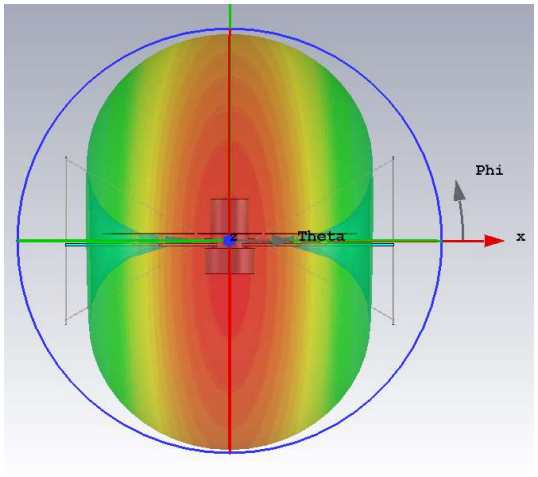


Center of gravity equals phase center of antenna → dipole-like reception

VHF Antenna installed at the UAS



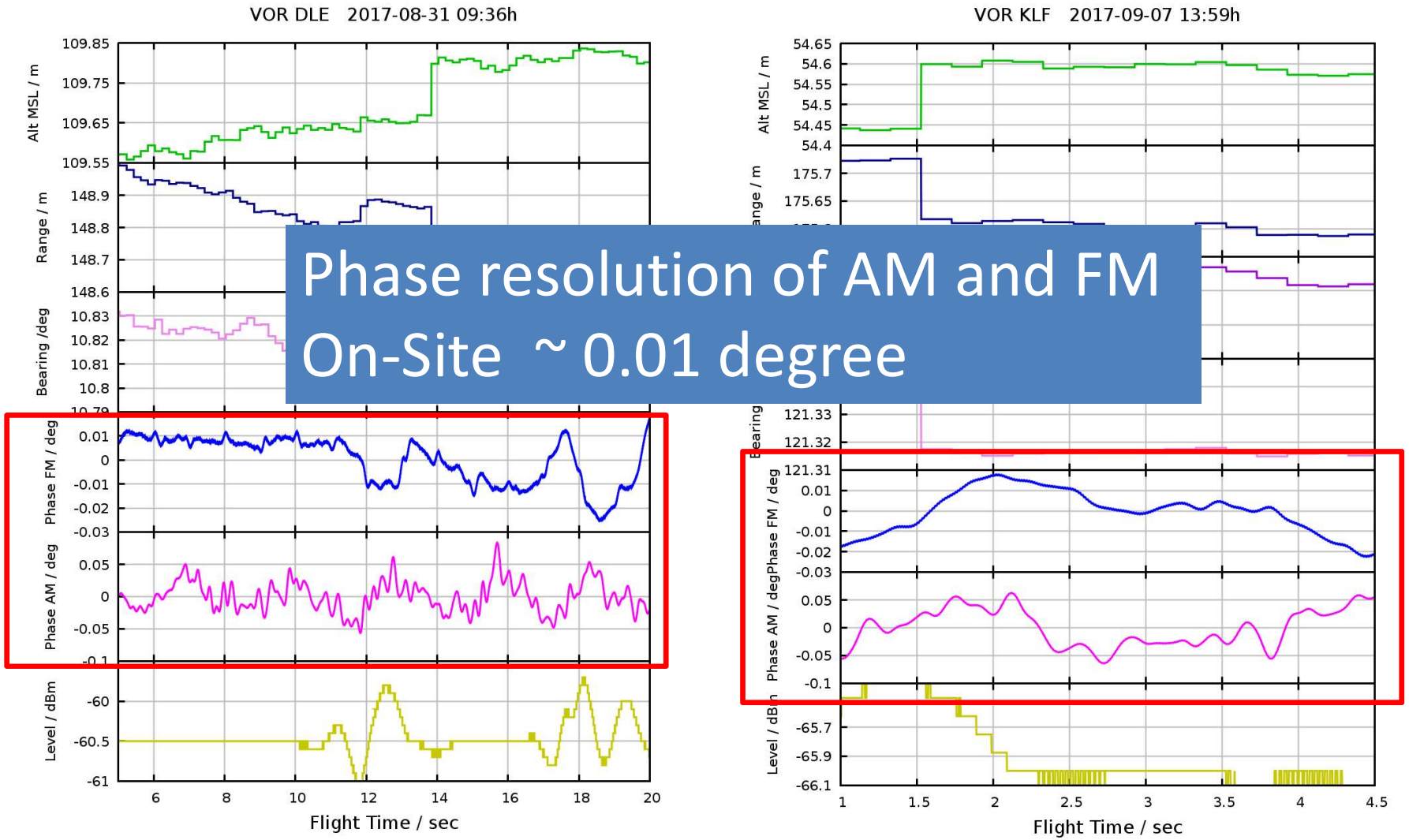




Dipole-like reception pattern, best uncertainty possible

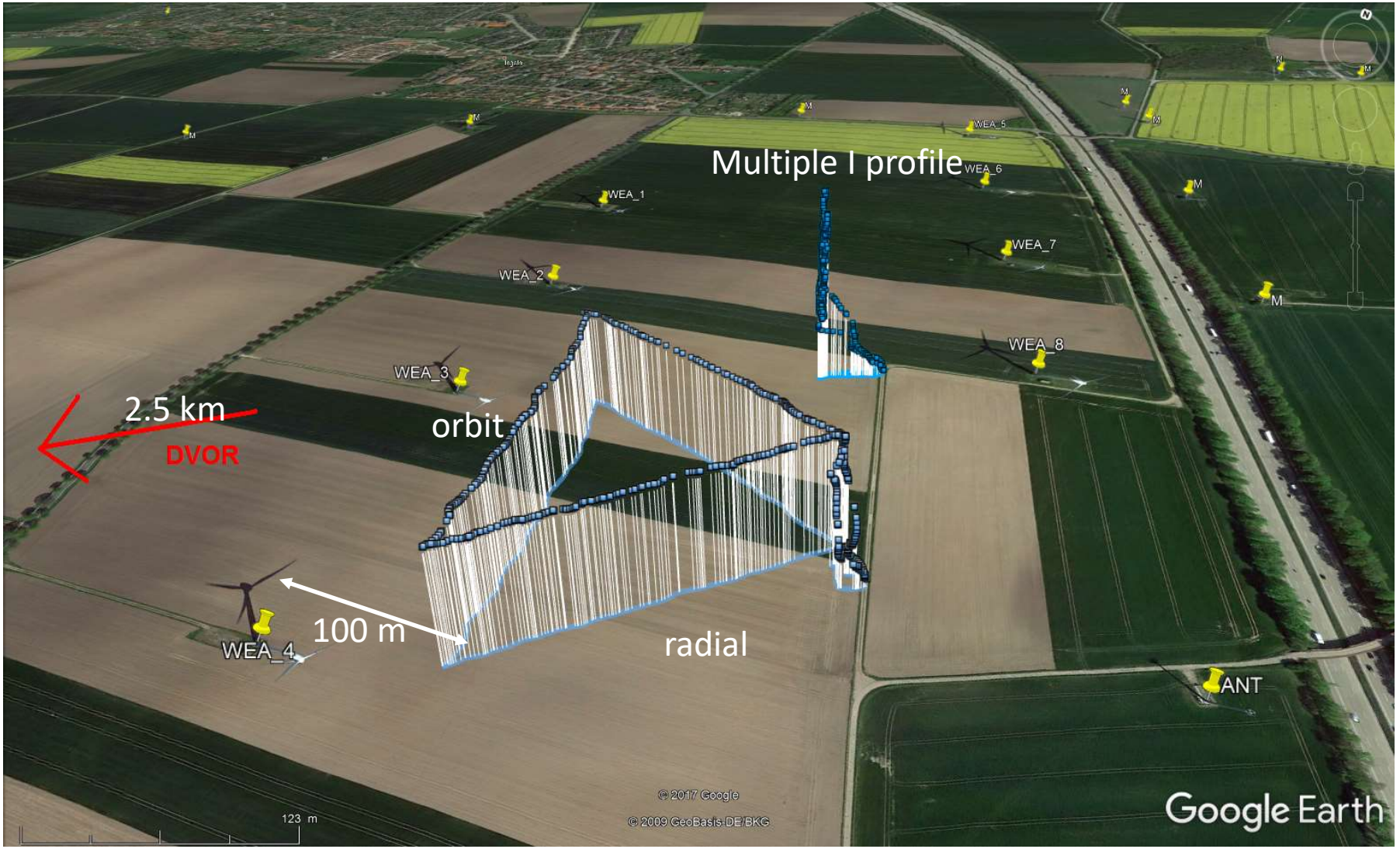
Simulation by PTB

DVOR Measurement at Ground Level (Phase test)

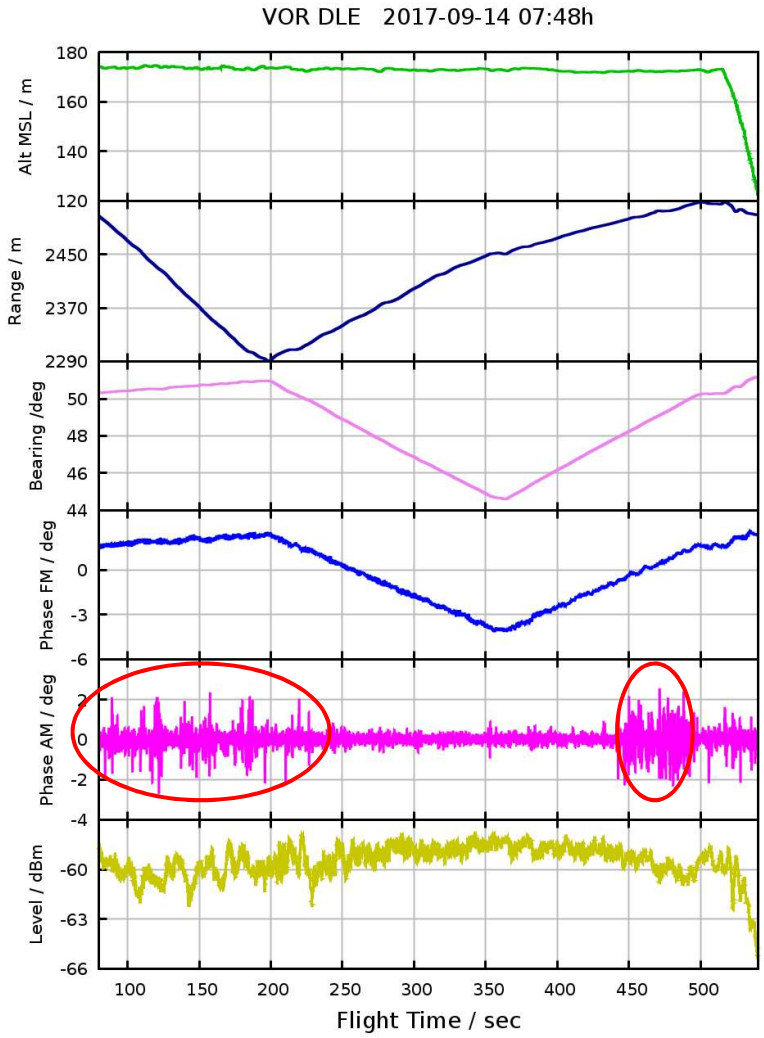


Phase resolution of AM and FM
On-Site ~ 0.01 degree

Measurement Setup DVOR Leine



Measurement DVOR Leine



„Triangle profile in wind park (2.5 km)“

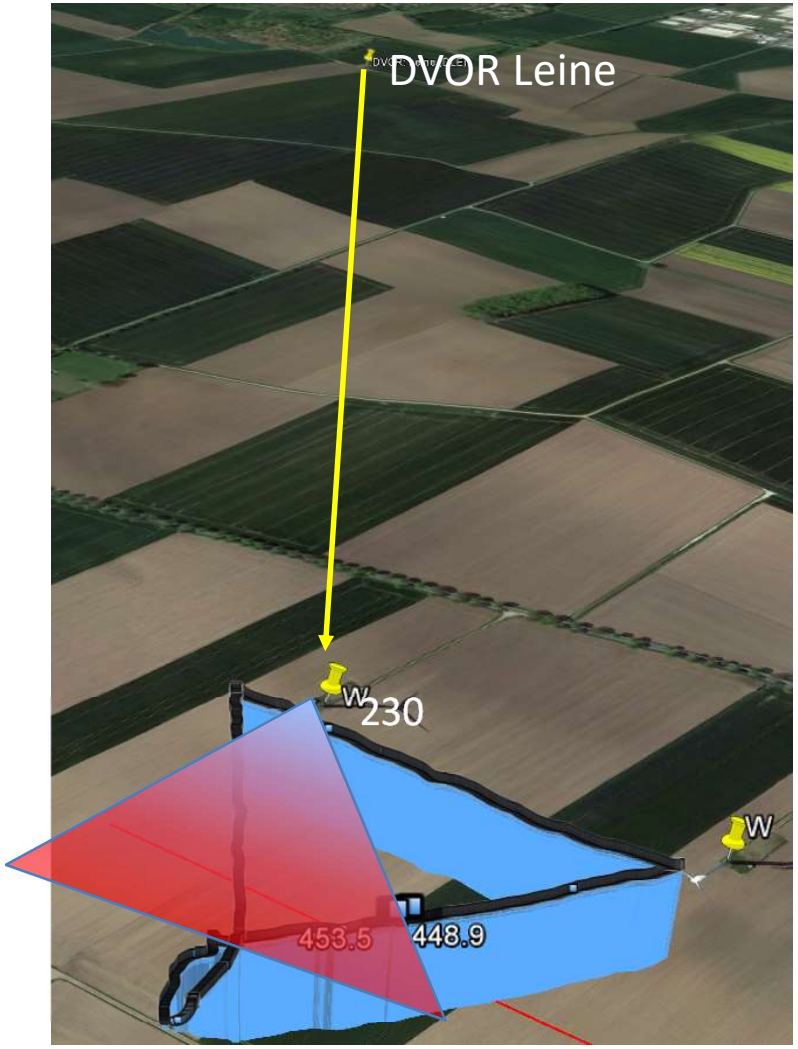
Bearing: calculated from geometry
FM phase must follow

Measured FM phase (flight along radial, orbit flights with respect to VOR)

Measured AM phase noisy /steady
(Rotor disk ⊥ to radial)

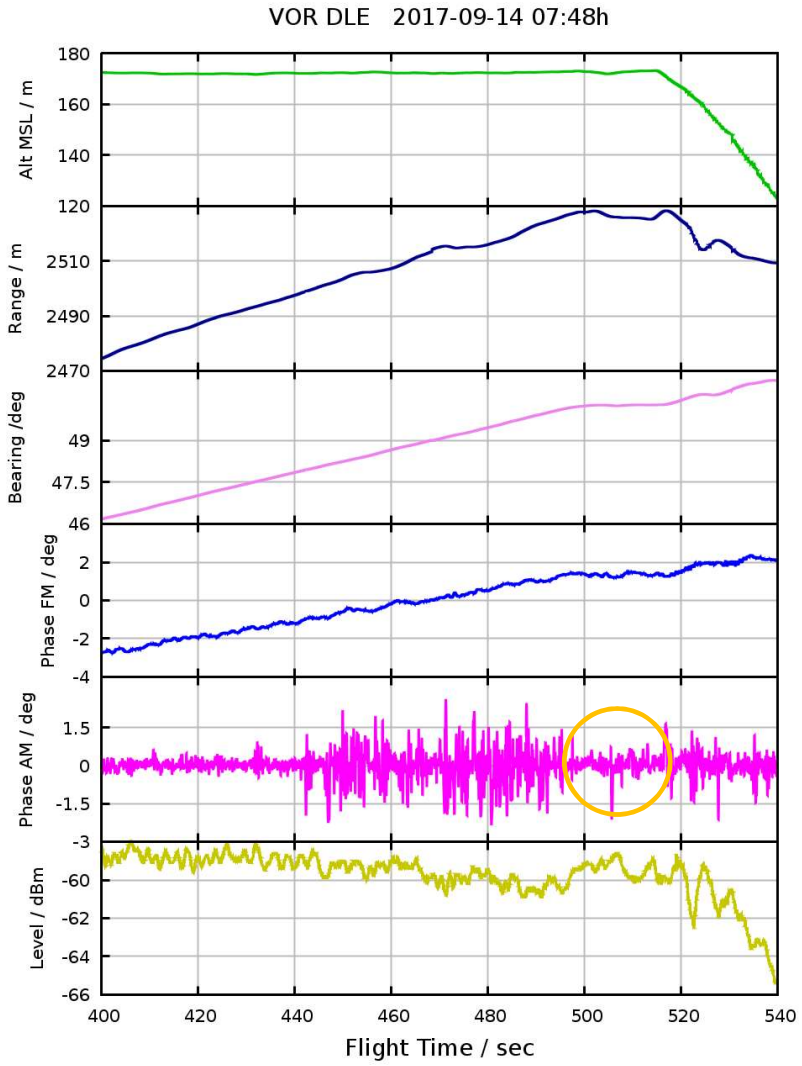
Receiver level with 40 dB SNR

Measurement DVOR Leine



Area of forward scatter

Measurement DVOR Leine



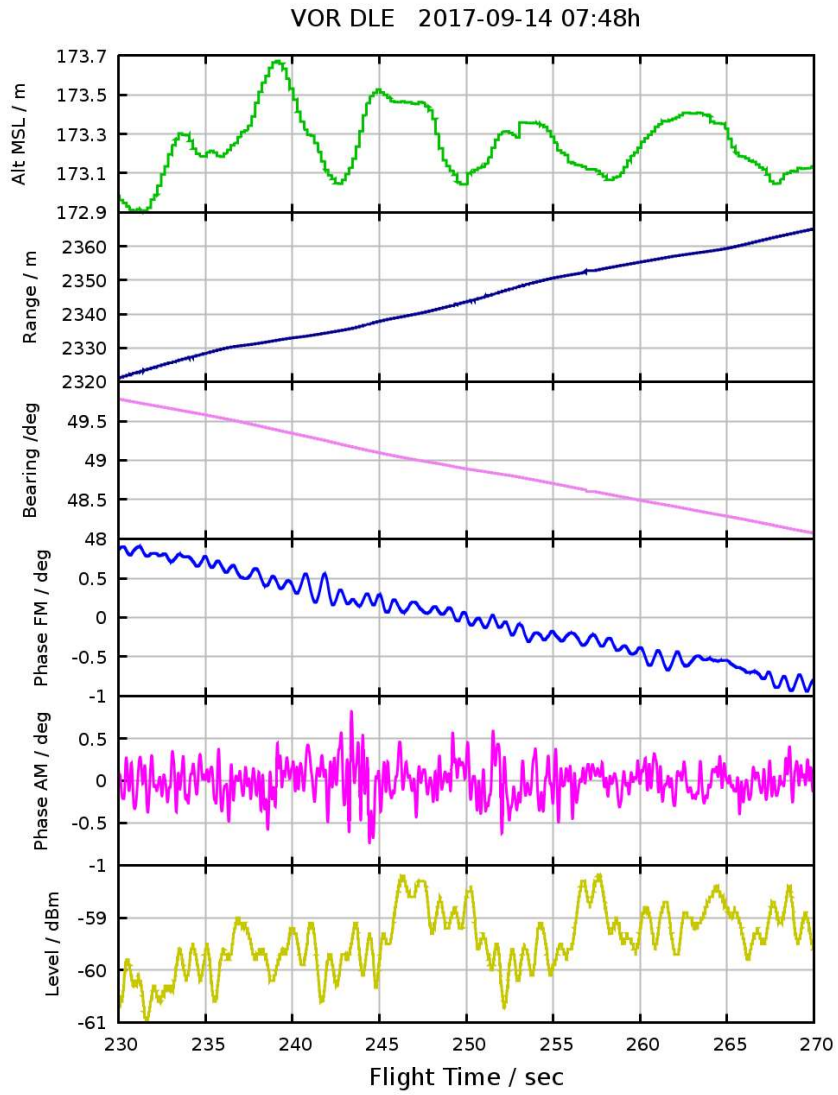
„Triangle profile in wind park“

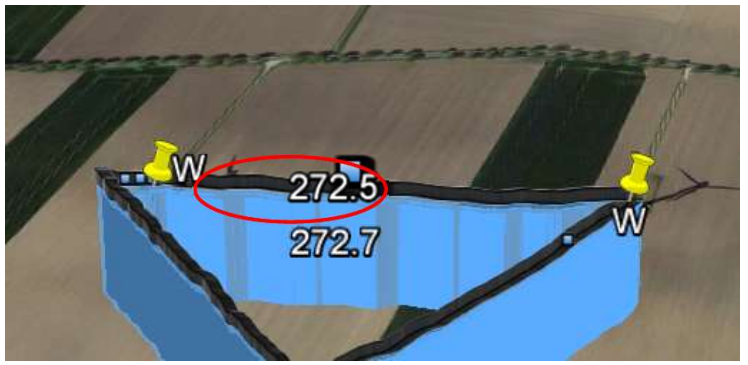
Eight E-66 in 2.5 km distance to DVOR:

„Noisy“ AM phase along track behind WT (forward scatter)

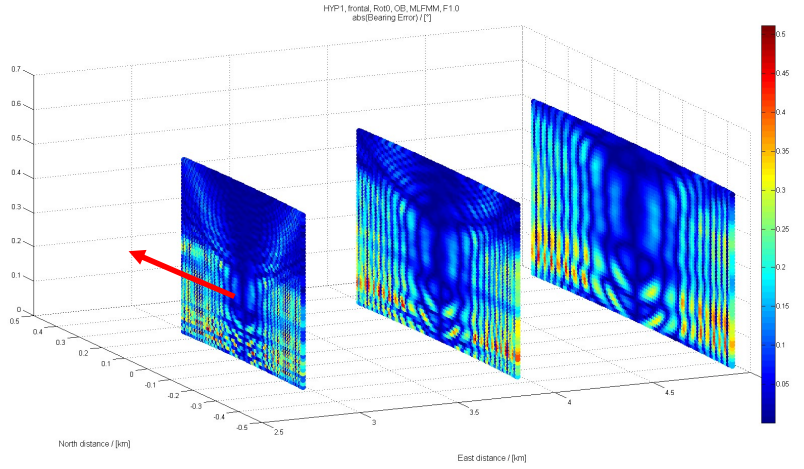
AM phase „quiet“ in direct line of sight

Measurement DVOR Leine



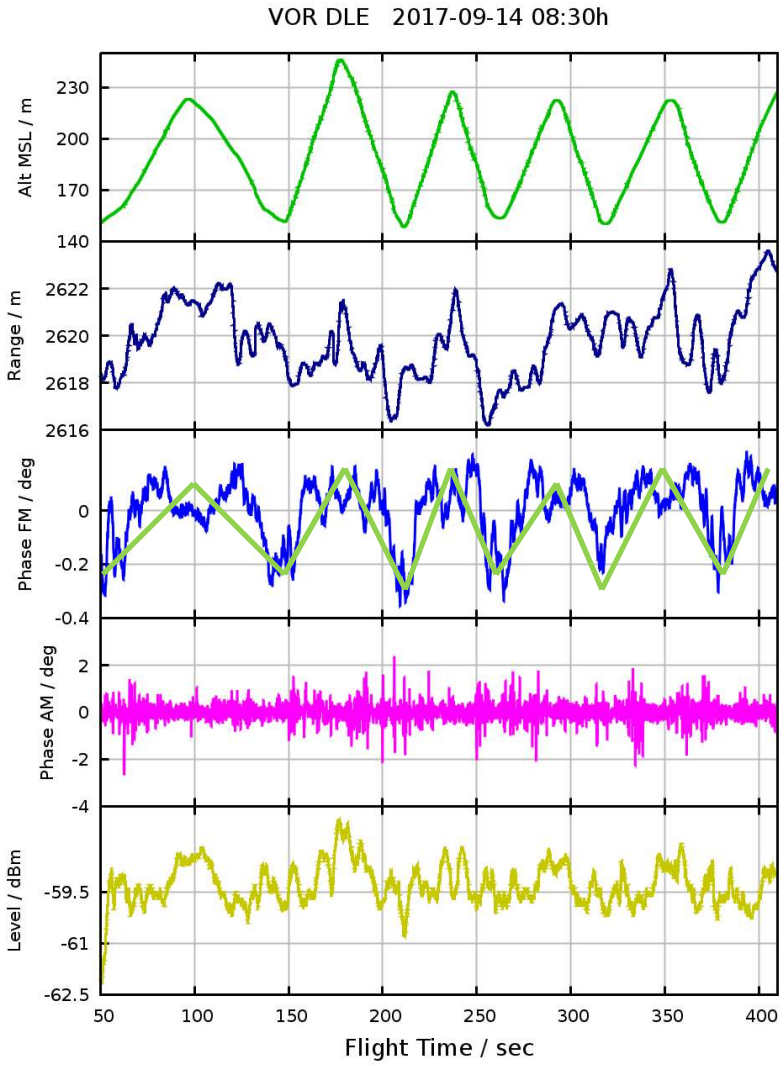


Rotating blades cause FM phase oscillations



→ Error propagation into space

Measurement DVOR Leine



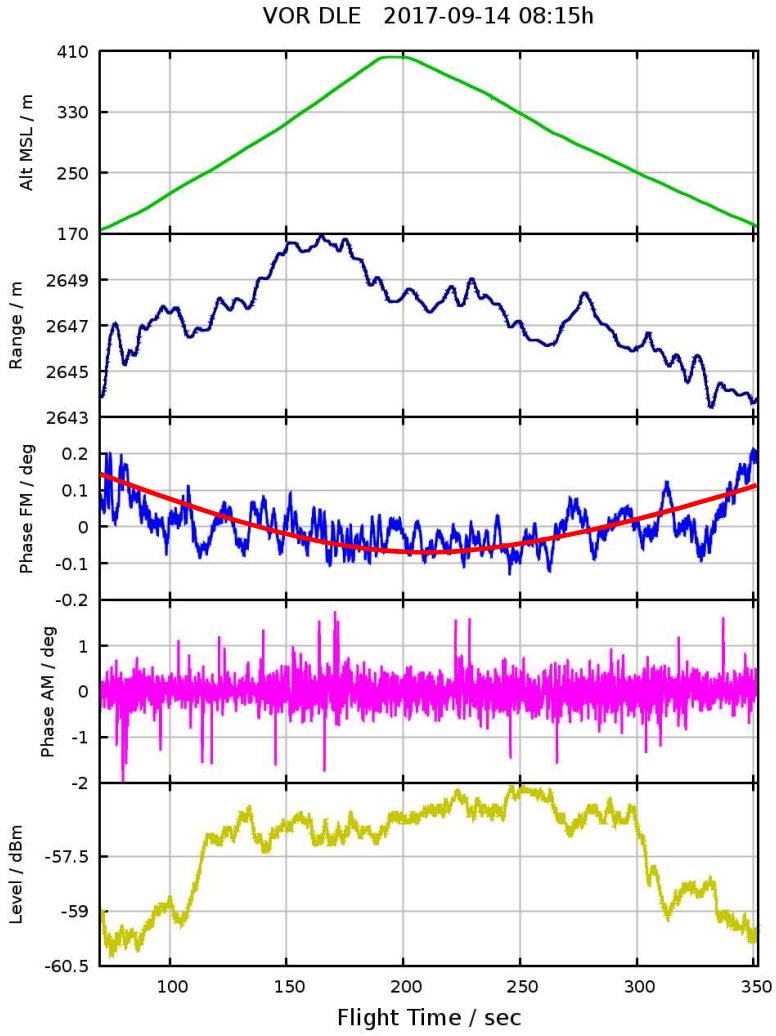
„Multiple I profiles in wind park“

correlation of altitude and FM phase offset
Above wind farm: FM phase offset decreases

-0.3° FM phase variation correlated

±1.5° AM phase variation uncorrelated

Measurement DVOR Leine



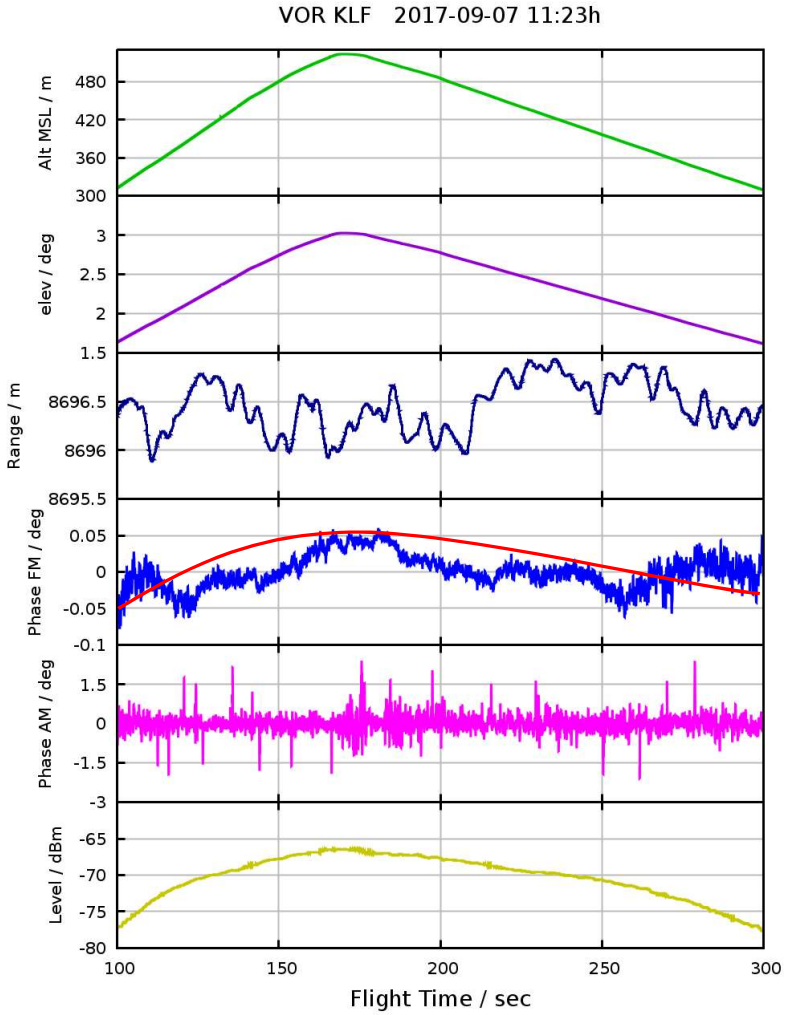
„High altitude I profile in wind park“

Bearing const @ 45.8 deg

0.2 ° FM phase offset depending on altitude

1.0 ° AM phase variation uncorrelated

Measurements at DVOR Klasdorf



„High altitude I profile behind 4 large WT“

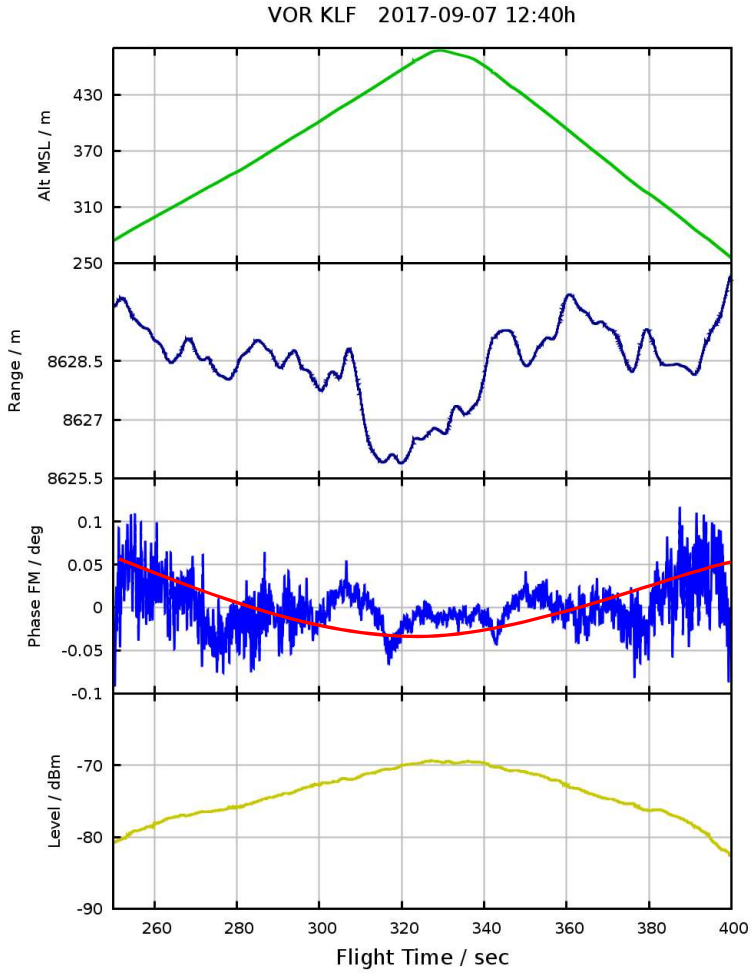
Four Vestas V-112 in 8 km distance to DVOR:

Bearing const @ 236.0 deg

0.1 ° FM phase offset symmetrically

1 ° AM phase variation uncorrelated

Measurements at DVOR Klasdorf



„High altitude I profile“

Second location 3 km away from 4 WT:
Still little offset only

Const. Bearing @ 246 deg

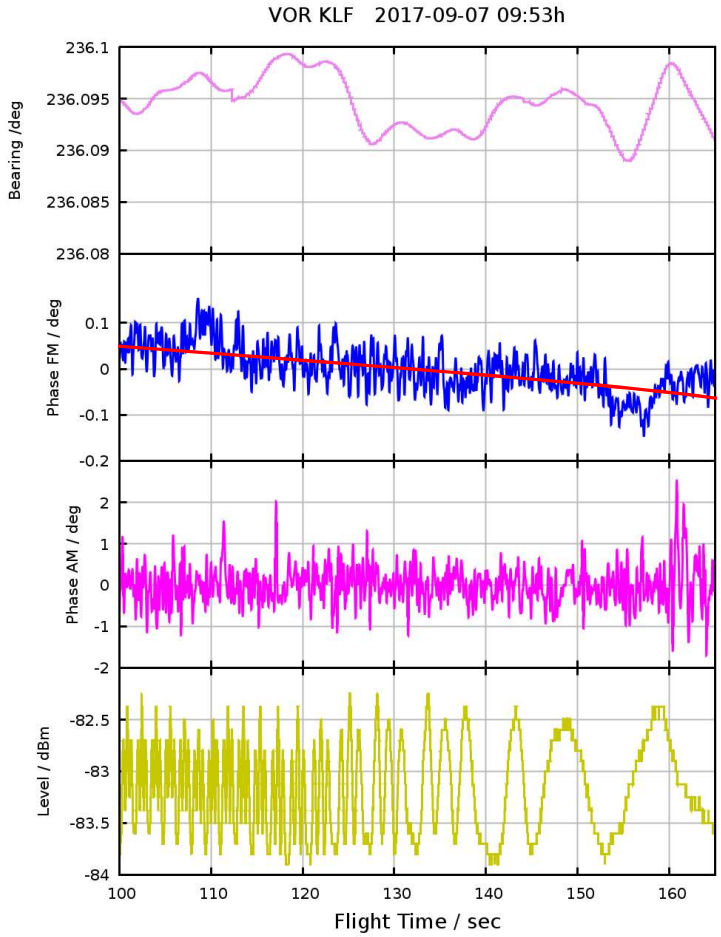
< 0.1 ° FM phase offset symmetrically

1 ° AM phase variation uncorrelated

Measuring Slow down, Stop and Restart of 4 WT at DVOR Klasdorf

Measuring Slow down and Stop of 4 WT at DVOR Klasdorf

„turn-off 4 WT“



FM-Phase
± 0.05 deg
Shift 0.1 deg

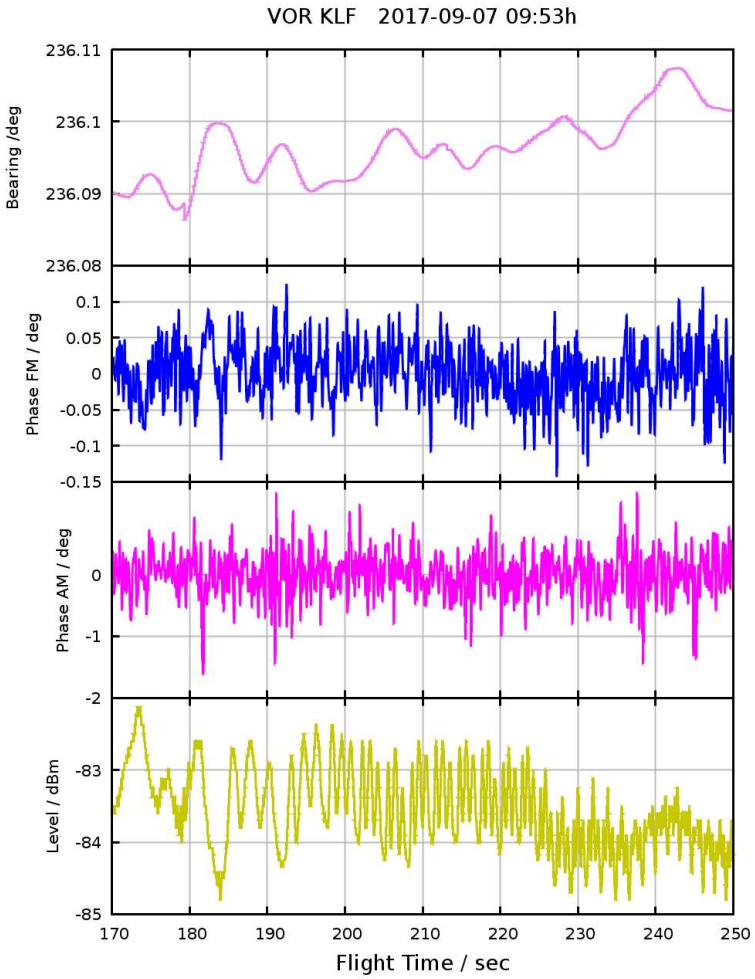
AM-Phase
± 1 deg
No Shift

Modulated receiver level
depending on rpm of WT

4 WT, in 8 km distance to DVOR, 140 m hub height, 112 m rotor diameter

Measuring Stop and Restart of 4 WT at DVOR Klasdorf

„turn-on 4 WT“



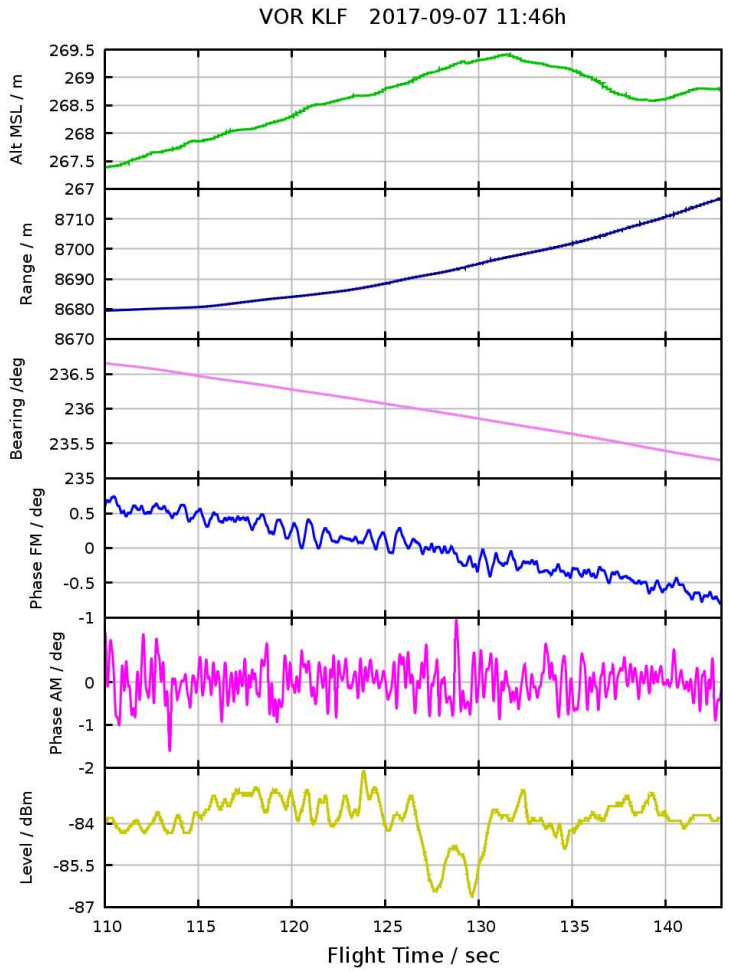
FM-Phase
± 0.1 deg
Shift 0.05 deg

AM-Phase
± 1 deg
No Shift

Modulated receiver level depending on rpm of WT

4 WT, in 8 km distance to DVOR, 140 m hub height, 112 m rotor diameter

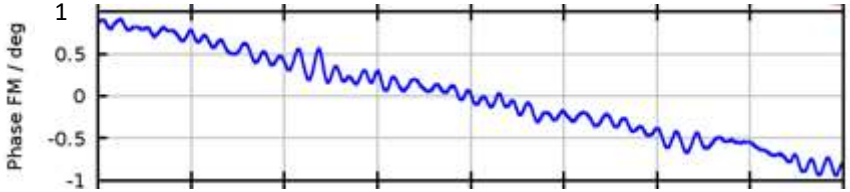
Measuring Slow down, Stop, and Restart of single WT at DVOR Klasdorf



„Horizontal flight track, 3 WT off, one WT on“

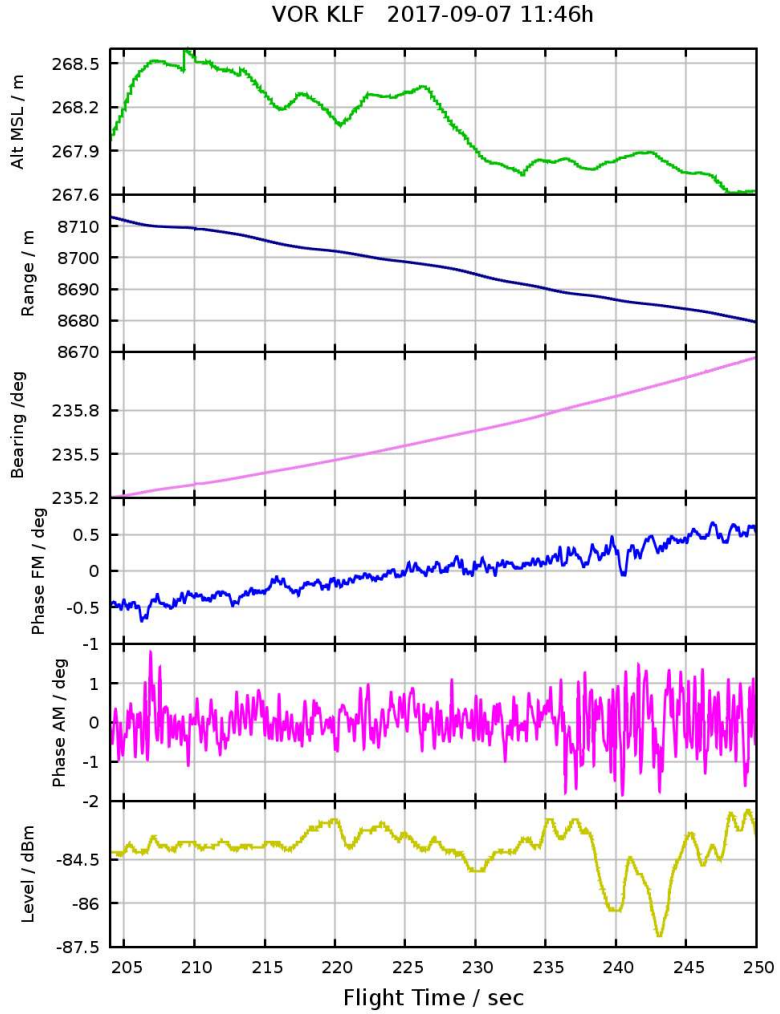
Oscillations of FM phase noticeable, caused by rotating blades, but no „noise“

Compare to DLE at horizontal flight track with rotating blades:
Same phase variations!



4 WT, in 8 km distance to DVOR, 140 m hub height, 112 m rotor diameter

Measuring Slow down, Stop, and Restart of single WT at DVOR Klasdorf



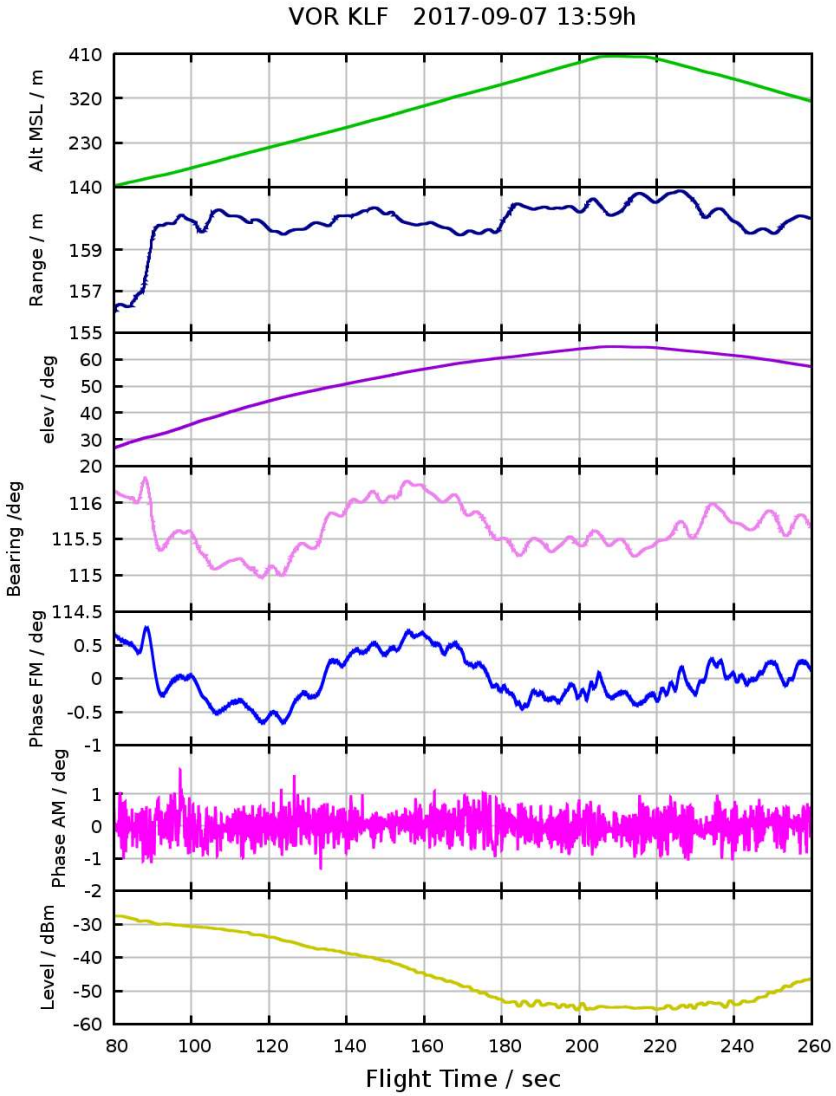
„Horizontal flight track, all 4 WT off“

Oscillations of FM phase are smaller and not as regular w/out moving rotor!

Only static scatterers:
FM phase ± 0.25 deg

4 WT, in 8 km distance to DVOR, 140 m hub height, 112 m rotor diameter

Measurements at DVOR Klasdorf



„I profile close to DVOR KLF (100 m distance)“

Level variation of 30dB does not change AM phase noise

AM phase noise ± 1 deg in spite of close distance to DVOR and large receiver level

Without scatterer: FM phase ± 0.05 deg

Lessons learned from DVOR Measurements so far

One WT: Noticeable FM phase variation at horizontal orbit flight, no offset

→ error mask ?

Four WT: FM phase tend to become „noisy“, no offset, no hot spot

Slow down-stop-restart of 4 large WT: FM phase 0.1 degree shift

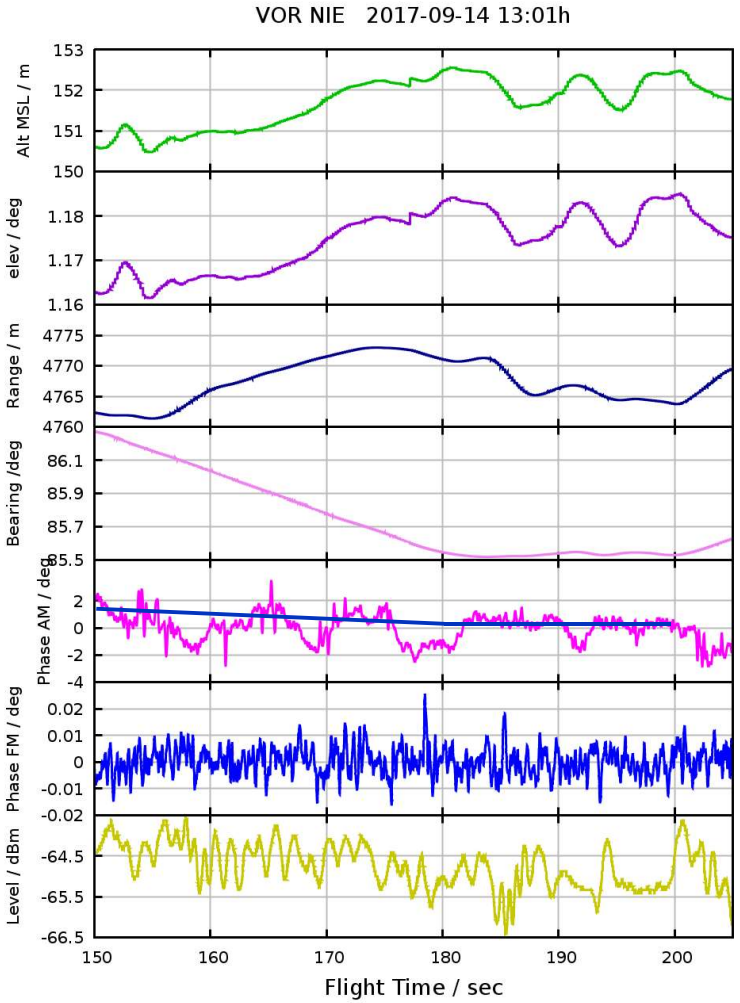
Receiver level‘s modulation follows rotor rpm

AM phase variation up to ± 2 deg at horizontal flights behind WT (noisy, no offset)

We have not seen orbit flights yet (receiver antenna 90deg CW to DVOR, used in RNAV).
Cp. antenna pattern of VOR dipole during flight inspection (orbit vs. radial flights)

Measurements at CVOR Nienburg

Measurements at CVOR Nienburg



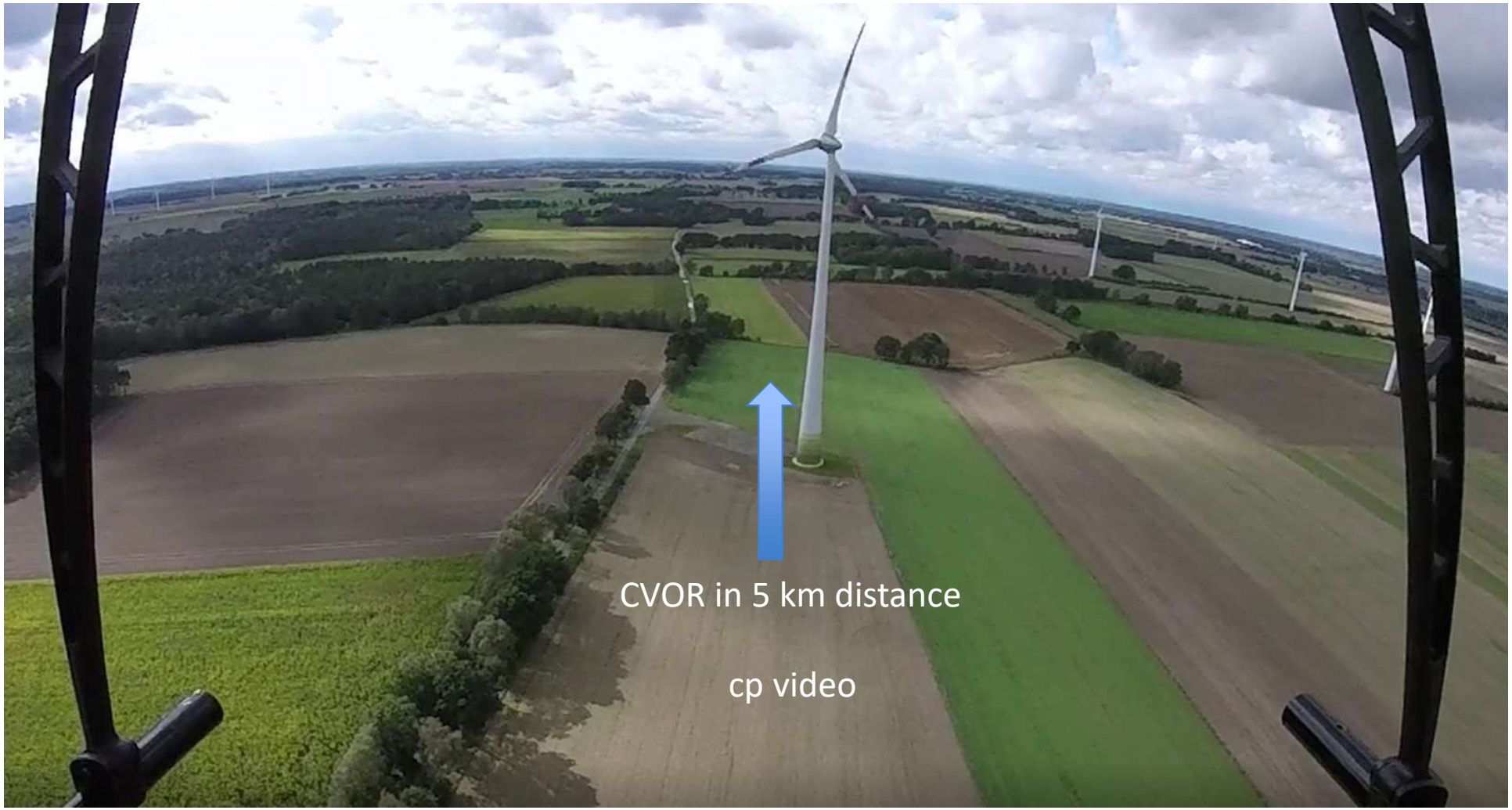
„flight track at hub height, passing large WT“

AM phase deviation ± 2 deg

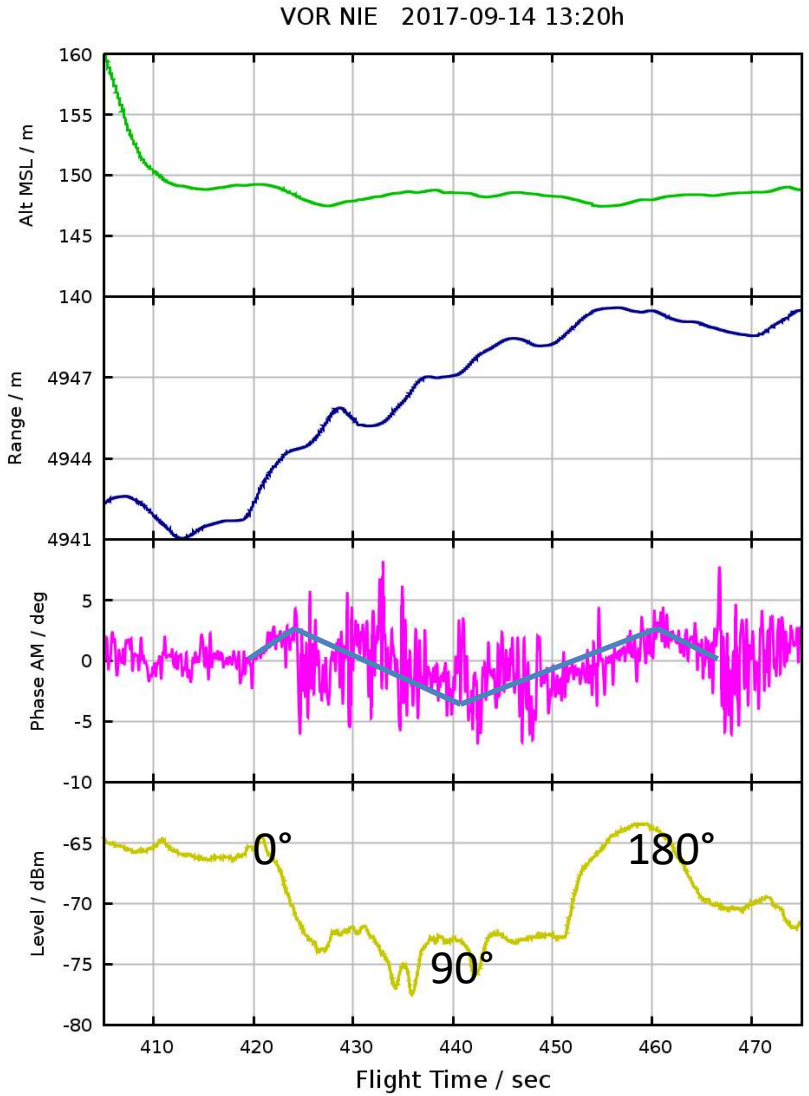
FM phase constant with low noise

108 m hub height , 82 m rotor diameter

Measurements at CVOR Nienburg (90 deg rotation)



Measurements at CVOR Nienburg



„hovering mode at hub height; rotation CW; Large WT“

Constant FM phase with low noise

AM phase changes considerably ± 5 deg

Level drops by 13 dB @90 deg to CVOR

Lessons learned from CVOR Measurements so far

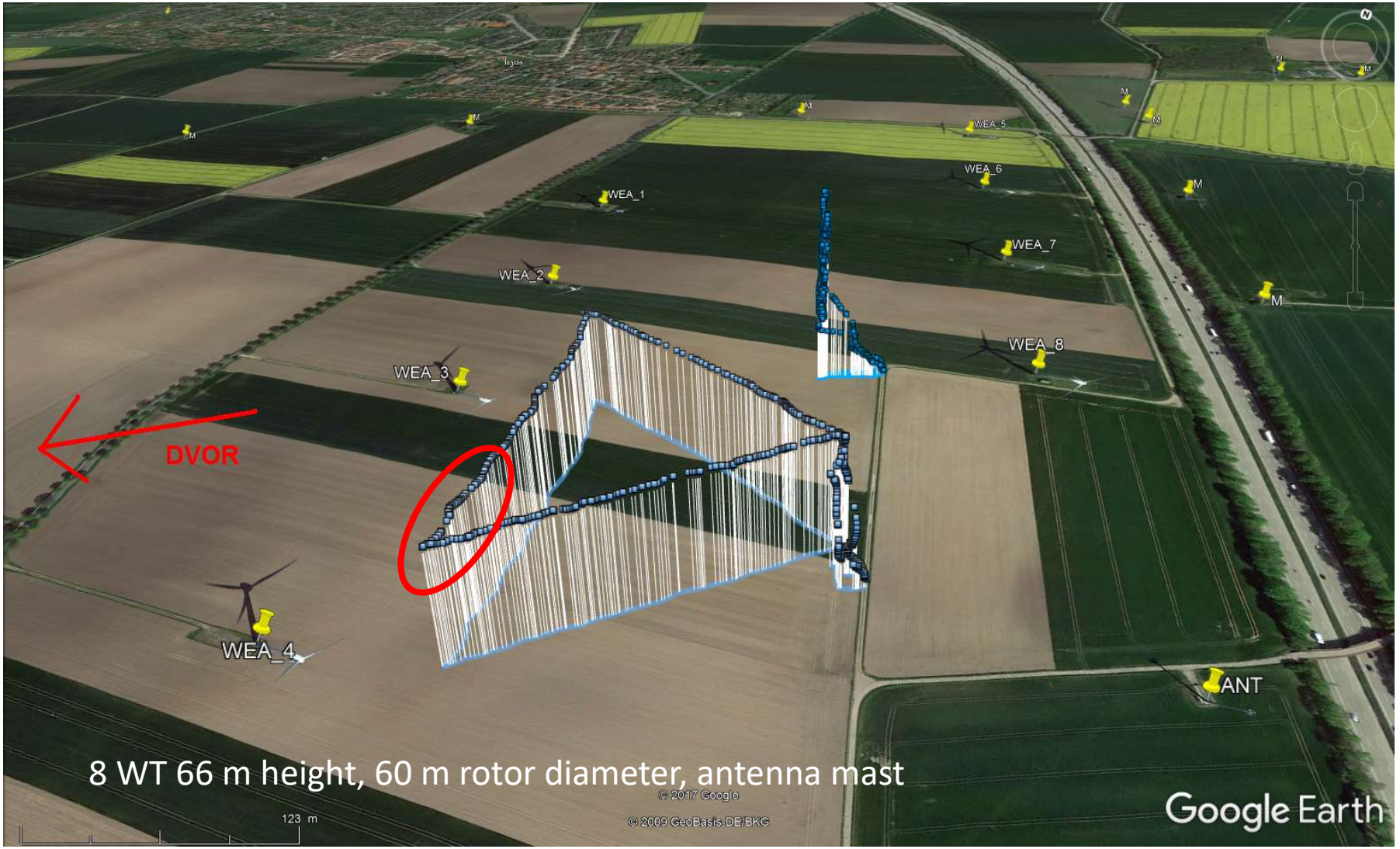
FM phase can be considered as constant, negligible noise, ± 0.01 deg

AM offset up to ± 2 deg when receiver is on horizontal orbit flight path

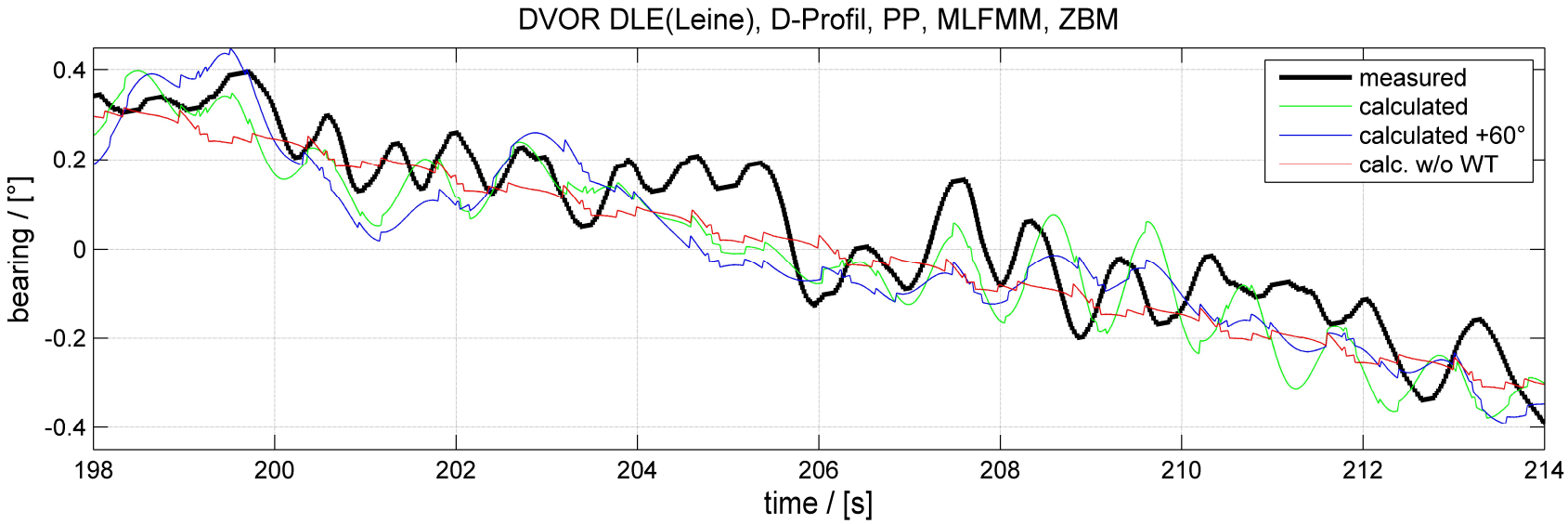
AM offset up to ± 2 deg and noise up to ± 5 deg when receiver turns 90 deg (reflected signal from other radials)

Orbit flights RNAV (± 5 deg) are more critical compared to flights along radials (± 2 deg) (cp. antenna pattern of VOR dipole during flight inspection).

Flight Track used for Comparison (DVOR)

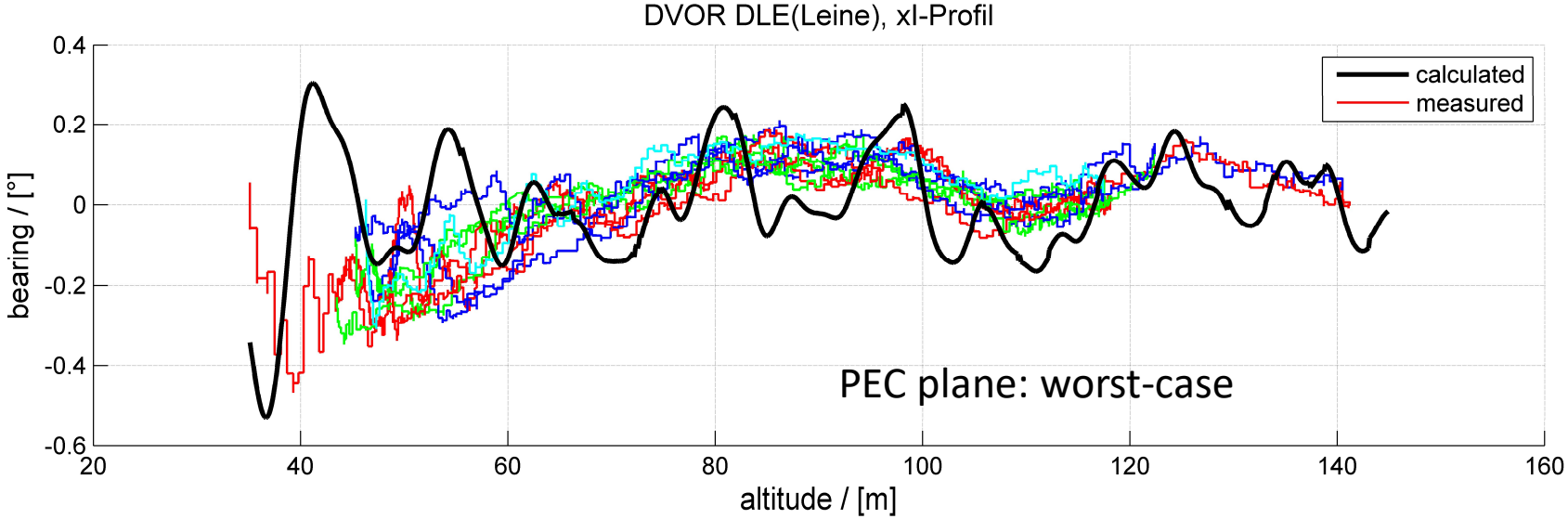


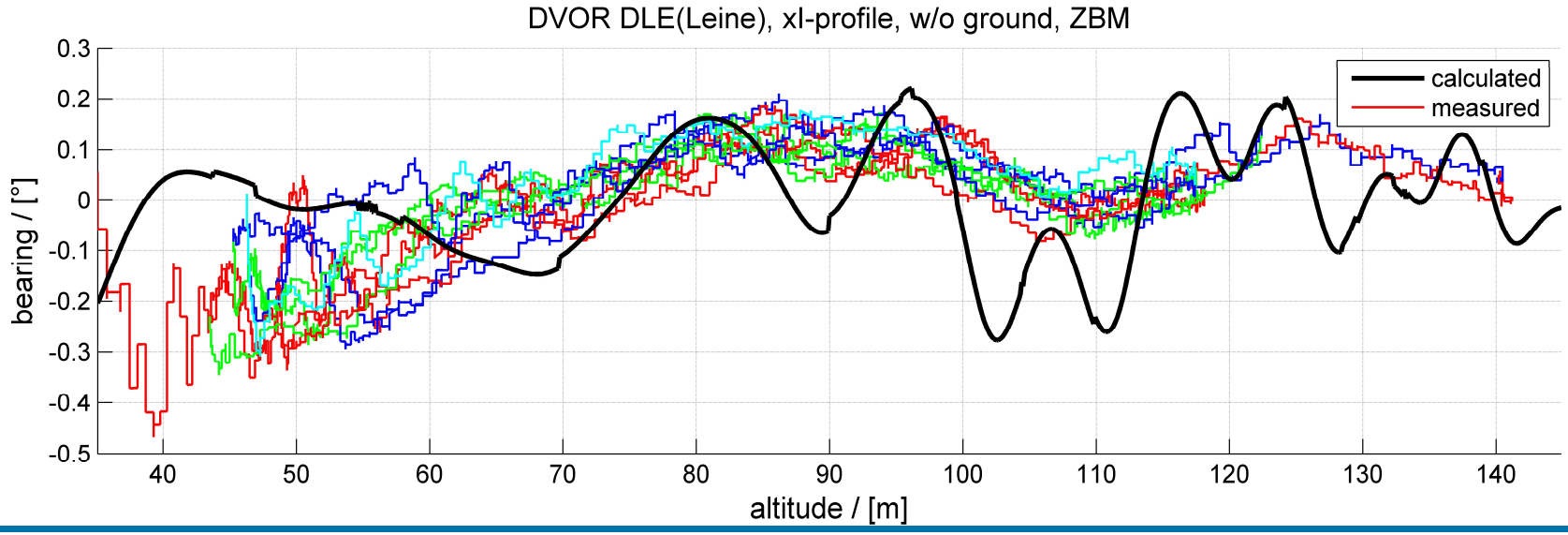
Comparison of Measurement and Simulation (DVOR)



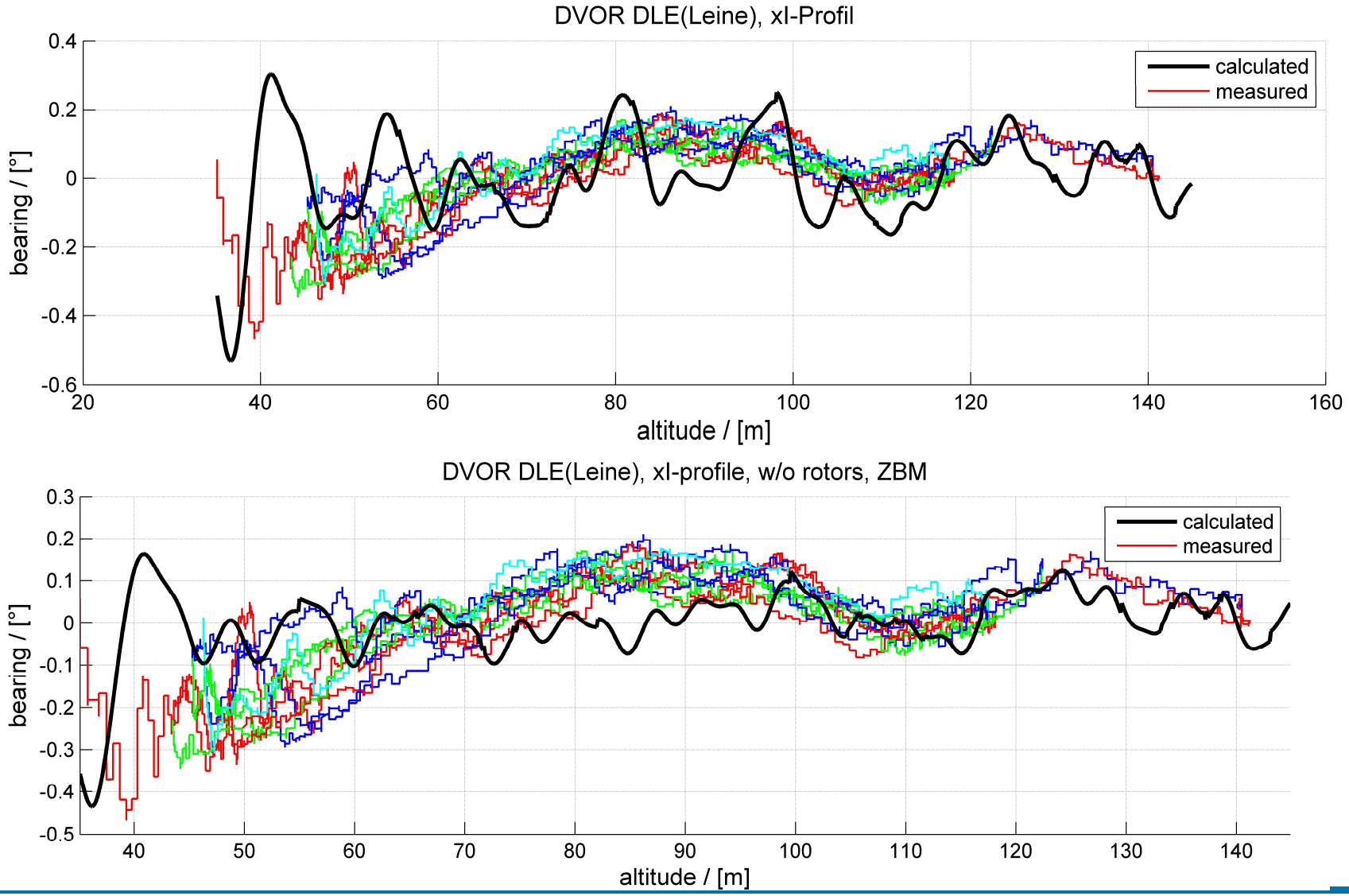
Horizontal flight track 100 m behind WT in 2.5 km distance to DVOR:
Good agreement for FM phase deviation

Comparison of Measurement and Simulation

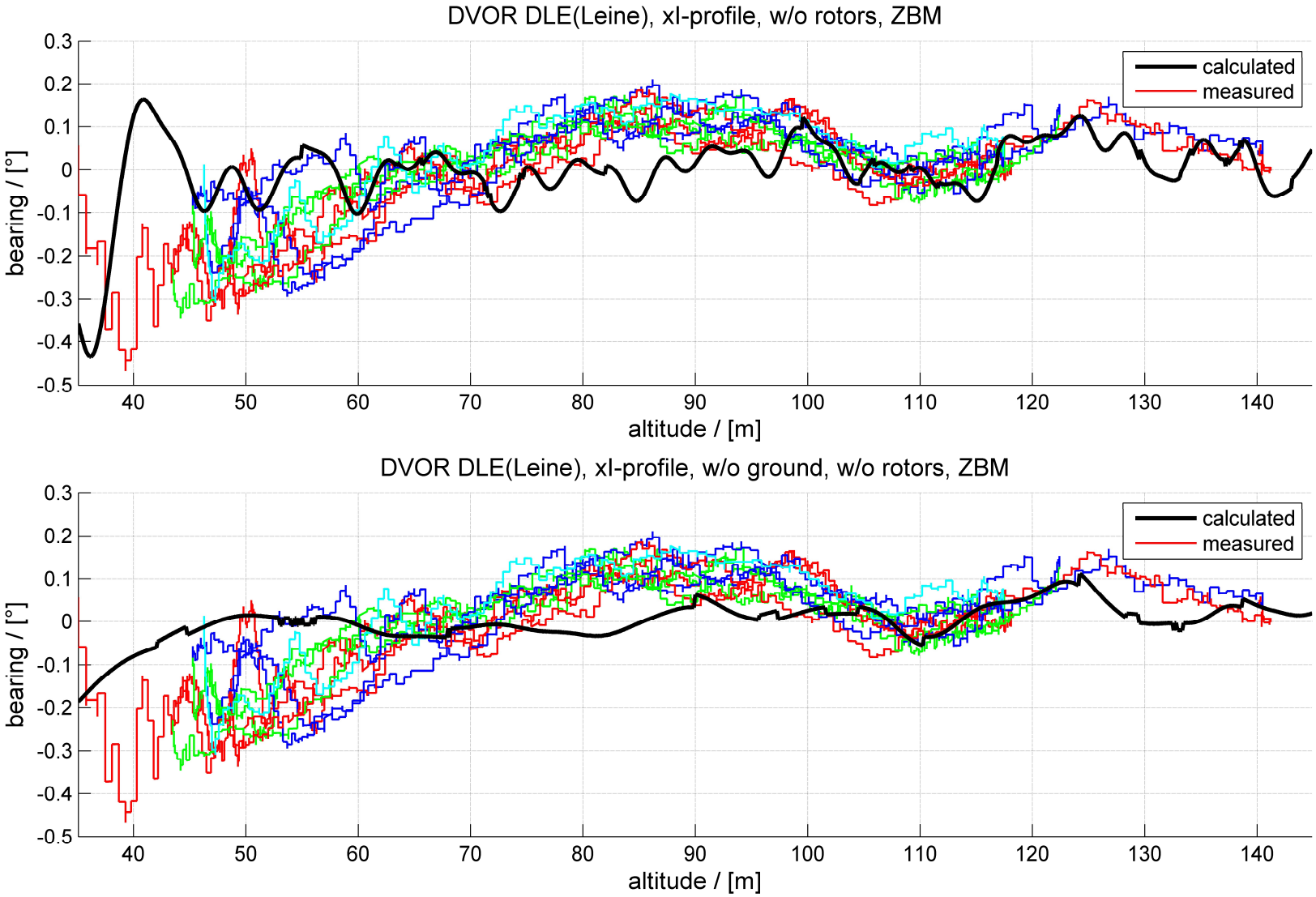




Comparison of Measurement and Simulation



Comparison of Measurement and Simulation



Lessons learned from Measurement/Sim so far

Comparison of FM phase only

FM phase measurement repeatability < 0.2 deg

Good agreement between meas/sim ± 0.25 deg

Simulation trend follows slope of measurements → very promising

Ground is not PEC plane

Rotor blades are not PEC

} But worst-case, if compared to measurements

Summary and outlook

- **For the first time worldwide: Influence of WT on DVOR was shown!**

- Measurements of DVOR/CVOR AM and FM signal channel properties now possible

- DVOR: FM phase shift 0.2 deg AM phase noise 2 deg
- CVOR: FM phase noise 0.01 deg AM phase shift 2 deg

- State-of-the-art instrumentation (receiver technology on UAS) and software tools for data mining

- Validation of numerical results by measurements (good agreement)

- Operator (ANSP) / regulator (CAA) decides about tolerable „change“ of key value such as bearing error

Need for measurements at critical sites. DVOR FM phase offset so far was 0.2 degree ….

Error propagation into free space → modeling and validation by measurement