Signal Integrity: Scientific Approach of WERAN project

Splitting of the signal path

Nonlinear part
(Radar signal processing)

Linear part
(channel, wave propagation)

Goal of WERAN project:
„Signal integrity of terrestrial navigation and radar systems – obtain changes caused by WT (by measurement and numerical simulation).“

Feed airborne receiver/radar
Obtain effect on airliner, aircraft
Measurement capabilities and results on

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-directional beacons (NDB) and direction finder (ADF)</td>
<td>500 kHz</td>
</tr>
<tr>
<td>VHF Omnidirectional radio range (CVOR, DVOR)</td>
<td>112 MHz</td>
</tr>
<tr>
<td>Airport surveillance radar (ASR)</td>
<td>some GHz</td>
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<tr>
<td>Military radar systems (LVR)</td>
<td>some GHz</td>
</tr>
<tr>
<td>DWD weather radar (C-Band precipitation radar)</td>
<td>5.6 GHz</td>
</tr>
<tr>
<td>DWD VHF Wind profiler</td>
<td>482 MHz</td>
</tr>
<tr>
<td>Instrument landing system (ILS) Loc and GP</td>
<td>110/330 MHz</td>
</tr>
</tbody>
</table>

**Image:**

- **Doppler-VOR (D-VOR) groundstation w/ DME**: Signal-in-space – AM and FM
  - Cone of silence
  - Antenna pattern

*Source: Wikipedia*
Geometry of the Problem

Minimum IFR height 3500 ft (~1000 m)

Distance to VOR ➞ 300 m, 4 km, 5 km, 23 km

80 NM, 150 km

Signal-in-space

“radio horizon”
Minimum service level at low altitude

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

Validation of VHF Antenna installed at the UAS

Traceable calibration against field probe using substitution method
**DVOR Measurement at Ground Level (Phase test)**

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

**W/out WT Influence: 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
Measuring Slow down, Stop and Restart of 4 WT at DVOR

DVOR in 8 km distance

cp video

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
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
Numerical Simulation of Error Propagation into Space

Contribution LUH

DVOR in coordinate center, 1 WEA @ 2 km (E-101, 150 m total height, λ-configuration)

Measurement of Error Propagation into Space
Measurement of Error Propagation into Space

![Graph and image showing measurement of error propagation into space](image-url)

**DVOR-WT 8 km, WT-Meas 1000 m**
Measurement of Error Propagation into Space

Does a simple model by Anderson & Flint hold?

\[ x \approx \frac{2AJ_1(2\beta_2 r \sin \left( \frac{90^\circ - \phi}{2} \right)) \cos \left( \frac{\phi - 90^\circ}{2} \right) \cos [\beta_2(r_0 - r_1) - \delta]}{\beta_2 r} \]

S. R. Anderson and R. B. Flint, „The CAA Doppler Omnirange“ in the Proceedings of the IRE, May 1959, Page 813:
Does a simple model by Anderson & Flint hold?
Summary and outlook

- For the first time worldwide: Influence of WT on DVOR was shown by experiment!
- Measurements of DVOR/CVOR AM and FM signal channel properties now possible
- State-of-the-art instrumentation (receiver technology on UAS) and software tools for data mining
- Validation of numerical results by measurements (show good agreement)
- Operator (ANSP) / regulator (CAA) decides about tolerable “change” of key value such as bearing error

WERAN plus

- Understand error distribution in close and far distance to obstacles (WT, tower, high-rise building)
- Understand error propagation into free space (i.e. by using full-wave numerical simulations)
- Validation by measurement
- → build up scientific foundation for simple model

Model based estimation of influence on DVOR signal integrity of future installations of WT