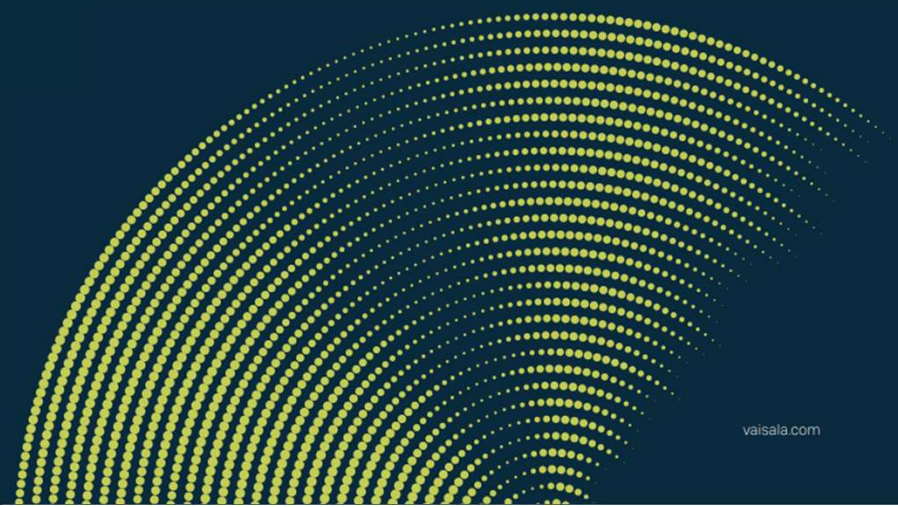
Enhancing Weather Radar Performance: Signal Processing Approaches in Vaisala Solid-State Technology

25th Symposium on Meteorological Observation and Instrumentation

Raisa Lehtinen, Marjan Marbouti, Jere Mäkinen, Pekka Puhakka

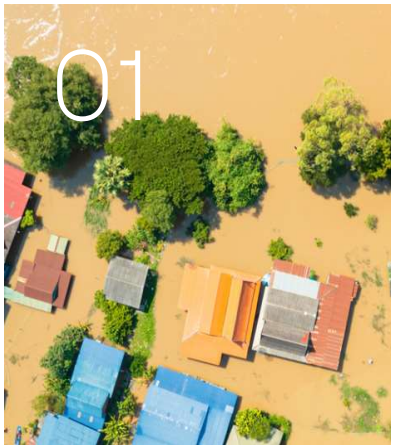
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Top five weather disaster types according to EW4ALL initiative

Early Warnings for All

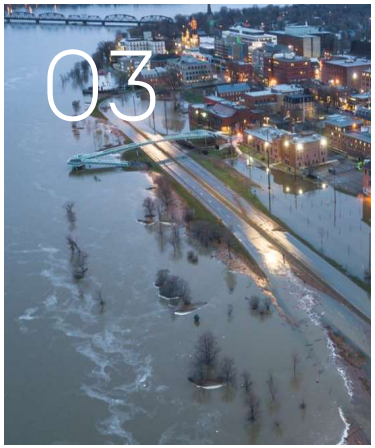
Flash floods



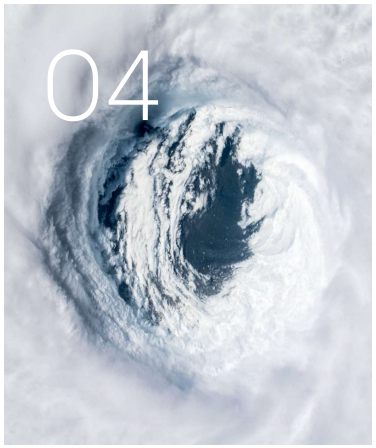
Droughts



Riverine floods



Tropical cyclones



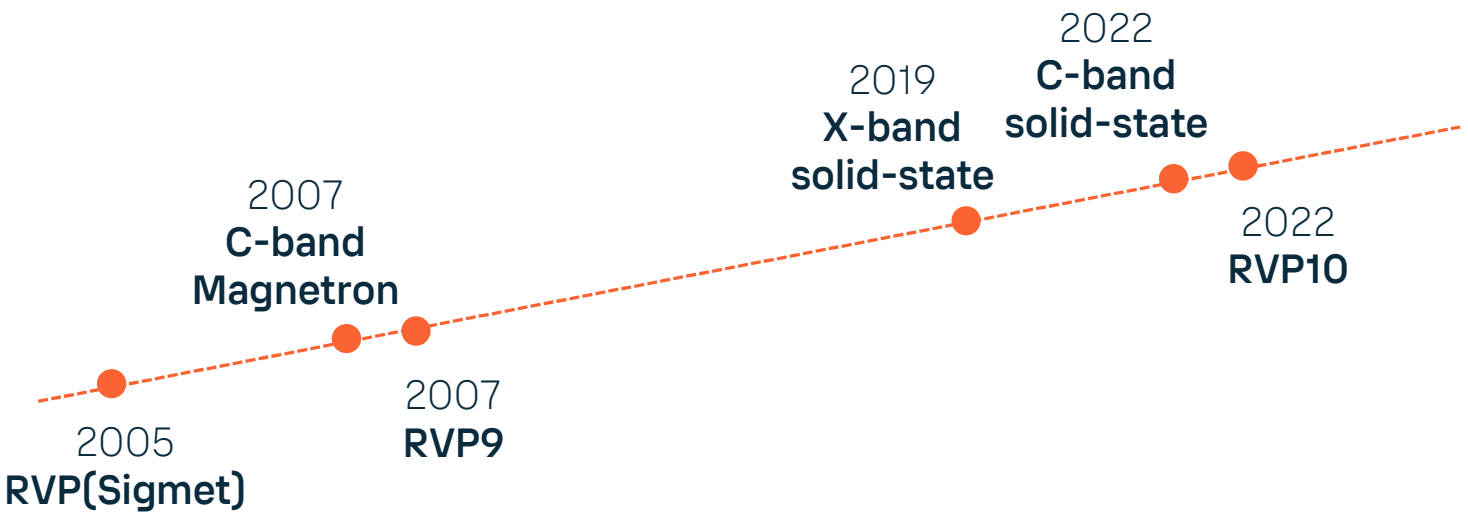
Thunderstorms



Accurate weather radar observations are essential for monitoring, predicting and alerting of extreme weather

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Vaisala – 20 years in weather radars

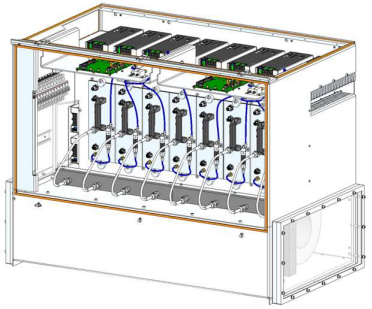




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Solid-state power amplifier (SSPA) technology in weather radars





- Transmitter has a major impact on weather radar performance
- **Traditional solutions**: Magnetron or klystron vacuum electron tube designs
- **New**: Solid-state power amplifiers (SSPA) using semiconductor components, i.e., Gallium Nitride (GaN) transistors

SSPA advantages:
- No high-cost consumable parts
- Component redundancy
- High performance
- Low lifetime costs and maintenance costs

- SSPA weather radar systems are now commercially available and viable for meteorological services and radar networks

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Vaisala WRS400 and WRS300 weather radars



WRS400 X-band

- Solid-state radar was **fully redesigned**: not just an upgrade of magnetron radar
- **Compact radar concept**: Two independent transmitters (H, V), receiver, and electronics are located at the back of the antenna
- SSPA is typically easier to mount to the rotating antenna module than a magnetron transmitter
- **Easy maintenance**: Lightweight semi-yoke pedestal with service hatches. Fewer wearable parts
- **Very short waveguide length**: Less power required due to reduced signal attenuation

WRS300 C-band

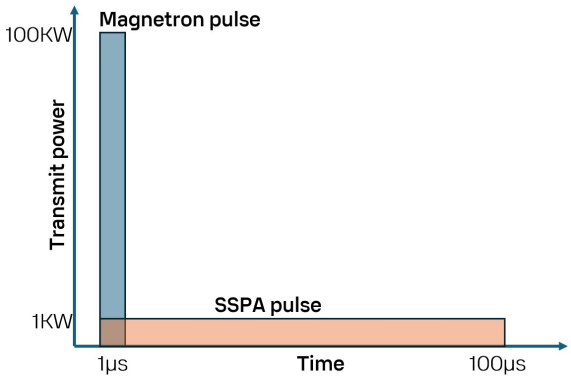


Specifications	X-band WRS400	C-band WRS300
Power	2 x 400 W, 2 x 200 W	2 x 2 kW, 2 x 4 kW
Antenna beam width	< 1°, < 1.8°	< 1°
Noise figure	< 3 dB	< 2 dB
Max pulse length	100 µs	200 µs
Weight	≤ 370 kg	~ 1600 kg

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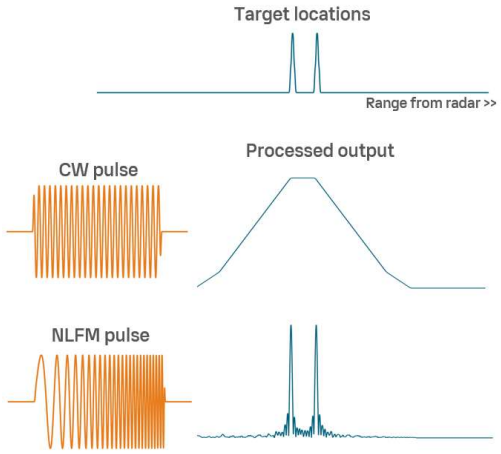
Pulse design and pulse compression

Peak power and pulse length



- Tube-based transmitters use **high peak power with short pulses**
- Solid-state power amplifiers use **low peak power with long pulses**
- The pulse energy is similar, resulting in comparable measurement performance

Pulse compression for long pulses



- Unmodulated long pulses can't resolve close radar targets
- **Pulse compression** with frequency modulated pulses is used to restore **high range resolution**

O'Hora, Vaisala "Method for using Pulse Compression in weather radar", U.S. Patent US7583222B2, March 1, 2007.

Signal processor RVP10



- Powerful processor with high sensitivity and dynamic range
- Waveform design is a balance of many desired characteristics, including sidelobe attenuation

RVP10 – released 2022	
Resolution	16 bit
Sampling rate	190 – 240 MHz
Maximum range	1024 km
Min range resolution	15 m

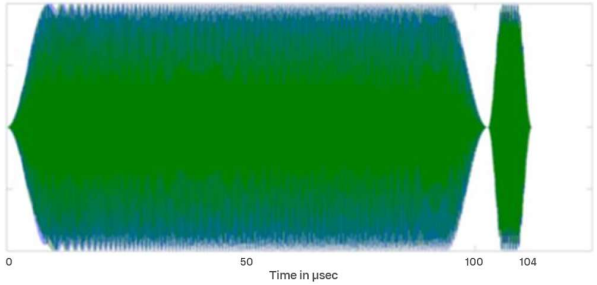
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Hybrid pulsing technique

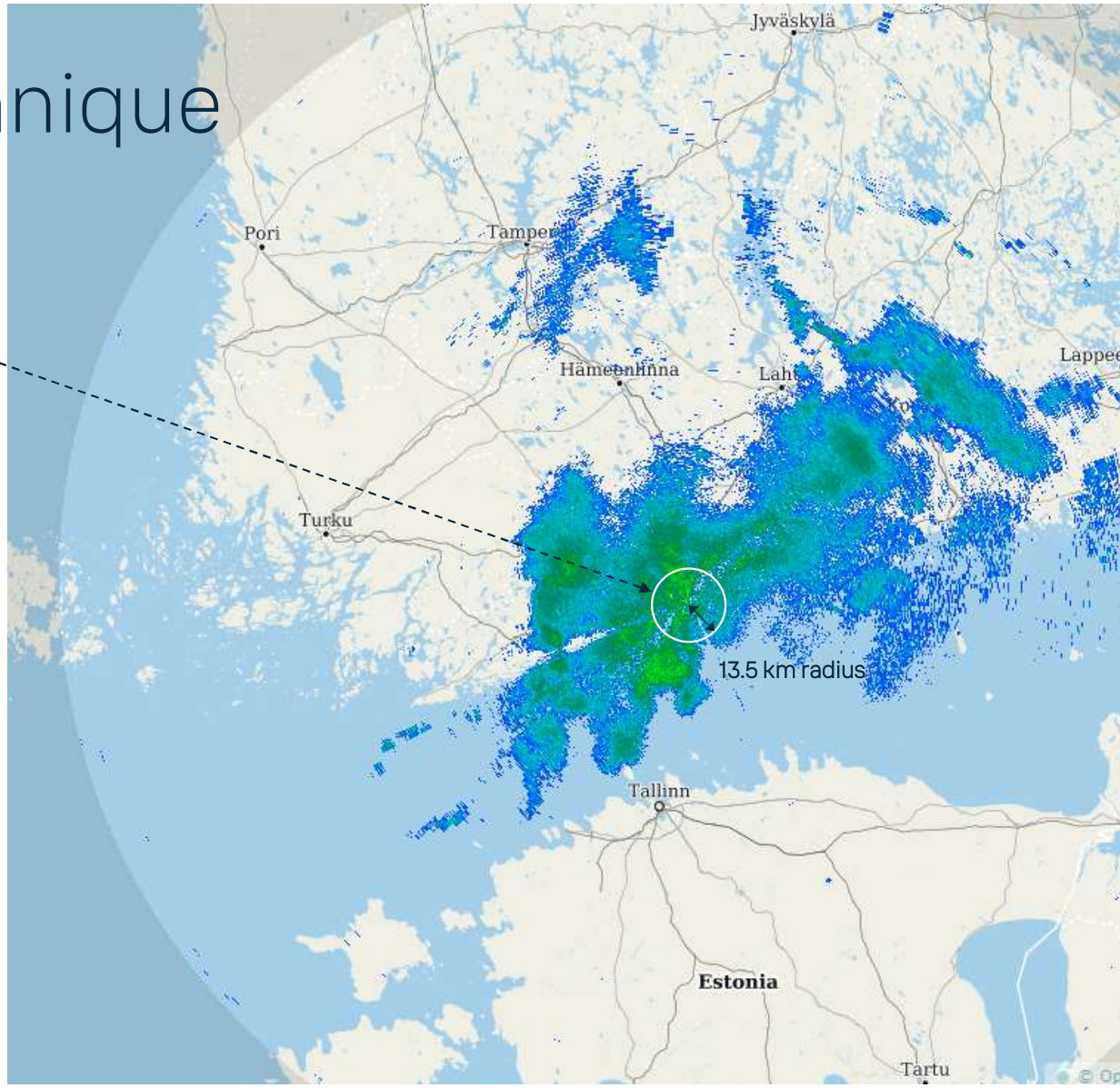
- **Blind range**: Region near the radar impacted by crosstalk.
- SSPA can have a blind range of several kilometers
- Vaisala uses **time-frequency multiplexed waveform** = hybrid pulsing

Long pulse covers far range

Short pulse covers near range



- Example: 100 µs + 4 µs
- A few MHz frequency difference for isolation

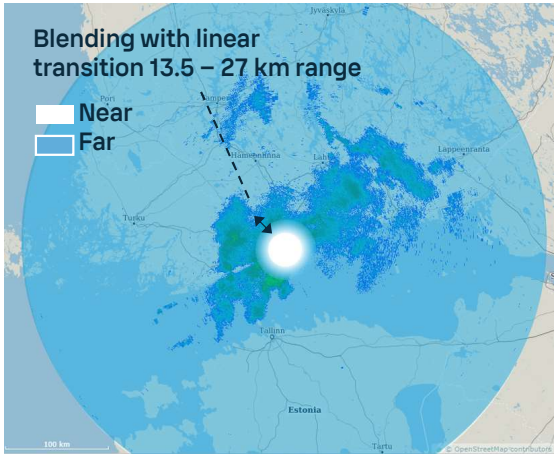


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O'Hora, 2013. "Waveforms for improving near range performance of meteorological radars using pulse compression" 36th AMS Radar Met. Conf.

Transitioning from near to far range

Minimized signal transition



- The radar image must maintain visual consistency without any discernible step transitions
- **Careful calibration** (Z, Zdr) and phase offset adjustment (PhiDP) is essential
- **Blending** smooths out any minor artefacts, using a linear transition in raw I, Q data

Range resolution

Table 1. Example pulse settings used in WRS300 and WRS400 weather radars.

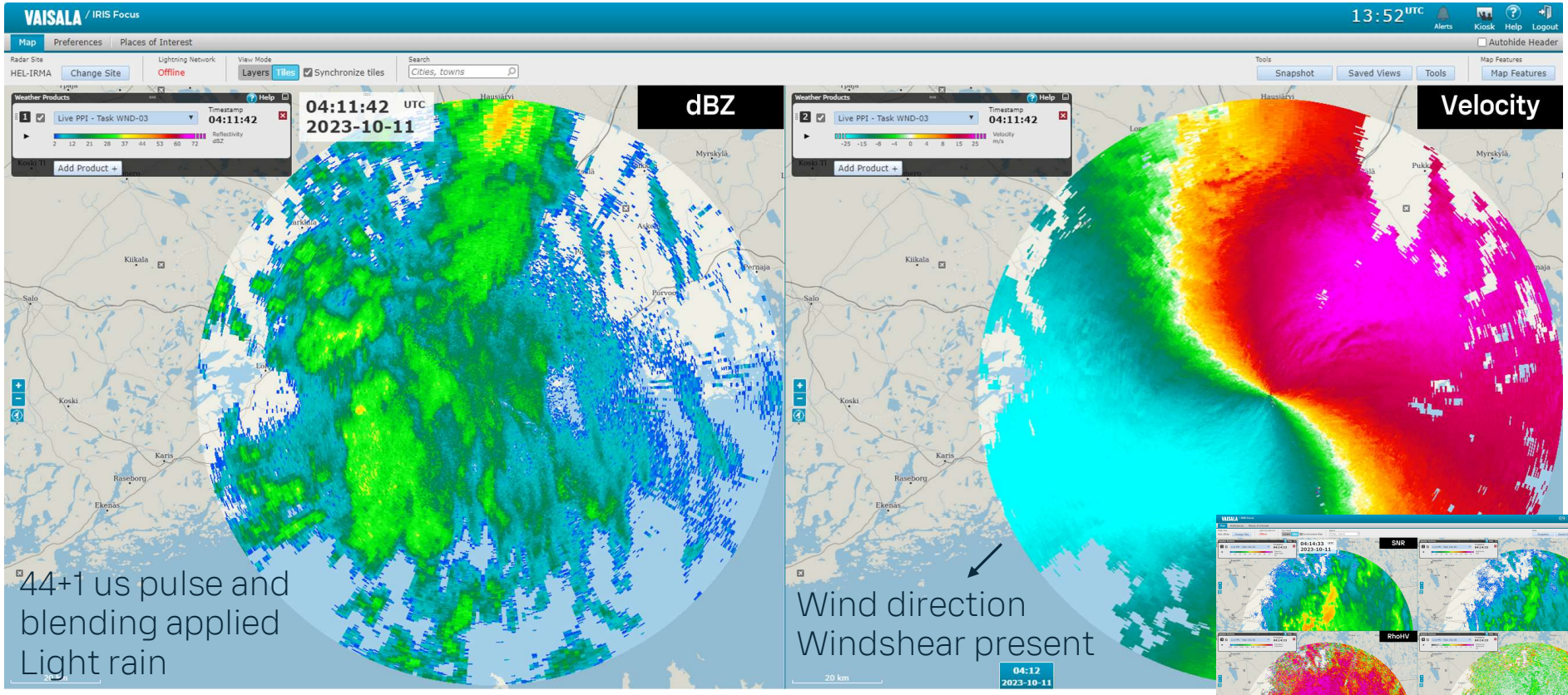
Pulse length	Pulse type	Blind range	Range resolution
1 µs	CW	600 m *	150 m
4 µs	CW	< 1 km *	600 m
44 µs	NLFM	6.6 km	75 m
90 µs	NLFM	13.5 km	150 m

* = *Including receiver recovery time after transmission*

- Example hybrid pulse pairs: 90+4 µs for reflectivity and 44+1 µs for wind
- For long range measurements, up to 200 µs pulses available (C-band)
- **Range bin size** of the data is identical for near and far ranges
- **Range resolution**: the near range is oversampled (smoothed)

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Data examples from WRS300 C-band radar



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Radar sensitivity

Radar performance metric:

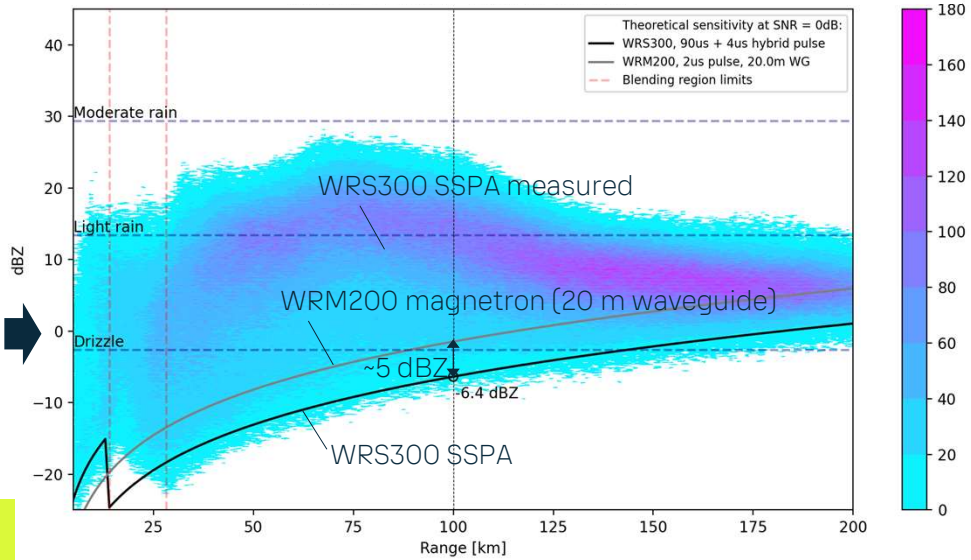
- Describes the weakest detectable target at a certain range (unit: dBZ)
- Theoretically derived from the radar equation with assumptions
- Validated through real radar measurements

Range vs. dBZ plot (lower value = better sensitivity):

- WRS300 C-band SSPA theoretical sensitivity
- WRM200 C-band magnetron " "
- WRS300 measured dBZ distribution from 10 hours, blending applied
- Lower bounds for precip (>0.025, >0.25, >2.5 mm/hour) based on Marshall-Palmer

- WRS300 measurements match theoretical estimates.
- At 100 km range, WRS300's -6.4 dBZ sensitivity is ~5 dBZ better than WRM200 magnetron radar
- Due to compact radar architecture and high sensitivity

WRS300 C-band SSPA data 2023-11-06 10:01 – 19:53
SQI > 0.4, Elevation = 0.49 deg



Puhakka, 2023. "Defining and validating the minimum detectable weather signal for an X-band weather radar system" 40th AMS Radar Met. Conf.
Puhakka, 2024. "Comparing the sensitivity of weather radars with conventional magnetron and modern solid state power amplifier transmitter technologies" 12th ERAD Conf.

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Calibration methods in Vaisala SSPA radars

Accurate calibration is critical for SSPA radar performance:

1. Temperature sensitivity
2. Two independent transmitters (H, V)
3. Two waveforms for hybrid pulsing



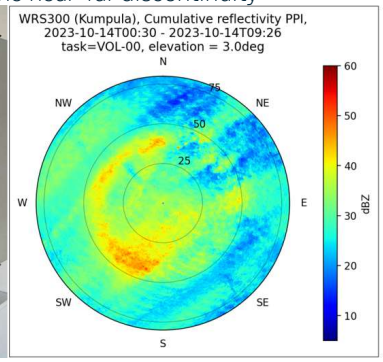
1) Annual calibration

- Check long-term changes and verify overall radar condition

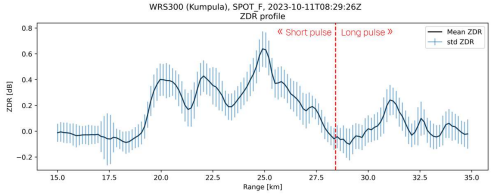
Calibration work inside X-band radome



Cumulative (9h) dBZ image showing no near-far discontinuity



Instant Zdr profile showing no near-far discontinuity

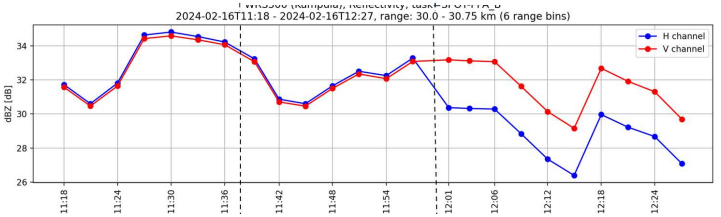


2) Continuous runtime calibration

- The signal processor samples every transmitted pulse (H, V) and makes corrections for drifts

1. **Maintain continuous Z, Zdr calibration without interrupting weather measurements**
2. **Correct radar data products even after component failure**

Cont. calibration **ON** | Cont. calibr. **ON** One SSPA unit **OFF** | Cont. calibration **OFF** One SSPA unit **OFF**



H and V channel calibration test

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Summary

- Solid-state transmitters offer **high performance**, **low lifetime and maintenance costs**, and **component redundancy**
- Signal processing approaches: **pulse compression, hybrid pulsing, and blending**
- Accurate **calibration is crucial**
- Vaisala continuously invests in advancing algorithms and signal processing methods

Want to continue the discussion?
Meet us at Vaisala booth #200!