Hybrid pulsing in Vaisala solid-state weather radars

Technical paper

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Hybrid pulsing is a radar transmission technique used in modern solid-state weather radars to cover the full measurement range, including the near range of the radar. The technique combines short and long radar pulses for their complementary advantages. Suitable pulse design, signal processing, and calibration procedures ensure consistent and high-quality observations of weather conditions.

Radar pulse transmission with SSPA

Solid-state power amplifiers (SSPA) are becoming the new standard in weather radar design. Advancements in GaN transistor technology have expanded the power and frequency range of semiconductor components, making SSPA a feasible alternative to traditional magnetron or klystron tube transmitters. SSPA radars have several operational advantages, including low maintenance and lifetime costs, long lifespan, and high reliability due to redundancy of components and low transmitter peak power. The Vaisala solid-state weather radar product range includes Vaisala X-Band Weather Radar WRS400 and Vaisala C-Band Weather Radar WRS300.

Traditional tube-based radars use high peak power and short unmodulated pulses with constant frequency (CW, continuous wave). In contrast, SSPA radars use lower peak power and much longer pulses to achieve similar average power and measurement performance. However, long pulse durations would result in degraded range resolution, meaning the radar would not resolve closely located targets or accurately detect precipitation areas. Fine resolution can be recovered with a technique called pulse compression. The Vaisala patented pulse compression technology [O'Hora, 2006] was first used in operational weather radars in 2004 to achieve range resolutions comparable to traditional tube-based radars. It is now deployed in nearly 100 weather radar systems.

With pulse compression, the radar transmits linear (LFM) or non-linear (NLFM) frequency modulated pulses and applies matched filter detection at the receiver. This processing compresses the pulse so that radar targets with small range separation can be individually detected with excellent accuracy. Good waveform design balances the range resolution with other desired characteristics, such as highly attenuated range sidelobes.

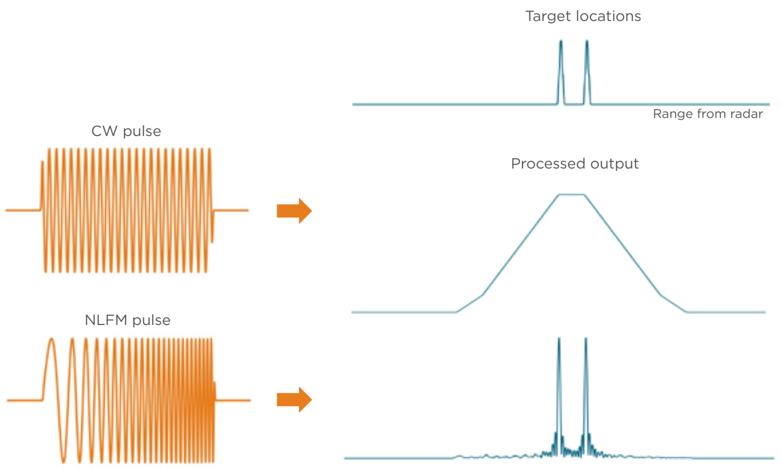

Figure 1. Illustration of conventional (CW) and non-linear frequency modulated (NLFM) radar pulses of identical length, and range plots of their processed output. The simulation contains two closely located point targets, shown top right as observed using a short CW pulse. Of the two longer pulses, only NLFM can detect and accurately locate the two targets.

Blind range

All pulsed radars have a region around the radar where observations are not available. This "blind range" exists because the transmitted signal leaks to the receiver and overwhelms any atmospheric signals while the radar is transmitting. The receiver must wait until the full pulse length has been transmitted and the receiver protector recovery time has passed before it can start measuring. For a typical conventional pulse radar the blind range is a few hundred meters, but for an SSPA radar the blind range could be several kilometers long. Therefore, additional techniques are required to make complete observations.

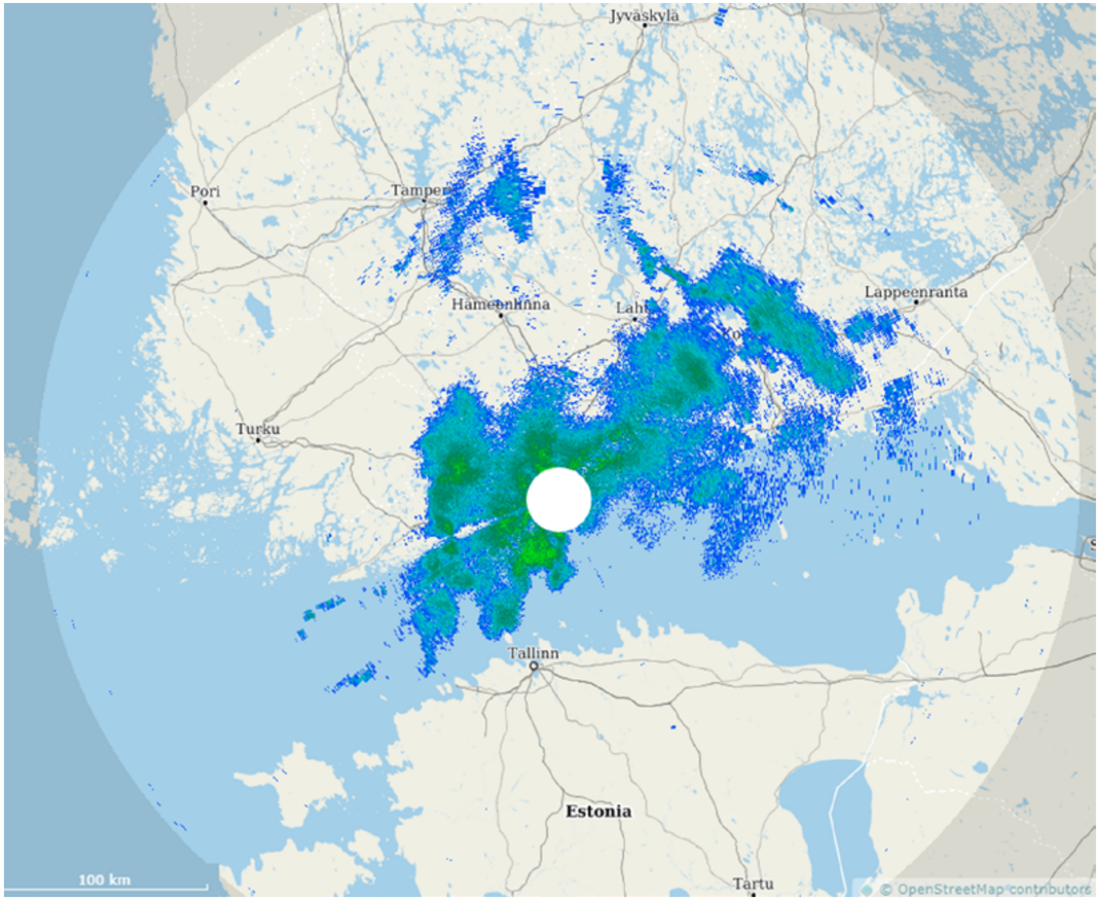

Figure 2. The small white sphere illustrates a blind range of 13.5 km radius corresponding to the 90 µs pulse of the WRS300 C-band weather radar.

Hybrid pulsing

Vaisala SSPA radars use the hybrid pulsing technique [O´Hora, 2013] to fill in the blind range near the radar. This is a well-known technique that combines short and long pulses, also known as time-frequency multiplexed waveform [Cheong, 2013].

A hybrid pulse (Figure 3) consists of a long, frequency modulated pulse that is used for far ranges, immediately followed by a short CW pulse that is used for the blind range. The pulses have a frequency difference, typically a few MHz, to provide isolation so they can be filtered and processed separately. The short CW pulse has lower average power, but as it is only used in the near region, it has sufficient sensitivity to produce good observations.

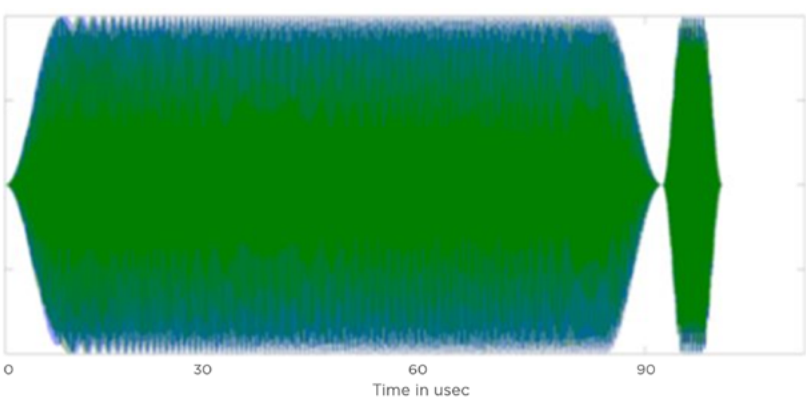

Figure 3. Hybrid pulse waveform consisting of a 90 µs NLFM pulse, followed by a 4 µs CW pulse. Pulses are used for far and near ranges, respectively. The image shows the pulse waveform as measured at the receiver.

The receiver divides the return signals into two streams for detection of short and long ranges, each with appropriate filters. The signal processor generates two streams of both I (in-phase) and Q (quadrature) values. These two streams are then combined into one continuous observation of the full measurement range. In the near region, only short pulse I/Q data is used, and in the far region, only long pulse I/Q data is used.

Table 1 presents typical pulse options used in Vaisala SSPA radars. Recommended hybrid pulsing pairs are 44+1 and 90+4 µs. These pulsing pairs have been designed to provide a good balance between the range resolution and the change in sensitivity when moving from the short pulse to the long pulse region. The range bin size can be configured independently of the range resolution or pulse length, but it must be identical for short and long pulses. Typically, the long pulse's range resolution is used, which means that oversampling is used in the short pulse region where the resolution is coarser.

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*

Blending

When the signal processor combines short and long pulse data into one observation, it is useful to do a gradual transition between the pulse regions. Otherwise, the sensitivity step between the near and far pulse regions may be discernible in radar images in some weather conditions.

In Vaisala SSPA radars the method is called blending. It is a linear transition from the short pulse to the long pulse region and is configurable between ranges A/2 and A, where A/2 is the blind range (Figure 4). For example, for the 90+4 µs hybrid pulse with maximum blending, the weight of the short pulse data decreases and the weight of the long pulse data increases between ranges 13.5 km and 27 km. Blending is performed separately on I and Q raw timeseries data and applies to all subsequent data products. Blending can be turned off, such as for calibration monitoring.

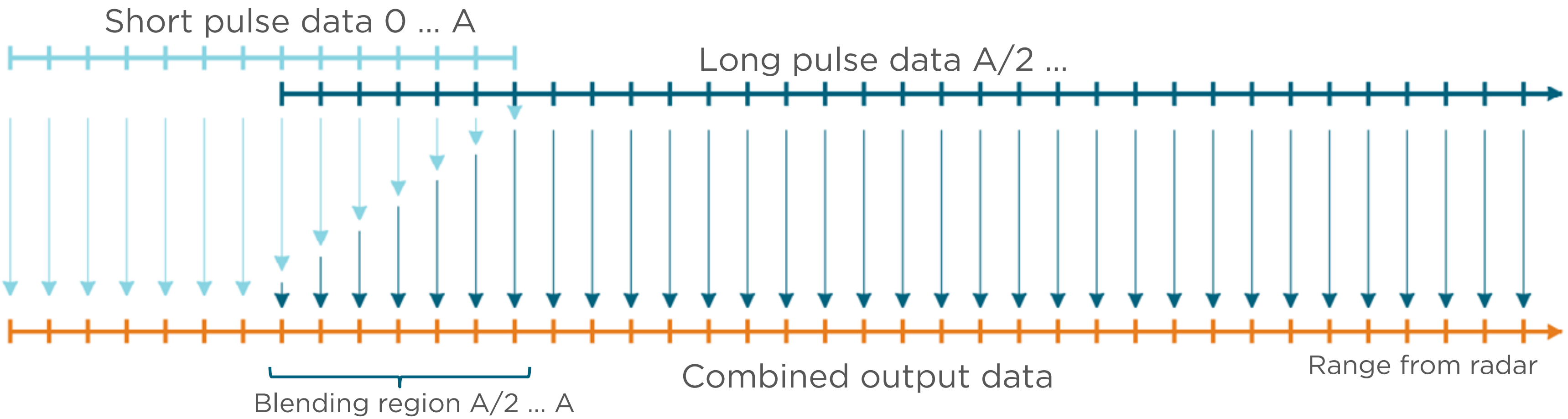

Figure 4. Illustration of the blending algorithm that creates a linear transition from short pulse to long pulse data. Downward arrows indicate the relative weights assigned to I and Q values to produce the combined output data.

The sensitivity step is approximately 15 dB for the 44+1 µs and 10 dB for the 90+4 µs hybrid pulse. Figure 5 shows that the step is visible in signal-to-noise ratio (SNR) where it is approximately the same as in radar sensitivity (10 dB). The reflectivity (dBZ) data is consistent and smooth over the transition, which demonstrates that a well-calibrated radar typically produces excellent weather results also when blending is not used. For some polarimetric variables, such as KDP, the sensitivity step may be more discernible. Therefore, it is recommended to apply blending in operational use, as shown in Figure 6. This ensures that the transition is always smooth and unnoticeable in all data images.

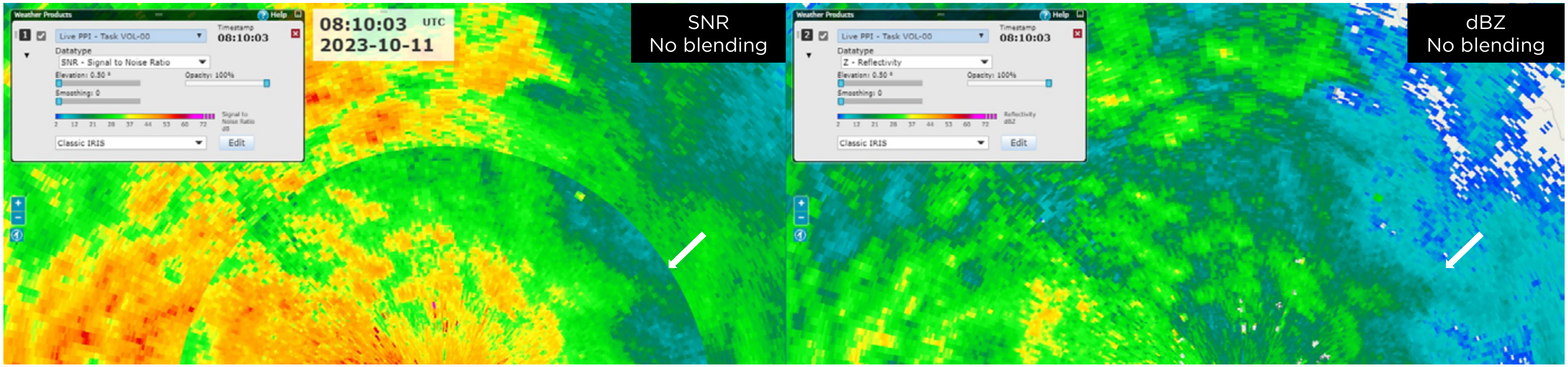

Figure 5. SNR and dBZ from the WRS300 C-band weather radar with 90+4 µs hybrid pulse and blending turned off. White arrows indicate the transition from short to long pulse region. dBZ data typically has good quality also when blending is not used.

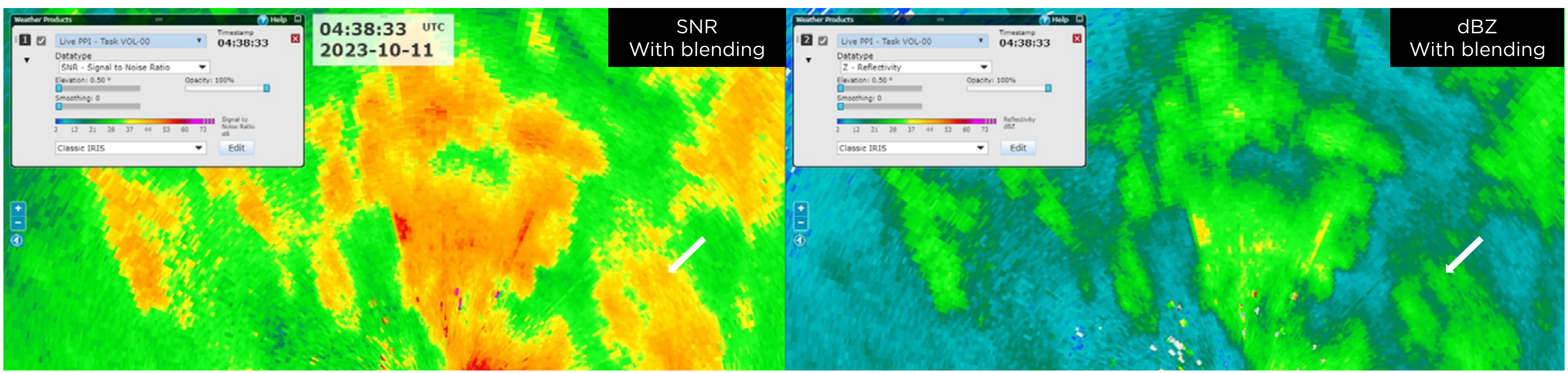

Figure 6. SNR and dBZ from the WRS300 C-band weather radar with 90+4 µs hybrid pulse and with the recommended setup with blending. White arrows indicate where the blending region ends. Both SNR and dBZ data are smooth and continuous.

Case examples

WRS300 C-band weather radar

Figures 7 and 8 show data examples from the Vaisala C-band research radar in southern Finland during a day of widespread areas of light rain. The melting layer is located approximately at 90 km of radar slant range (1300 m altitude). Main system parameters can be found in Table 2. The results demonstrate high precision, good data coverage in the near range, and consistency over the short and long pulse regions.

Note that the wind measurement task in Figure 7 uses 44+1 µs hybrid pulse combination to demonstrate performance, for example, in aviation applications. The short 1 microsecond pulse is sufficient for good quality wind measurements even in light drizzle, which is the natural lower boundary for weather radar applications. For clear air measurements, a wind lidar with its excellent data availability is the recommended technology.

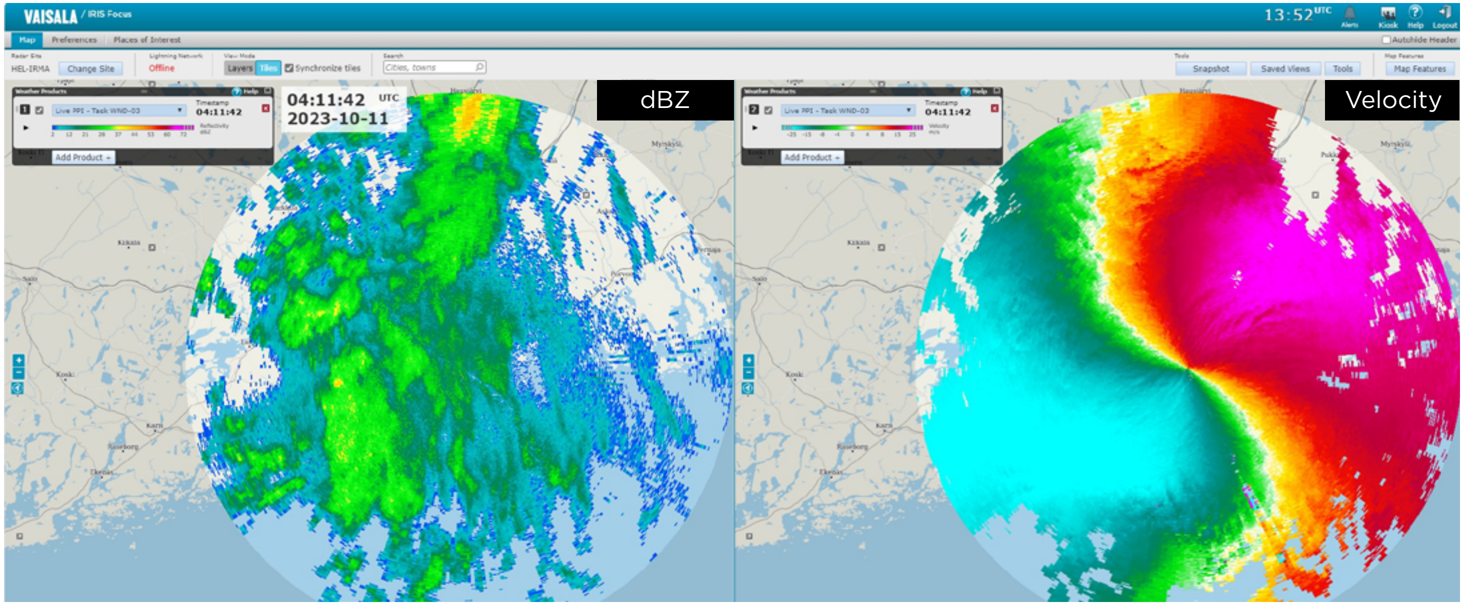

Figure 7. Examples of dBZ and radial wind velocity from the WRS300 C-band weather radar with 44+1 µs hybrid pulse and with blending applied.

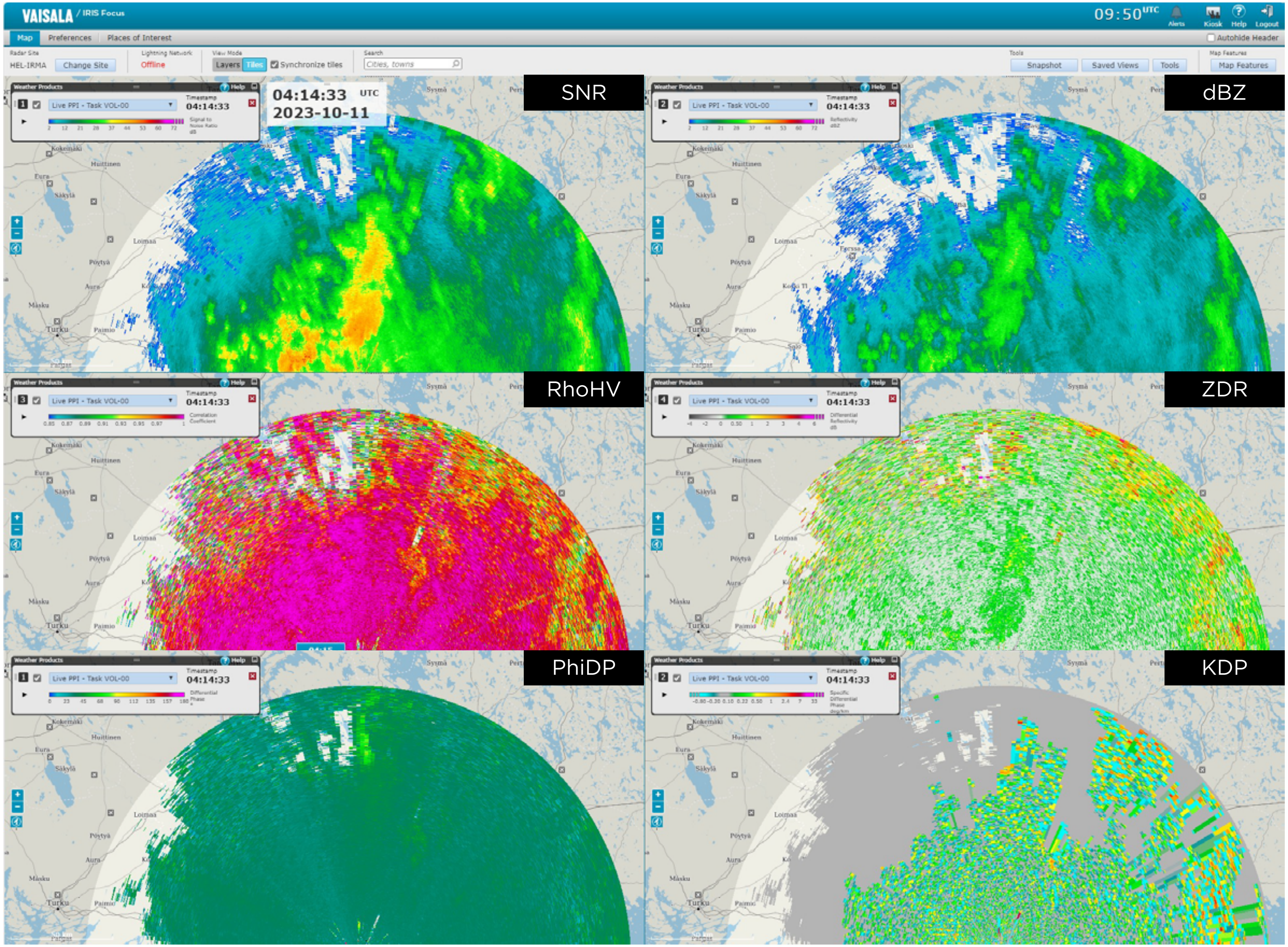

Figure 8. Data examples from the WRS300 C-band weather radar with 90+4 µs hybrid pulse and with blending applied.

WRS400 X-band weather radar

Figures 9 and 10 show data examples from the Vaisala X-band research radar in southern Finland during a day of widespread areas of light rain. The melting layer is located approximately at 22 km of radar slant range (460 m altitude). Main system parameters can be found in Table 2. The results demonstrate high precision, good data coverage in the near range, and consistency over the short and long pulse regions.

The wind measurement task in Figure 10 uses 44+1 µs hybrid pulse combination to demonstrate performance, for example, in aviation applications. Like C-band radar, the 1 microsecond pulse is sufficient for good quality wind measurements in light rain and drizzle.

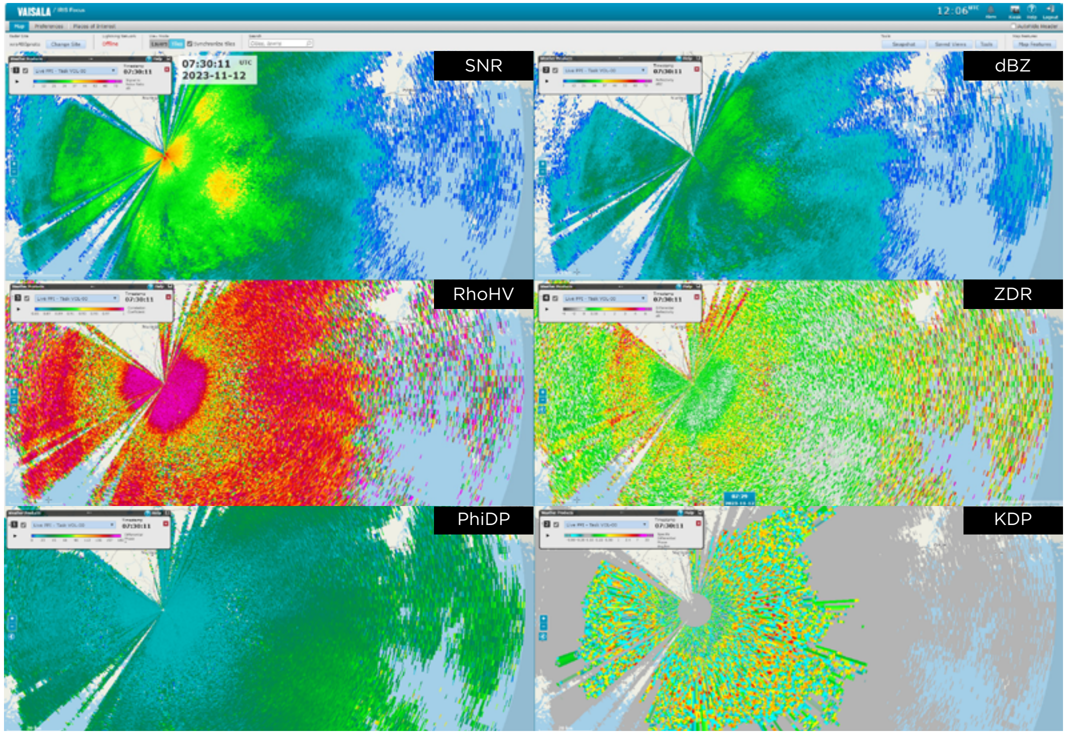

Figure 9. (right) Data examples from the WRS400 X-band weather radar with 90+4 µs hybrid pulse and with blending applied. Blind sectors are caused by nearby obstacles at the research radar site.

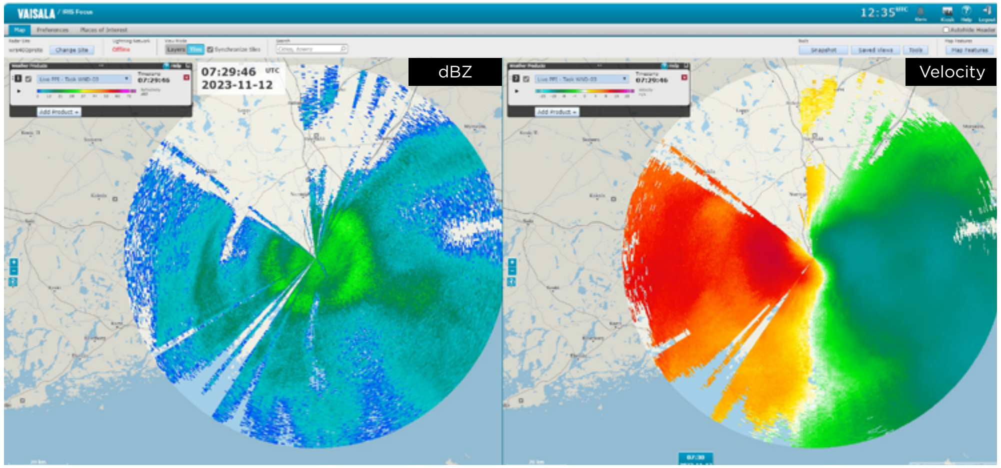

Figure 10 (left). Examples of dBZ and radial wind velocity from the WRS400 X-band weather radar with 44+1 µs hybrid pulse and with blending applied. Blind sectors are caused by nearby obstacles at the research radar site.

Radar sensitivity with hybrid pulsing

Radar sensitivity is a useful parameter for understanding the measurement performance limits of a radar system. It is an estimate of the weakest weather target that can be detected at a specific range. Sensitivity can be computed theoretically from the radar equation with suitable assumptions, such as the SNR required for detection [Puhakka, 2023].

This chapter presents both theoretical and observed sensitivity for WRS300 and WRS400 in the short and long pulse regions of hybrid pulsing. Main system parameters are shown in Table 2.

WRS300 C-band weather radar

The theoretical sensitivity curve representing typical performance of the Vaisala C-band SSPA radar is shown with dashed black line in Figure 11. Sensitivity is expressed in terms of reflectivity (Z), with lower values indicating better detection capability. The theoretical values were verified with real weather data from a WRS300 system located in southern Finland, shown by the colored background of distributions of reflectivity value (dBZ) detections. The data were collected during 10 hours on October 22, 2023.

The theoretical sensitivity and lowest observed values compare well. Transition from short to long pulse of hybrid pulsing shows as a sharp transition in the theoretical curve, while the observed values are more continuous due to blending.

Figure 11 also shows examples of lower bounds for reflectivity of drizzle and rain, estimated using Z = 200×R1.6 [Rinehart, 2004]. Comparison to radar sensitivity shows that the radar performance is sufficient for detecting all rain and drizzle intensity levels at all ranges.

Comparison with the Vaisala C-band magnetron radar (dashed blue line) shows that the SSPA radar has better (by 3.2 dB) sensitivity over most of the measurement range. This is remarkable as the SSPA radar also has a better range resolution compared to the magnetron radar (150 m vs. 300 m). It is also worth noting that if the magnetron radar results were estimated for 20 m waveguides instead of 5 m, the sensitivity gap would further increase by 1.8 dB.

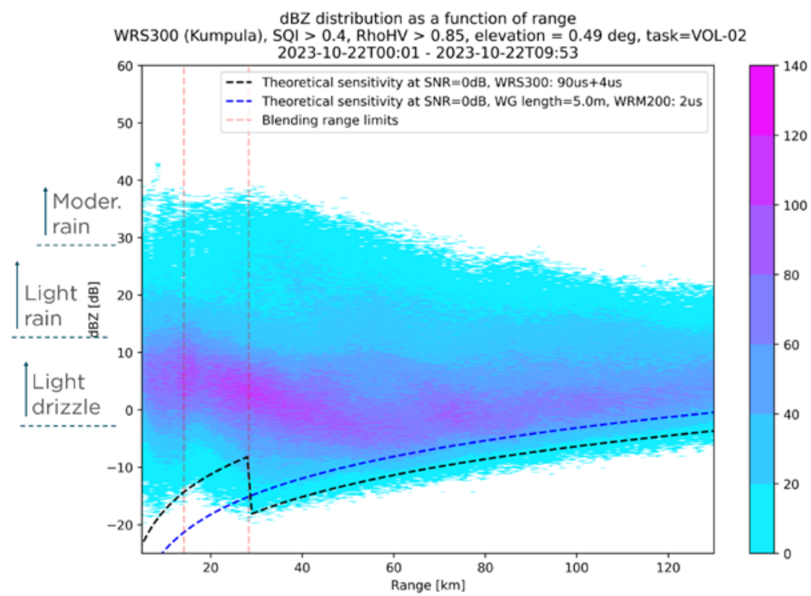

Figure 11. Dashed lines: theoretical sensitivity for WRS300 (SSPA, black) and WRM200 (magnetron, blue) as a function of range. Colored background: real measurements from WRS300 as distributions of cumulated dBZ values. Example reflectivity ranges for drizzle and rain (defined as >0.025, >0.25, and >2.5 mm/hour) are shown on the left.

WRS400 X-band weather radar

The theoretical sensitivity curve representing typical performance of the Vaisala X-band radar is shown with a dashed black line in Figure 12. The theoretical values were verified with real weather data from a WRS400 system located in southern Finland, shown by the colored background of distributions of reflectivity value (dBZ) detections. The data were collected during 8 hours on November 4, 2023.

The theoretical sensitivity and lowest observed values compare well. Transition from short to long pulse of hybrid pulsing shows as a sharp transition in the theoretical curve, while the observed values are more continuous due to blending.

Figure 12 also shows examples of lower bounds for reflectivity of drizzle and rain, estimated using Z = 200×R1.6 [Rinehart, 2004]. Comparison to radar sensitivity shows that the radar performance is sufficient for detecting all rain and drizzle intensity levels.

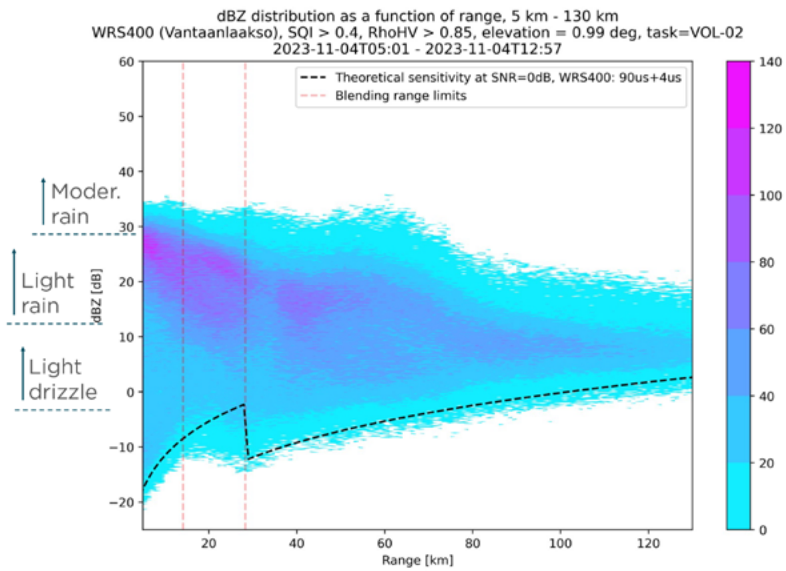

Table 2. Weather radar system parameters in experiments.

	WRS300	WRS400
Wavelength	5.3 cm	3.1 cm
Transmitter *	2 x 4 kW	2 x 400 W
Antenna	4.5 m	2.4 m
Hybrid pulsing	90+4 μs	90+4 μs
Samples averaged	32	32
PRF	1000 Hz	1000 Hz
Angular resolution	1°	1°
Elevation angle	0.5°	1.0°

** = For 2 x 2 kW (WRS300) and 2 x 200 W (WRS400) transmitter options, estimated values of the theoretical sensitivity curve would be 3 dB higher than those shown in Figures 11 and 12.*

Figure 12. Dashed black line: theoretical sensitivity for WRS400 (SSPA) as a function of range. Colored background: real measurements from WRS400 as distributions of cumulated dBZ values. Example lower bounds for reflectivity of drizzle and rain (defined as >0.025, >0.25, and >2.5 mm/hour) are shown on the left.

Radar calibration with hybrid pulsing

Maintaining accurate calibration is crucial for making correct weather analyses from radar data. This is especially important with hybrid pulsing, where the results from two distinct pulse waveforms - the short and the long pulse – are present in the same data file. Any differences between them would be immediately noticeable in the radar image. Furthermore, SSPAs are generally sensitive to temperature variations, and Vaisala SSPA radars have independent transmitters for horizontal and vertical polarizations. Even a minor drift in transmit power could have a clear effect particularly in polarimetric data products.

To counteract these issues, Vaisala has carefully designed the basic calibration procedures and supporting hardware and software features. The calibration consists of an annual calibration and a real-time transmit power correction. A major benefit of the real-time correction is that there is no need for a specific calibration measurement mode - the radar measures weather continuously, without calibration breaks.

Vaisala SSPA and magnetron radars use similar annual system calibration procedures. During annual calibration, the basic reflectivity calibration is performed by measuring the receiver gain and transmit pulse energy and verifying the digital filter loss (Figure 13). The last two are critical with long pulses and complex waveforms, as they typically have higher filter losses.

Figure 13 Calibrating a WRS400 X-band weather radar with a thermal power sensor during annual system calibration. Working space inside the radome is convenient for carrying out the test procedures.

During continuous calibration, the signal processor measures a sample of each transmit pulse for both polarizations in real time. It then compares this sample with a stored reference value that was measured during the annual system calibration. An advantage of the real-time transmit power correction is that the samples are measured using the same channel as weather signals. This ensures that any possible transmit power drifts are corrected in the data accordingly. Moreover, possible drifts in certain parts of the receiver path are corrected.

This real-time transmit power correction is also used to calibrate the differential reflectivity (ZDR). As a result, Vaisala SSPA radars can use the conventional calibration method with a vertically pointing rotating antenna using the ZDR data from the short pulse range to also calibrate the long pulses. The Vaisala radar software provides the Zdrcal utility to automatically perform this calibration measurement. This calibration procedure also automatically calibrates the long pulse.

The calibration methods have been extensively validated with actual weather measurements and have been found to work very well. The offset between the short and long pulse regions in the radar data is almost zero. Figure 14 provides an example of a ZDR measurement that shows no significant offset between them.

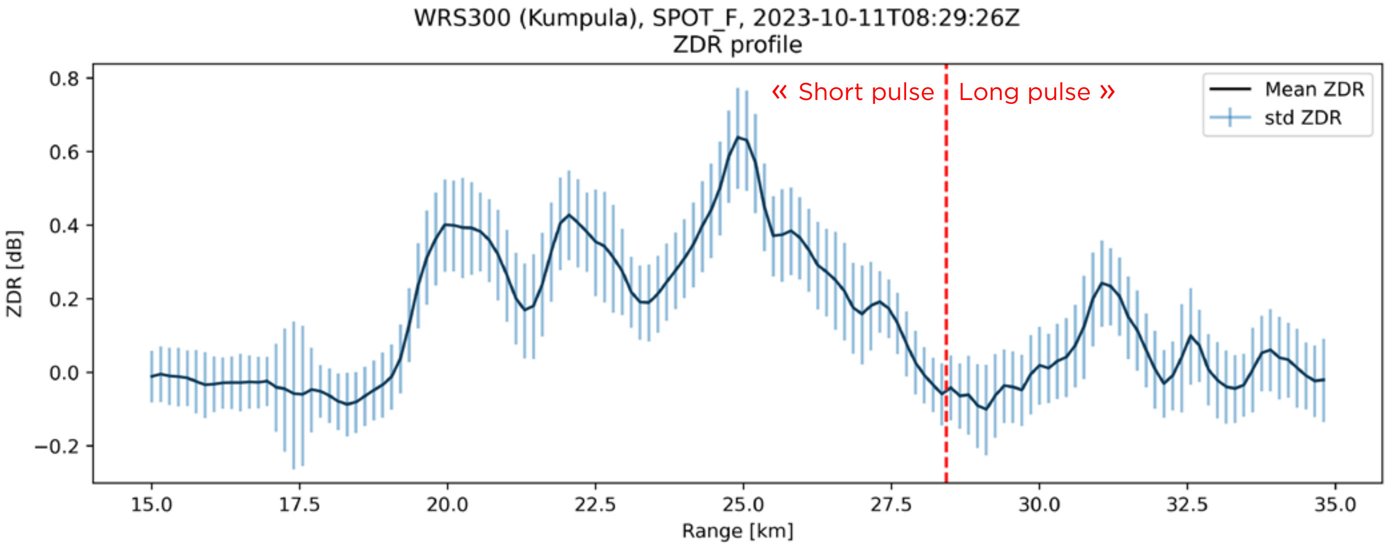

Figure 14. Example range plot of ZDR for a well-calibrated WRS300 measured with a stationary pointing antenna using 0.5° elevation angle and 11 s time average. Blending is not used. The transition from the short to long pulse region is smooth and continuous.

Summary

The Vaisala hybrid pulsing technique is a powerful tool that combines long and short radar pulses to achieve better sensitivity and range coverage in solid-state weather radars. The technique has been extensively validated with actual weather observations and has consistently shown to produce high-quality measurements. The standard Vaisala radar calibration procedures apply with hybrid pulsing and have proven to work very well.

Why Vaisala?

As the global leader in weather and environmental measurements, Vaisala provides trusted weather observations for a sustainable future. With over 85 years of experience and customers in 170+ countries, from the North and South Poles to Mars, we help provide the most reliable and accurate weather and climate information for better and safer daily lives.

Our instruments and intelligence are known as the gold standard for precision and reliability. As a sustainability leader we enable meteorology professionals to better understand, forecast and explain climate change. We continue to channel our curiosity into climate action and new ways of enabling a better planet for all.

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