DEFINING AND VALIDATING THE MINIMUM DETECTABLE WEATHER SIGNAL FOR AN X-BAND WEATHER RADAR SYSTEM

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1. INTRODUCTION

Minimum detectable weather signal (MDWS) is one of the key parameters when estimating the basic performance of any weather radar system. It describes how weak target can be detected by the radar at a certain range, or it can be used to solve the maximum range of detection for weather target having certain intensity.

Detected signal at the radar receiver is a combination of echo signal and thermal noise, and they both vary significantly from sample to sample. For this reason, certain threshold value for the signal to noise ratio (SNR) required for weather detection must be used. This threshold depends on the expected fluctuations of the echo signal, signal processing techniques used as well as false alarm rate (FAR) and probability of detection (POD) accepted. In the literature, there are theoretically computed values available for SNR required for different kind of fluctuations, FAR, POD and number of samples averaged.

In this study, the MDWS of a Vaisala WRS400 polarimetric X-band weather radar is examined. WRS400 is a compact radar system equipped with antenna mounted transceiver, solid state power amplifiers (SSPA) and Vaisala RVP signal processing technology. MDWS is first estimated using the conventional weather radar equation and the theoretical value of the SNR required from the literature. Benefits of certain signal processing techniques, such as enhanced reflectivity computation are also considered. After this, the actual performance of the installed WRS400 system is verified by analysis of actual weather data.

2. THEORETICAL BACKGROUND

Several factors affect the value of MDWS, including factors that are independent of the radar system design, such as physical backscattering properties of the target or propagational properties of the atmosphere. However, when comparing the performance of different radar models, the most relevant factors are those defined by the technical properties of the radar itself, such as transmit pulse energy, various attenuations, antenna characteristics, receiver characteristics and signal processing methods.

With the conventional weather radar equation, these factors can be used to calculate the power of the received echo signal from a target of known intensity. However, as weather target consists of distribution of moving scatterers, the intensity varies significantly from pulse to pulse. At the same time the receiver also detects thermal noise with varying amplitude. For this reason, detected signal must be threshold so that data points with weak echo signals are not removed too aggressively, while most of the data points with noise will be removed.

Amount of remaining noise after threshold is quantified with FAR, which describes how often in average the noise power is high enough to pass the threshold. Amount of weak echoes passing the threshold is quantified with POD. The threshold value is called signal-to-noise ratio (SNR) required for detection and is also known as detectability factor in the literature. Fluctuations of both echo and noise signals can be reduced by averaging number of radar pulses for a single data point. This consequently reduces the SNR required for detection but increases the time for the radar scan to complete.

In the literature, there are theoretically computed graphs available for the dependence between the FAR, number of samples and the SNR required. Separate graphs are typically available for targets with different kind of expected fluctuations and different POD. For example, if assuming weather target to fluctuate according to Swerling case 1, averaging 40 pulses and allowing FAR = 10^{-4} and POD = 50%, the resulting SNR required for detection according to Skolnik (1990) is 0 dB, meaning that the received echo signal from the actual weather equals the noise power. This value can be considered typical for a modern polarimetric weather

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radar system considering constraints, such as time available for an operational scan.

When the SNR required for detection is known, then corresponding minimum radar reflectivity factor z_{min} for a target with range r can be solved from the conventional weather radar equation as

$$z_{min} = \frac{1024 \ln(2)}{c\, \pi^3 |K|^2} \left(\frac{s}{n}\right)_{min} \frac{\lambda^2\, r^2\, n' b}{p_t\, \tau\, g_f\, g_e^2\, \theta^2}\, a\, r\,, \qquad (1)$$

where c is the speed of light, K is the dielectric constant of liquid water ($|K|^2 = 0.93$) and a is the 2-way specific attenuation of air, having value of 0.018dB/km for X-band radar according to International Organization for Standardization, ISO (2019). The ratio inside the parenthesis is the SNR required for detection, s being the echo signal power and n the noise power.

Other parameters of equation (1) are related to the radar system. λ is the wavelength used. n' is the spectral noise and when multiplied by the noise equivalent bandwidth b of the receiver signal processor, it yields to total noise power n. p_t is the transmit peak power and when multiplied by the pulse length τ, it yields to transmit pulse energy. g_f takes into account the pulse energy that is lost due to digital filtering of the signal processor. g_e and θ are the antenna gain and beamwidth values respectively.

As this article concentrates on compact radar system with an antenna mounted transceiver, separate terμσ for transmit and receive attenuations are left out of the equation (1). The attenuation of the fixed waveguide components is taken into account in the values of the transmit power p_t and the antenna gain g_e. This is illustrated by a block diagram in figure 1, which shows that the transmit power, the antenna gain and the spectral noise n' are all defined at the waveguide directional coupler. This is the calibration reference plane of the radar system.

SNR required for detection can be further reduced by using advanced signal processing methods, such as Vaisala enhanced reflectivity algorithm, which utilizes coherent averages of the echo signals from both the horizontal and vertical channels of a polarimetric weather radar. In case of 40 averaged pulses, the SNR required reduces approximately by 3 dB according to Keränen (2014). Furthermore, the actual FAR can be reduced up to two orders of magnitude by utilizing speckle filtering, where isolated pixels of detected signals are removed from the data.

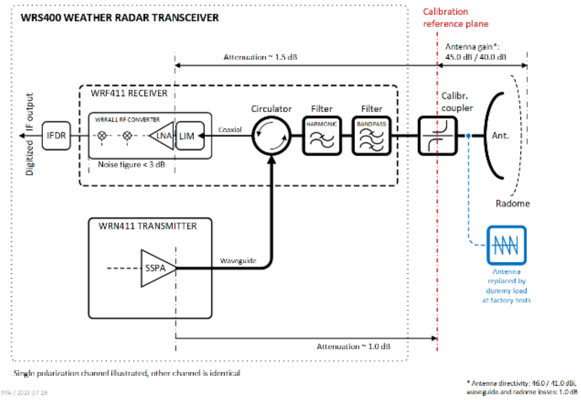

Fig 1. *Calibration block diagram of the WRS400 compact X-band weather radar system. Transmit power, antenna gain and noise of the receiver are all defined with respect to the calibration reference plane, which is the waveguide directional coupler between the transceiver and the antenna.*

3. WRS400 WEATHER RADAR

Vaisala WRS400 is a polarimetric X-band weather radar with an antenna mounted transceiver, using solid state transmitter and Vaisala RVP signal processor technology. X-band frequency provides measurement data with high resolution and excellent precision for short-range meteorological surveillance typically up to 50….150km, depending on application. By filling gaps in radar networks, the X-band weather radar can improve radar network coverage, for example, in mountainous areas, rain catchment areas and around wind parks.

WRS400 operates in frequency range of 9.3…9.7GHz with transmit peak power of 400W per polarization. Antenna is a conventional parabolic center fed reflector with dish diameter of 2.4m, having typical beam width of 0.95° and gain of 45.0dB. Noise figure of the receiver is better than 3dB and dynamic range of the receiver is 95dB or better. There are also options available for lower transmit power (200W) and smaller dish size (1.4m / 1.60°/ 40.0dB). Figure 2 illustrates WRS400 weather radar system with a 2.4m antenna.

Fig 2. *WRS400 polarimetric X-band weather radar with 2.4m antenna.*

The longest available pulse length of the WRS400 with RVP900 signal processor is 90µs and uses non-linear frequency modulation (NLFM) for pulse compression to 1.0µs (150m range resolution). The blind region of the long pulse in the vicinity of the radar is covered by hybrid pulsing, where a conventional 4µs short pulse separated by 4MHz in carrier frequency is transmitted right after the long pulse. Maximum pulse repetition frequency (PRF) with this pulse length combination is 1000Hz.

In the standard configuration of the WRS400, there are also 44µs NLFM and 1µs conventional pulses available for hybrid pulsing with higher PRF (2100Hz), better range resolution (75m) but lower sensitivity. However, this study concentrates on the performance of the 90µs + 4µs hybrid pulsing only. To make the sensitivity gap between the long and short pulse regions less pronounced, the signal processor can be configured to blend the data streams of short and long pulses within a transition range, being 14…28km for the 90µs pulse.

All relevant parameters of the WRS400 with 400W transmitters and 2.4m antenna are listed in table 1. Specified values apply only for certain parameters and are rather conservative. For this reason, typical values are used to estimate the performance of the radar. They are based on the average values obtained from eight manufactured WRS400 systems during 2020-2023. Actual values are obtained from the calibration performed in September 2021 for the WRS400 system used in this study.

Substituting tabulated values, all in linear scale to equation (1), produces values for calibration reflectivity as well as for MDWS as listed in the bottom rows of the table. For example for the 90µs pulse, the MDWS at 100km range is typically -0.2dBZ and for the radar used in this study it was -0.3dBZ according to system calibration in September 2021. In figure 3, graphs of the typical MDWS are plotted as a function of range.

Parameter	Spec.	Typical value		Actual value	
Wavelength (λ[cm])	-	3.1		3.11	
Antenna gain (g_e[dB])	> 45 [1)]	45.0 [3)]		45.0 [3)]	
Beamwidth (θ[°])	< 1	0.95		0.95	
Transmit power (p_t[W])	> 400 [2)]	400 [3)]		480 [3)]	410 [3)]
Pulse length (τ[µs])	-	4	90	4	90
Digital filter loss (g_f[dB])	-	1.2	4.5	0.85	4.60
Noise eq. bandwidth (b[MHz])	-	0.4	0.4	0.42	0.41
Spectral noise (n'[dBm/MHz])	<-108.5 [4)]	-111.5 [5)]		-111.8 [5)]	
Cal. reflectivity @ 1km (Z_0[dB])	-	-31.8	-42.0	-32.9	-42.1
MDWS @ 100km (Z_{min}[dB]) [6)]	-	**10.1**	**-0.2**	**8.9**	**-0.3**

[1)] Directivity [dBi] without waveguide or radome losses.
[2)] Defined at the transmitter output flange.
[3)] Defined at the calibration reference plane.
[4)] Antenna replaced by a dummy load in room temperature.
[5)] Antenna pointing at clear sky.
[6)] SNR required = 0 dB, 2-way gaseous attenuation = 0.018 dB/km, conventional computation of Z used.

Table 1. *Parameters of the radar equation and corresponding minimum detectable weather signals (MDWS) of the WRS400. Values according to technical specification, a typical installed radar system and the research radar at Vaisala headquarters are listed.*

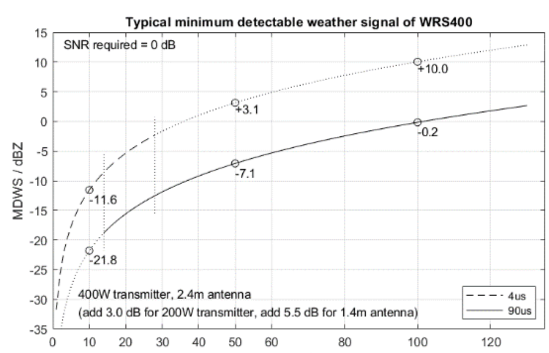

Fig 3. *Typical MDWS of WRS400 plotted as a function of range. Transition range of the hybrid pulsing is the area where the curves of the long and short pulse overlap.*

4. ACTUAL RADAR MEASUREMENTS AND RESULTS

A research WRS400 system located in southern Finland, with 2.4m antenna and 400W transmitters was used to verify the actual MDWS with real weather data, see figure 4. Main dataset for this study was measured in November 25th, 2021. A PPI scan at 1° elevation was used and radar reflectivity data was collected from 50 scans with weather echoes present, over time span of 14 hours starting at midnight UTC. Scan was configured to use 90µs + 4µs hybrid pulsing with 32 samples averaged, PRF of 1000Hz, angular resolution of 1° and resulting antenna rotation rate of approximately 31°/s. Maximum range was 136km with range gate size of 150m. Range averaging was not used. Doppler filtering was used to reduce the ground clutter returns but other data quality thresholding was only applied in post processing while analyzing the data. To clearly distinguish the performance between the long and short pulse regions, the blending algorithm was not used in these measurements.

Figure 4. *Research WRS400 used in this study was installed in summer 2020. It is located at the roof top of Vaisala headquarters, 12km north of Helsinki, Finland. This radar is equipped with 2.4m antenna (Picture P. Puhakka).*

The cumulated distribution of measured radar reflectivity is plotted as a function of range in figure 5. Data is post-processed with signal quality index (SQI) threshold of 0.4. SQI describes the coherency between transmit and receive pulse and has value range of 0…1 (from non-coherent to fully coherent). In this case it was used to remove most of the noise and possible 2nd trip echoes. Figure 5 shows that the measured reflectivity distribution clearly goes below the typical MDWS of the WRS400, plotted with a dashed line in the figure. More precise views of the distributions at 50km and 100km ranges from a single PPI scan are plotted in figure 6. Note that these measurements were done with 32 averaged pulses, while the typical MDWS curve assumes 40 samples. According to Skolnik (1990), 32 samples correspond to 0.5…1.0dB higher SNR required for detection as compared to 40 samples with the same FAR.

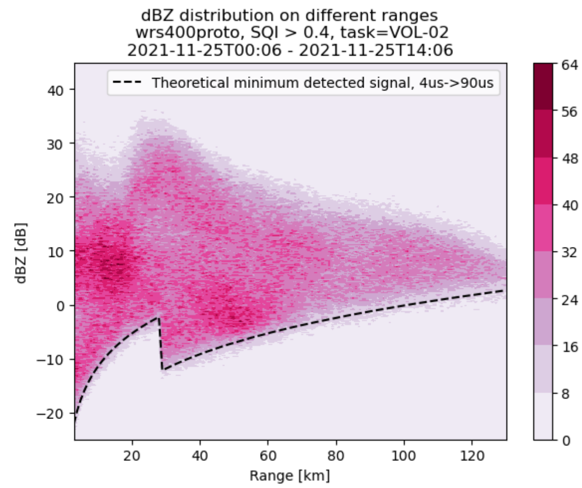

Fig 5. *Cumulated distribution of measured radar reflectivity Z as a function of range. Color scale denotes total number of hits with certain value of Z. Typical MDWS curve of WRS400 with 90µs + 4µs hybrid pulsing is plotted with a dashed line.*

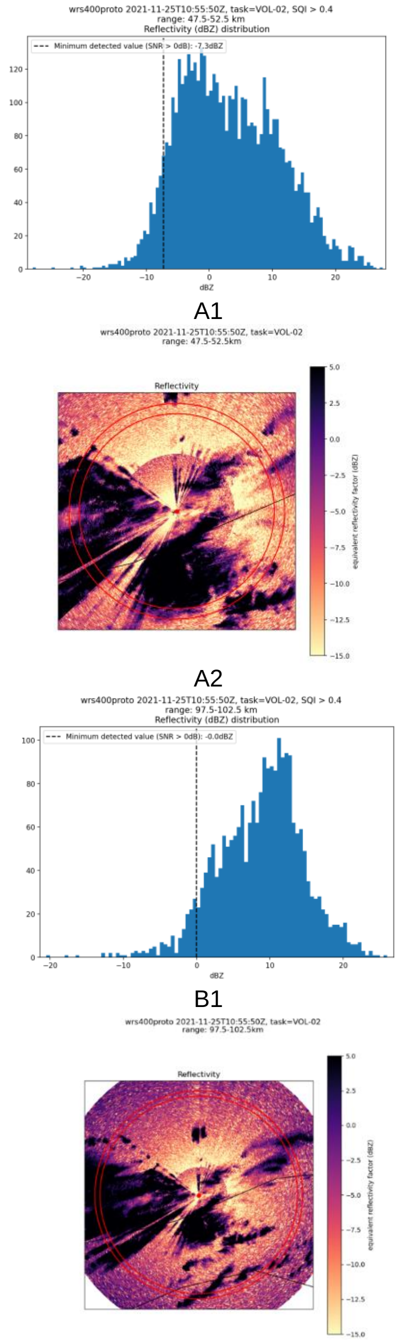

Fig 6. *Reflectivity distributions of a single PPI scan at 50km (A1) and 100km (B1). Corresponding PPI images (A2, B2) denotes with red rings the range span of ±2.5km used to gather data for each distribution. Due to non-optimal radar horizon of the research site, there are many blocked sectors visible in the PPI scan.*

To verify the improved performance achieved by the enhanced reflectivity algorithm, minimum measured values of the conventional horizontal reflectivity and enhanced reflectivity from the same data set of 50 PPI scans were compared. From the data set, we can find minimum measured reflectivity in every scan file at each range bin for both conventional and enhanced algorithm. Computing difference between these two at every range in every scan gives a quantitative comparison that shows how much sensitivity typically improves with the enhanced reflectivity algorithm. The average difference obtained was 2.8dB, which is well in line with the theoretical values according to Keränen (2014) when 32 pulses are used. Figure 7 shows overall minimum measured conventional (dBZ) and enhanced reflectivity (dBZE) values and average difference of the minimum values at every range bin. Also in this analysis, data is post-processed with SQI threshold of 0.4 to remove most of the noise and possible 2nd trip echoes. Since this data set is based on the absolute minimum measured reflectivity value at each range, the curve appears noisy as expected with such a low signals.

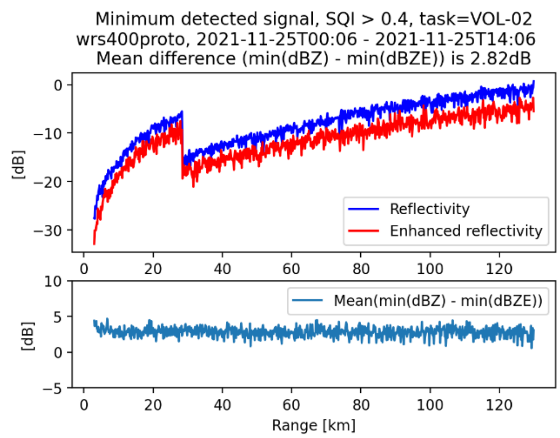

Fig 7. *Minimum measured value from conventional horizontal reflectivity (dBZ), enhanced reflectivity (dBZE) and their difference as a function of range from the data set of 50 PPI scans.*

To study the noise statistics and actual FAR, a special set of measurements with transmitter off was executed on 20th June 2023, comprising of nine PPI scans. To avoid excess noise from ground and higher obstacles of the radar horizon, the analyzed data was limited to a sector between azimuth of 40° and 195° and elevation of 10° was used. Furthermore, only data from the range of the 90μs pulse was used, even though there was no significant difference when comparing with the

4μs data at near range. Otherwise, the configuration was similar with the measurements in November 2021.

Resulting data set contained 757485 data points in total. SNR threshold with different values between -10 and +2 dB were applied to the data set and corresponding FAR was calculated simply as a ratio of number of noise data points left after threshold divided by number of data points in total. Results are in figure 8, where FAR is plotted as a function of SNR threshold. With the SNR required for detection of 0 dB as assumed in earlier sections, the corresponding FAR is $10^{-3.2}$, which is more than the assumed 10^{-4} according to Skolnik (1990). This is mostly explained by the fact that in these measurements, 32 averaged pulses were used instead of the assumed 40.

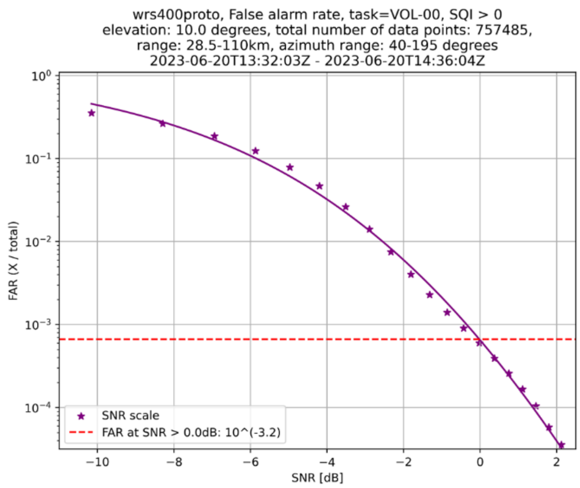

Fig 8. *Measured FAR as a function of applied SNR threshold when only noise is present (transmitter off).*

5. DISCUSSION AND CONCLUSION

This study verifies that an installed WRS400 X-band weather radar system achieves well the theoretically estimated minimum detectable weather signal, being typically -0.2dBZ at 100km range when SNR of 0dB is assumed to be required for proper detection of weather. The observed FAR of noise was slightly more than what was expected in the literature, but relatively well in line considering the number of pulses averaged in the measurements. The improvement of the MDWS using the enhanced reflectivity algorithm was verified to be 2.8 dB for 32 averaged pulses, which is in line of the expected value of approximately 3dB with 40 averaged pulses.

6. REFERENCES

ISO, International Organization for Standardization, 2019: Meteorology – Weather radar – Part 1: System performance and operation (ISO standard 19926-1:2019), Ch. 6., table 5.

Keränen, R., Chandrasekar, V., 2014: Detection and Estimation of Radar Reflectivity from Weak Echo of Precipitation in Dual-Polarized Weather Radars, *J. Atmos. Oceanic Technol.*, 31, 1677 – 1693, figure 3.

Skolnik, M., 1990: Radar Handbook, 2nd edition, Mc Graw-Hill, 2.1 – 2.68., figure 2.6.