Operational implementation of a fully dynamic pulse width and matched filter scheme

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1 Introduction

Nowadays the ability to configure each individual elevation scan of a volume coverage pattern has achieved a high degree of flexibility. The best possible data quality over the entire volume scan with specific individual tuning from scan to scan is the target to be reached. What remains inflexible is the pulse width which is typically limited to the choice of 3-4 presets. A rich choice of available supported pulse widths would provide a useful additional tool to optimize the SNR with respect to the selected radar range of each scan. Each pulse width comes with its individually designed matched filter. As a consequence a high resolution of available pulse widths necessitates a correspondingly high resolution of individually designed matched filters. The ideal approach would be a scheme that allows the free scan-to-scan definition of the best matching pulse width within a given pulse width range. Such a free definition cannot be supported with static predesigned matched filters. As a consequence a dynamic pulse-to-pulse matched filter design would be a precondition to meet the targeted flexibility.

A free and dynamic definition of pulse widths has implications on the implementation of the matched filter scheme. Typically matched filters are designed statically, once assigned to a static defined pulse width and used in future without change. With dynamic defined pulse widths, in order to avoid drops of SNR due to pulse width mismatch of the filter, matched filters must be available at a minimum for each possible pulse width within the range of pulse width definition. An alternative and more general approach is the dynamic definition of matched filters. This again could be done once at the operational start of each scan using a well-defined pulse width or, as it is realized by the Selex approach, fully dynamic with each transmitter pulse.

This paper describes the implementation of a dynamic pulse width scheme that is supported by a dynamic operational pulse-to-pulse matched filter design.

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2 Motivations

2.1 Optimization of SNR with respect to the selected radar range

In this paragraph the focus is on the signal to noise ratio (SNR) in relation to the selected radar range. It is explained that the dynamic pulse width scheme results in an optimized signal to noise ratio (SNR) compared to predefined, discrete pulse width definitions.

According to the weather radar equation the received signal power depends on the length of the transmitted radar pulse (Doviak and Zrnic, 2006, eq. 4.35). The signal to noise ratio (SNR) is the ratio of received power and receiver noise. Receiver noise depends on the matched filter bandwidth. Generally the bandwidth of a matched filter is related to the inverse of the transmitter pulse width (more details related to the matched filter are discussed below). So the SNR of weather signals depends on the square of the transmitted pulse width (Doviak and Zrnic, 2006, eq. 4.36).

$$\mathrm{SNR}_{\mathrm{lin}} \sim \tau^2 \quad (1)$$

The selected pulse width should therefore be as large as possible (if range resolution effects are ignored). The transmitter hardware typically defines a maximum supported duty cycle (product of PRF and pulse width). This maximum duty cycle is valid between a minimum and maximum pulse width. For a given PRF the pulse width may not be larger as the ratio between maximum duty cycle and PRF.
For a user selected radar range the related unambiguous PRF is typically chosen in order to get a maximum Nyquist velocity range and to collect as many radar echoes as possible. The maximum duty cycle limit now defines the related pulse width target value. A predefined pulse width scheme cannot realize all possible pulse width target values. For several selected radar ranges the pulse width that is used with the dynamic pulse width scheme may be larger compared to the pulsed width obtained with the predefined pulse width scheme. The increased pulse width goes along with an SNR improvement.

Example:

Predefined pulse width values 0.5, 1.0, 2.0 and 3 µs are compared with a dynamic pulse width range between 0.5 and 3.5 µs. The maximum duty cycle of the transmitter is 0.0012 within the pulse width range of 0.5 to 3.5 µs. Figure 1 shows the usable transmitter pulse width for both schemes over the selected radar range. The pulse width is calculated from the maximum duty cycle and the unambiguous PRF that is related to the selected radar range. The predefined scheme needs to change the pulse width to avoid duty cycle limit violations. For range selections below 63 km both schemes use the minimum available pulse width. In the range selection interval above 63 km the dynamic pulse width scheme allows an increased transmitter pulse width compared to a system using predefined pulse width values. If the selected range is above 439 km the dynamic pulse width scheme uses the maximum available pulse width value of 3.5 µs.

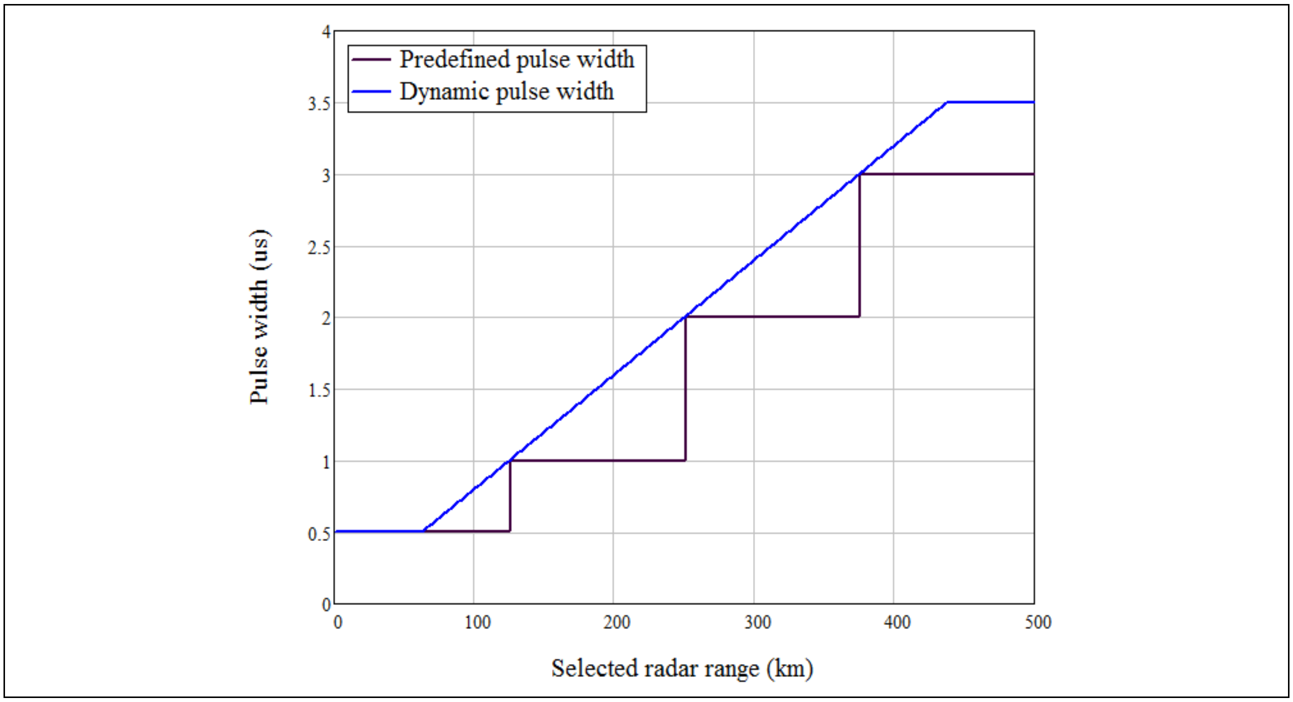

Figure 1: Usable pulse width for given example parameters, predefined pulse width (maroon color), dynamic pulse width scheme (blue color). Horizontal axis is the selected radar range (km)

Figure 2 shows the SNR improvement ΔSNR of the dynamic pulse width scheme against the predefined pulse width scheme. The SNR itself is proportional to the square of the pulse width τ according to equation (1). ΔSNR is calculated in logarithmic units as:

$$\Delta SNR_{\log} = 10\log_{10}\left(\frac{\tau_{dynamic}^{\;2}}{\tau_{predefined}^{\;2}}\right) \qquad (2)$$

Figure 2 uses the pulse width values for each selected radar range from Figure 1. For the example values given the dynamic pulse width scheme shows an SNR improvement of up to 6 dB against the predefined pulse width scheme for range selections above 63 km.

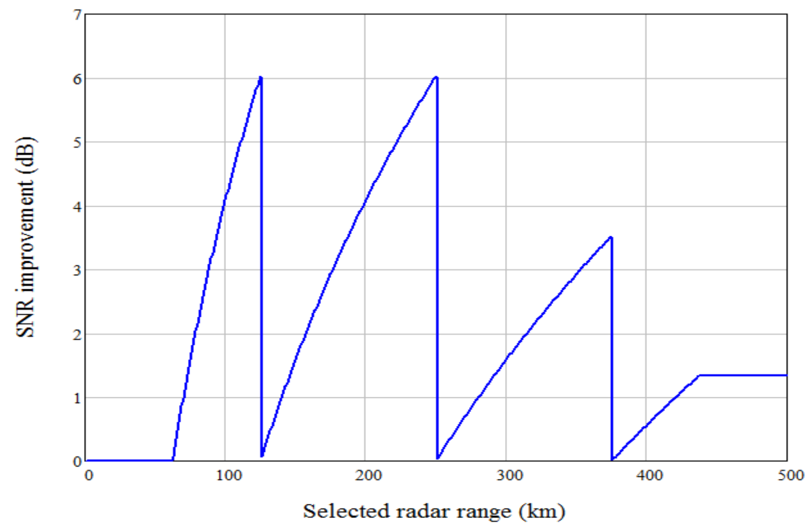

Figure 2: SNR improvement (dB) of dynamic pulse width scheme against predefined pulse width scheme for given example parameters. Horizontal axis is the selected radar range (km).

2.2 Transmitter frequency stability

In magnetron based transmitters, the output frequency is subject to change due to thermal drifts of the magnetron´s body temperature. Beside a change in environment temperature, this is mainly caused by the self-heating of the magnetron because of dissipation loss. The dissipation loss directly refers to the so called duty cycle which is the product of pulse width and PRF. Let us consider a C-band magnetron based transmitter that is aligned to its nominal radio frequency (RF) output at 50 % of the maximum duty cycle. For a volume scan the PRF and/or pulse width is aligned to achieve the optimum results regarding acquisition range and maximum Nyquist velocity range. For C-band magnetron radars a change of the operational duty cycle can cause a RF drift of ±3 MHz around the nominal RF. Free selectable pulse widths provide the potential to keep the duty cycle constant and thus reduce the operational frequency drifts to effects caused by environment temperature variation. The operational frequency drift is thus reduced considerably.

3 Implementation

3.1 Transmitter

A fundamental precondition to realize free selectable pulse widths is the technology of the transmitter modulator. In the past modulators were equipped with a so-called pulse forming network (PFN). Depending on presets of internal inductors and capacitors, only specific pulse widths could be retrieved. This technology is nowadays replaced by IGBTs and high-bandwidth pulse transformer technology. But even such state-of-the-art modulators may be limited to fixed pulse widths if they use integrated time generators.

A modulator design that does not raise any pulse width forming demands but realizes the pulse width in consequence of the width of a controlling trigger is a must. Such a modulator, if it provides a definite relation between trigger width and final transmitted pulse width provides the ideal precondition to realize free selectable pulse widths. The Selex designed modulator family for magnetron and klystron transmitters serves as a perfect precondition for dynamic selectable pulse widths.

3.2 Modulator timing control

All triggers of a radar system are derived from the same master clock source. The generation and timing of the triggers is typically realized by a trigger generator that is based on a state machine. The radar digital receiver, which is synchronized to the radar system master clock, generates the radar triggers. In awareness of the applied transmitter modulator and its timing characteristics the digital receiver must generate the modulator trigger in consequence to the commanded pulse width.

Under the precondition that the transmitter modulator supports the free definition of pulse width via a controlling trigger there are different schemes that must be realized for magnetron and klystron transmitter types. For magnetron transmitters, the resulting pulse width directly relates to the controlling trigger, merely the delay time to self-oscillation of the magnetron must be taken into account. For klystron transmitters, the controlling trigger switches the high voltage to the tube. The actual pulse width is defined by the timing of the RF drive signal which is up-converted from the digital receivers D/A waveform generator output. Both trigger and RF drive signal must be aligned via delay constants.

It was found that for each modulator type a 2nd order polynomial defines a clear and definite relation between the duration of the stimulus (trigger / RF drive signal) Δt and the resulting pulse width τ .

$$\Delta t = a\tau^2 + b\tau + c \qquad (3)$$

For each modulator type one standard coefficient set (a, b and c) is available. In series test of one modulator type it was found that the nominal to real pulse width deviation of a type specific coefficient set is small, below 8 %. Based on this parameter set a calibration routine is available. This routine steps through the supported width interval using the standard coefficient set to command and measure the pulse width. Finally a new, system specific coefficient set is calculated from the measured results. Using this adjusted coefficient set, the pulse width deviation is below 4 %. An example plot for the deviation against the nominal pulse width is shown in Figure 3. The maximum deviation between nominal and real pulse width occurs for narrow pulses. In this example the maximum measured deviation is 2 %.

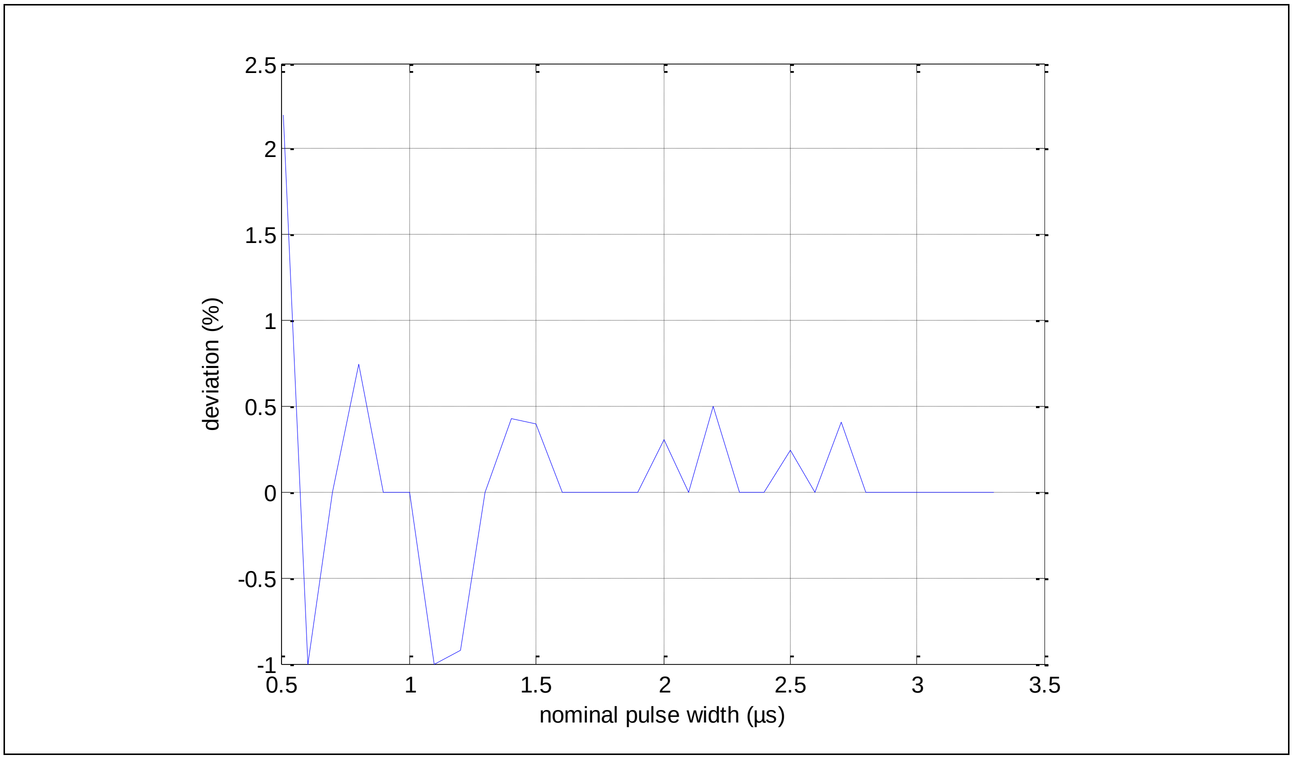

Figure 3: Final deviation from nominal pulse width (example)

The resolution with which a certain pulse width can be defined is limited by the resolution of the trigger timing. In case of Selex GDRX5 this is 5.56 ns, corresponding to the 180 MHz reference clock.

Once a pulse width is commanded, typically at the start of a 2D slice acquisition, the related trigger timing is derived from the polynomial and commanded to the modulator. When the related pulse is established an initial pulse measurement is performed by means of the TX burst data. The measured width is checked against a configurable acceptance window and, if the window is exceeded, a second linear correction is applied to the trigger timing. In operational long-term tests it was found that for an acceptance window of ± 20 ns the second linear alignment is not required, the typical deviation is below that threshold.

3.3 Dynamic Matched Filter

The receiver of a pulsed radar system uses a matched filter to improve the SNR (Signal to Noise Ratio) of the echo signals. In general this filter is a low pass filter, its bandwidth depends on the transmitter pulse width, i.e. the larger the transmitter pulse width the smaller the filter bandwidth.

Conventional radar systems usually apply static predefined filter sets in order to cover all configurable transmitter pulse widths. During system setup a static relation between each transmitter pulse width and a filter coefficient set is determined via a matched filter design process. Follow-up changes in temperature and also hardware aging effects cause mismatches, which are not taken into account.

When the transmitter pulse width is changed during operation, the radar automatically applies the associated filter coefficient set.

With the introduction of dynamic pulse widths, the static filter approach would require a large pool of coefficient sets in order to avoid or at least reduce bandwidth mismatching and SNR loss. Therefore a functionality is required that dynamically designs the matched filter for the actual pulse width in use. In final consequence and based on the transmitter burst sampling of the actual transmitted pulse an ideal approach was realized that designs a pulse-to-pulse specific filter coefficient set. The signal processor hardware with its computation performance as well as the signal processing software architecture must meet the related high performance demands of such an implementation.

Dynamic matched filters are SNR optimizing filters that automatically, pulse-to-pulse, adapt to the actual transmitter pulse shape. These filters use the waveform of every transmitter pulse to create a corresponding matched filter for the respective pulse. The transmitter pulse waveform is known from the complex baseband transmitter sample created by the digital receiver with every PRT.

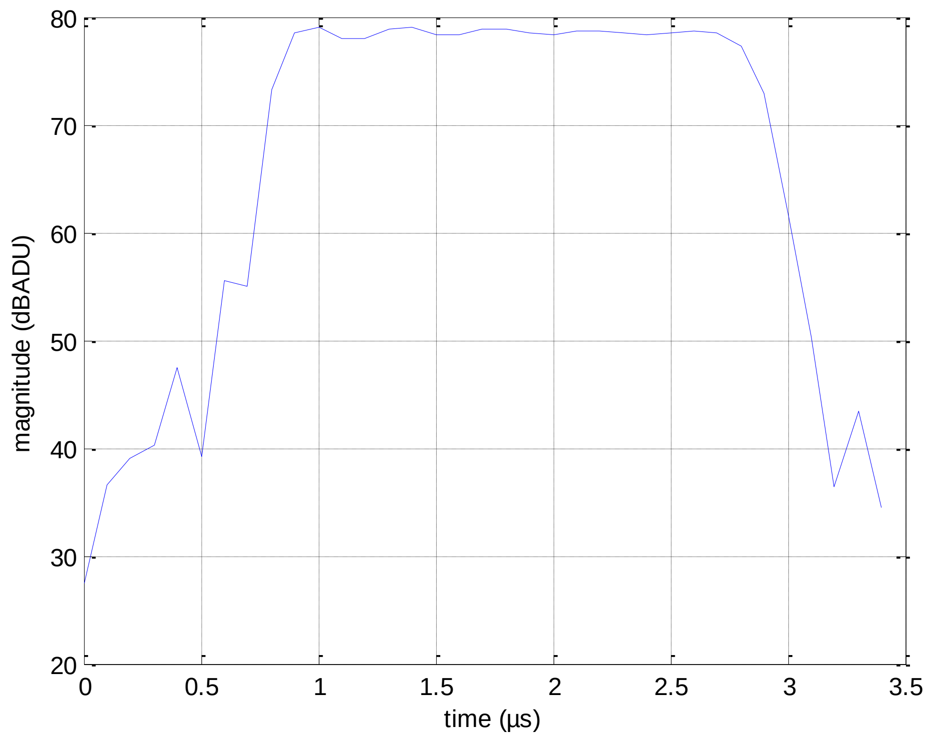

Figure 4: 2 µs TX pulse baseband sample

Based on this, the signal processor dynamically creates a matched filter coefficient set, which represents the time inverted and complex conjugated version of the transmitter pulse shape. An example TX baseband sample of width 2 µs is shown in Figure 4. The related transfer function of the dynamic matched filter is visualized in Figure 5. It perfectly follows the spectral shape of the actual transmitter pulse.

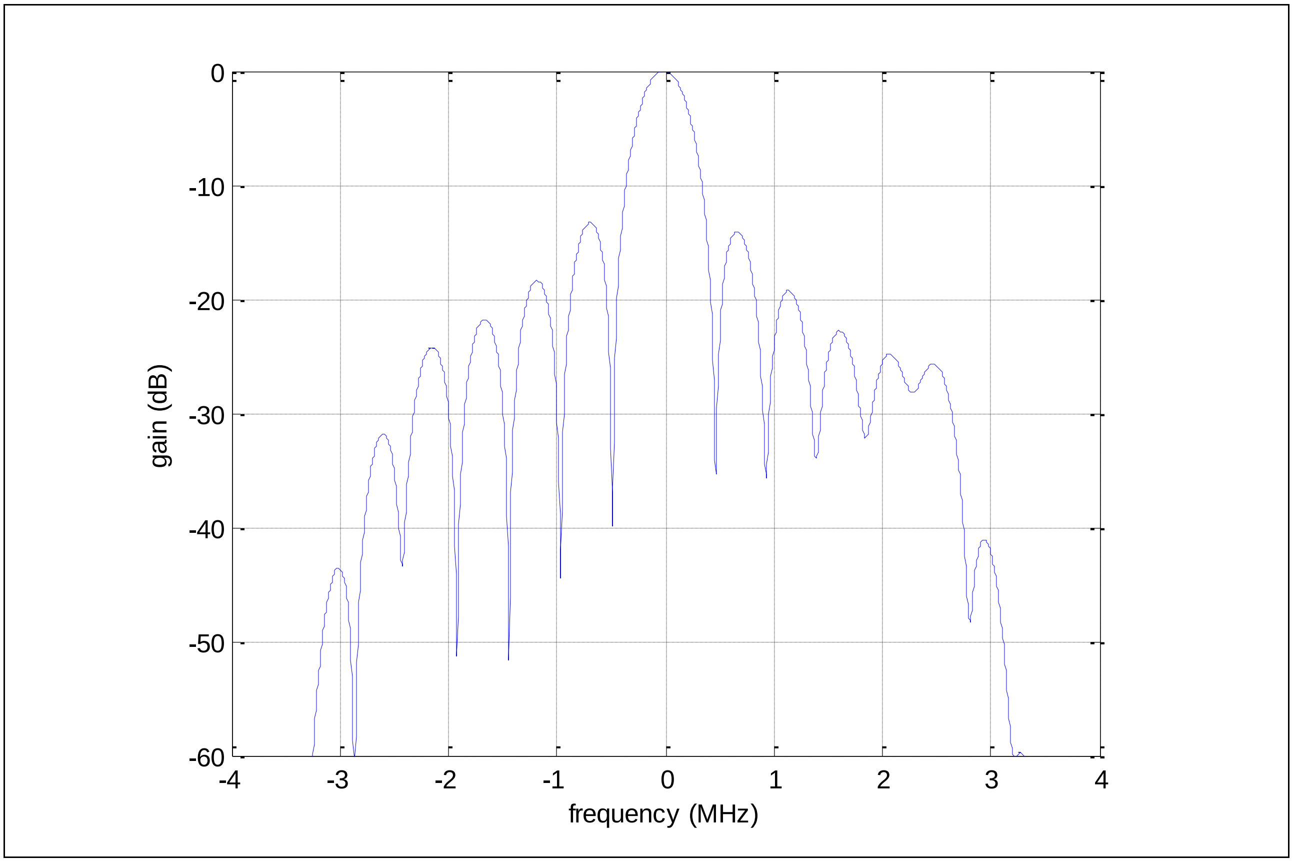

Figure 5: Frequency response of dynamic matched filter for a 2µs pulse

Filter theory explains that this approach maximizes the peak SNR of the filtered signal. Additionally the sequence of filtered signals is automatically corrected for pulse to pulse phase variations, so the phase coherency of the filtered signal is also maximized. In case of dynamic pulse widths, the dynamic matched filters are the ideal and necessary choice. A fixed pulse width related filter definition cannot fully account for dynamic pulse widths.

4 Results

4.1 Dynamic pulse width definition scheme

Figure 6 shows results from operational tests using the dynamic pulse width and dynamic matched filter scheme. A Meteor 735CDP10 magnetron weather radar system was configured to operate a scheme of 31 PPI slices with pulse widths increasing from 0.5 µs up to 3.5 µs in steps of 0.1 µs. The PRF per slice was defined in such a way that a constant duty cycle of 0.001 is realized over the complete scheme.

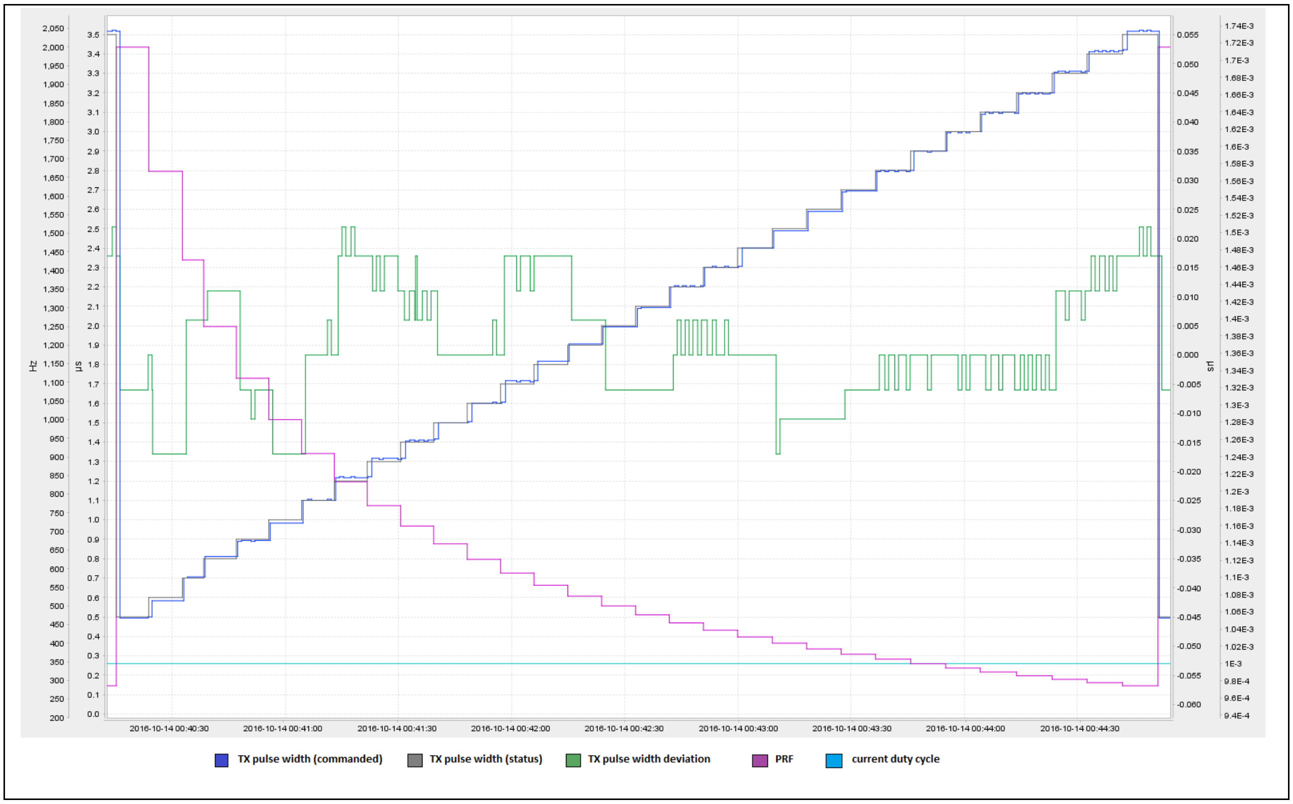

Figure 6: Constant duty cycle volume scan, 31 different pulse widths ranging from 0.5 µs to 3.5 µs in steps of 0.1 µs

As can be seen from Figure 6 the TX pulse width deviation (green color, most left y axis on the right) of the dynamic pulse width definition scheme remains within the expected range of ±20 ns if the pulse width measurement resolution of 5.56 ns is taken into account. This measurement resolution is related to the 180 MHz clock used for data sampling.

4.2 Matched filter investigations

In this paragraph an experimental comparison between predefined and dynamic matched filters is described. In a C-band magnetron system an attenuated signal from a waveguide coupler behind the circulator is fed into the RX channel of the analog receiver (Figure 7). The received signal may be seen as an echo from a point clutter target at range 0 km. For visualization purposes the range sampling is configured in such a way that the echo appears at a range > 0 km. A TX sample signal is taken from a coupler behind the magnetron and fed into the TX channel of the analogue receiver. It is used to determine frequency, phase and amplitude of the TX burst signal.

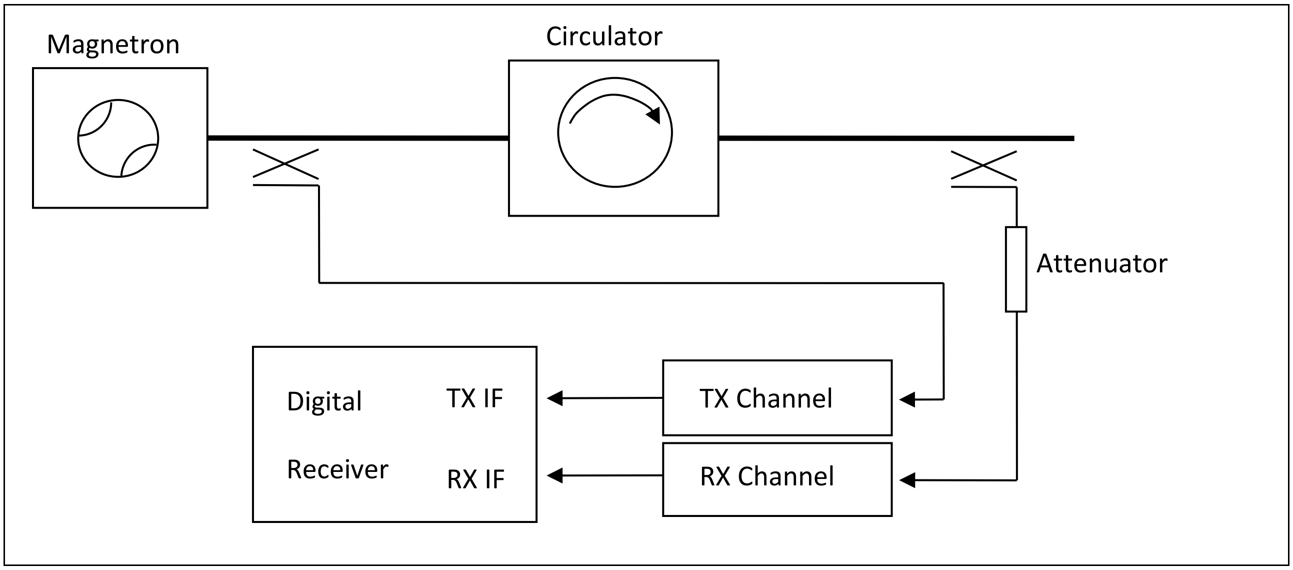

Figure 7: Transmitter pulse feedback test setup

Now the properties of the received signal can be analyzed for different matched filters configurations.

Static, predefined matched filters are chosen from a set of predefined (offline) designed FIR filters. This set of predefined filters realizes bandwidths from 0.2 to 4 MHz in steps of 0.1 MHz. As described, dynamic matched filters are created directly out of each TX burst sample. Figure 8 and Figure 9 show the received raw power (dBm) versus range for the two filter configurations. The transmitter amplitude pulse width is 2.1 µs at a PRF of 600 Hz. The power is averaged from 512 transmitter pulses. The range sampling resolution is 17.5 m.

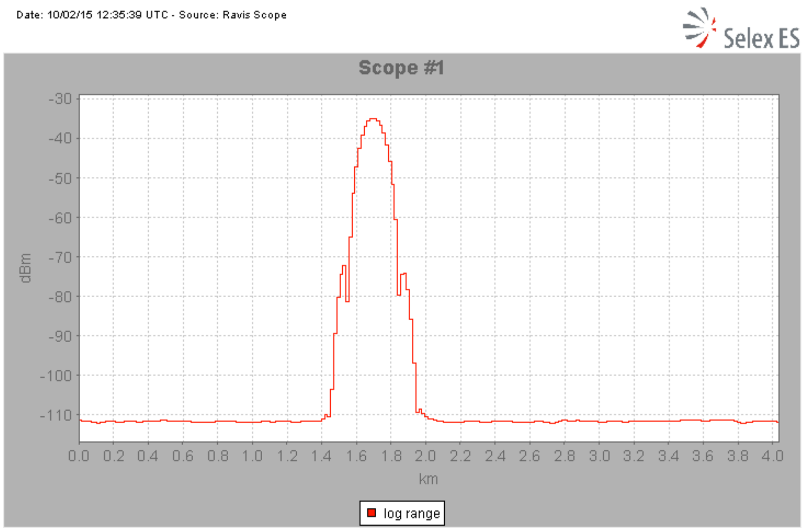

Figure 8: Power versus range for an attenuated TX pulse of width 2.1 µs and a predefined filter of width 0.5MHz.

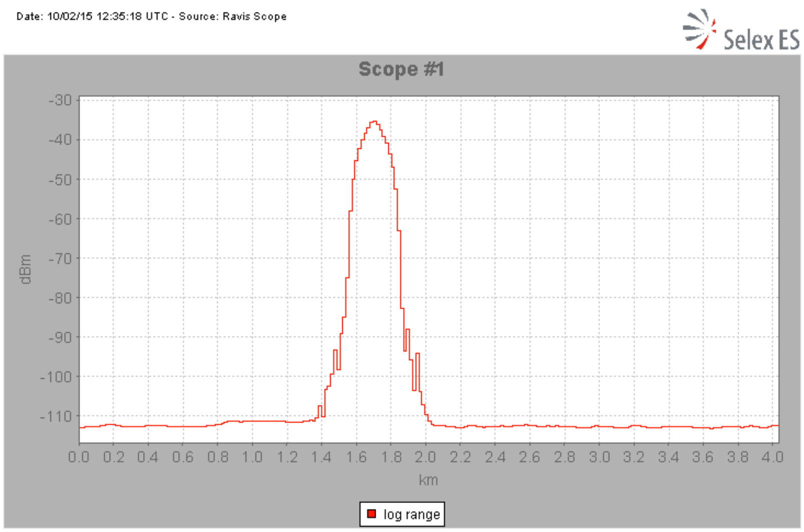

Figure 9: Power versus range for an attenuated TX pulse of width 2.1 µs and a dynamic matched filter.

In both images the signal and noise floor are easily identified. Applying the dynamic matched filter results in less range side lobes and a more pronounced signal peak compared to the static filter. Closer inspection reveals that the noise floor measured with the dynamic filter is decreased by about 0.4 dB.

In contrast to point targets weather signals are obtained from volume targets. To get the related volume target signal power it is therefore necessary to determine the average power of the point target signal, i.e., it is necessary to calculate the area under the signal envelope above the noise floor. The SNR (Signal to Noise Ratio) for weather signals is calculated from the ratio of average signal power to average noise power.

Generally the selection of a matched filter is a compromise between SNR optimization and radial range resolution. The SNR of a weather echo signal increases with decreasing filter bandwidth, whereas the radial range resolution decreases with decreasing filter bandwidth (Doviak and Zrnic 2006, chapter 4.5). The range resolution depends on the TX pulse width and the matched filter. It can be described as the 6 dB range width of the signals shown in Figure 8 respectively Figure 9.

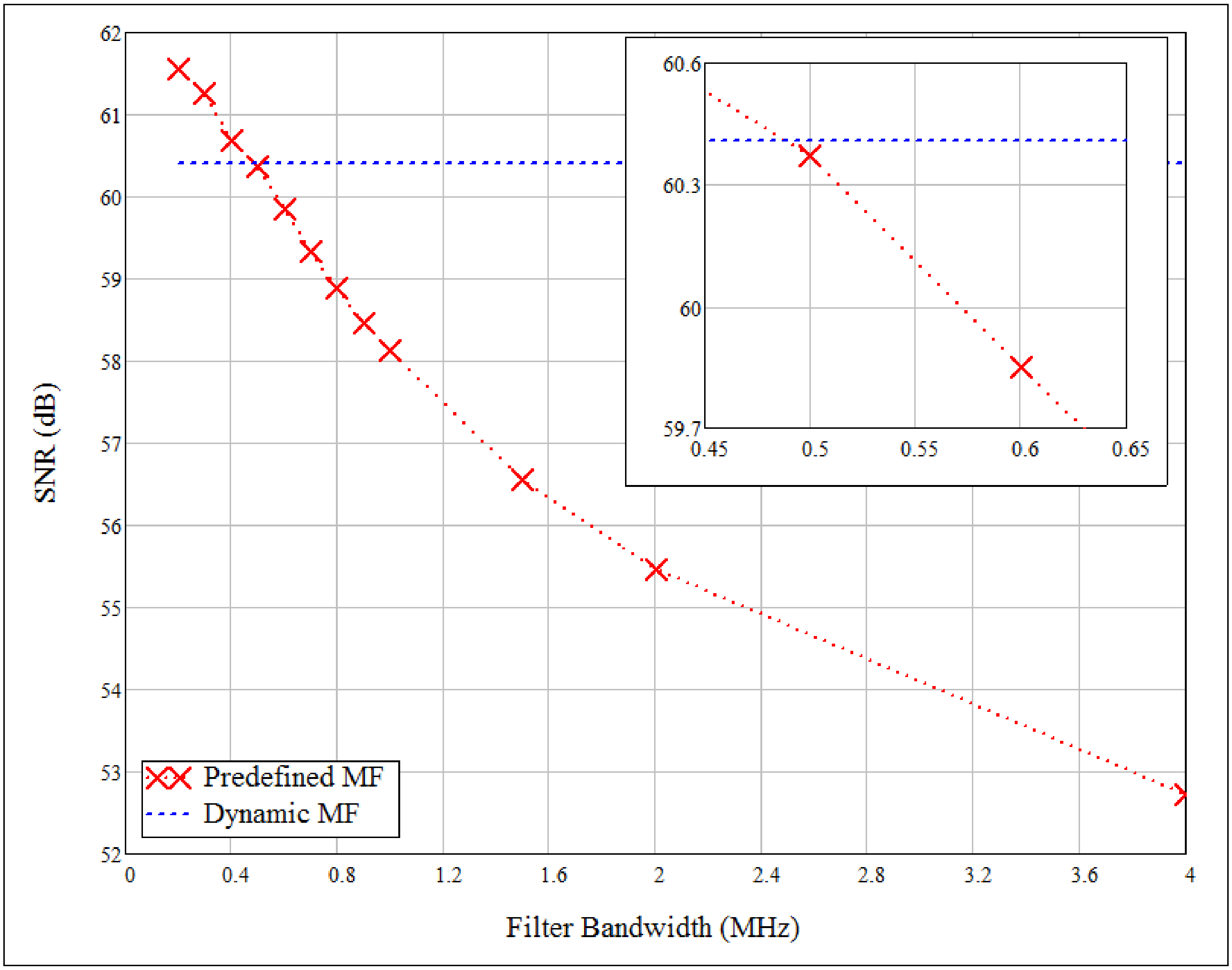

Figure 10: SNR of test signal (red line) versus bandwidth of predefined matched filter. The TX pulse width is 2.1 µs. The SNR using a dynamic matched filter (blue dashed line) is given for comparison. Zoomed area shows data between 0.45 and 0.65 MHz bandwidth.

For the experimental example test setup described, the calculated SNR versus the bandwidth of the predefined matched filters is shown in Figure 10. As expected, the SNR for predefined filters (red line) increases for decreasing filter bandwidth. The SNR using a dynamic matched filter is not related to the bandwidth of the predefined filters and is therefore displayed as a constant line (dashed blue line). The data between 0.45 and 0.65 MHz bandwidth are visualized in a zoomed view for closer inspection. The SNR value for the dynamic matched filter equals the SNR value of a predefined matched filter with a bandwidth of approximately 0.5 MHz.

From the experimental data it was found that the range resolution of the dynamic matched filter is centered in between the range resolution values related to two predefined filters of bandwidth 0.5 and 0.6 MHz. It is therefore not possible to find a filter from this set of predefined matched filters that gives the same range resolution as the dynamic matched filter. With a constraint of equal range resolution and the data given in Figure 10 one can extract an SNR advantage of approximately 0.3 dB for the dynamic matched filter against a hypothetical, predefined filter of bandwidth 0.55 MHz.

5 Summary

A dynamic pulse width scheme supported by a dynamic, pulse-to-pulse matched filter definition scheme has been implemented for Selex magnetron and klystron weather radars. The usage of the dynamic pulse width scheme enables the user to select a larger TX pulse width for given selected range / PRF combinations compared to typical values of static, predefined pulse width values. In consequence this leads to an SNR improvement of up to 6 dB for selected radar range / PRF combinations.

The free selection of a TX pulse width is supported by a pulse-to-pulse based, dynamic matched filter. First tests against a typical set of predefined matched filters reveal an SNR improvement of about 0.3 dB under the constraint of comparable radial range resolution. Transmitter hardware aging effects, which are not covered by predefined filters, might increase this improvement.

6 References

Doviak, Richard J, and Dusan S. Zrnic, 2006, *Doppler Radar and Weather Observations*, reprint of second edition, Dover Publications, 562pp.