

On the Equalization of F-Scan SAR Imaging Performance

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Abstract

This paper introduces optimization techniques to equalize the performance of F-Scan across the swath width. Namely, the processing of a variable power beamwidth, i.e., not restricting to the -6 dB points of the two-way elevation pattern, is considered to equalize the ground range resolution. In addition, the use of nonlinear chirps is analyzed to adjust the illumination time at near and far range, and, hence, to equalize the noise-equivalent sigma zero or the signal-to-noise ratio. Finally, processing aspects are discussed to verify the feasibility of the techniques from an image formation perspective.

1 Introduction

Synthetic aperture radar (SAR) imaging has proven to be of great value to monitor the dynamic processes on Earth [1]. However, at the current state of technology, it takes months, or even years, to map the whole Earth with very high imaging quality. For this reason, substantial efforts have been made by the scientific community and the industry to increase the performance of SAR systems, especially in terms of resolution and coverage.

The current most promising approaches to considerably enhance the well-known trade-off between swath width and azimuth resolution are based on digital beamforming (DBF) techniques [2, 3]. In azimuth, the partitioning of the antenna into multiple receive channels improves this trade-off by a factor given by the number of channels used. Such an approach is already considered for the next generation of the European Space Agency (ESA) missions, such as ROSE-L and Sentinel-1 NG [4, 5]. In elevation, in contrast, a fully-fledged DBF receiver is harder to realize, given the higher complexity and costs that emerge from the requirement of a large number of channels and the onboard beamforming processing [6].

Recently, a beamforming technique in elevation named frequency scanning (F-Scan) was introduced as a middle ground in terms of performance and complexity [7, 8]. It consists of an analogue beam steering approach making use of phase shifters and true-time delay lines to scan over the scene of interest. The main drawback is that the transmit bandwidth is spread across the scene in range, thus reducing the effective bandwidth of each target to only a fraction of the total transmit bandwidth. Therefore, F-Scan is envisaged to frequency bands where a large bandwidth is available, such as in X band and above.

Since the first publication of the application of frequency scanning to SAR imaging, several investigations have been published in the direction of how to design and process an F-Scan acquisition [9, 10, 11, 12], and also how to creatively tailor it to obtain ultra-wide swaths [13, 14, 15].

Typical F-Scan acquisitions aim at obtaining swath widths of about 80 km in Stripmap mode [6], but the swaths

can be as large as 500 km using multiple-elevation-beam (MEB) F-Scan with ScanSAR [15]. These swaths lead to a significant variation of the slant range and the incidence angle, consequently leading to a strong variation of the ground range resolution and the noise-equivalent sigma zero (NESZ). An approach to equalize these parameters by using nonlinear techniques has been introduced in [11], and further developed in [16]. The ideas shown, however, involve having an antenna with an adaptive scanning law (frequency by pointing behavior), which is currently not easily technologically feasible with an F-Scan system. Further alternatives to equalize the resolution and the NESZ have been introduced in [15]. The paper at hand aims at expanding the techniques introduced in [15], namely the processing of a variable power beamwidth, and the use of nonlinear chirps. These techniques are analyzed in more details in this paper, and also processing alternatives are briefly discussed.

The paper is structured as follows. Section 2 recapitulates the important aspects of F-Scan, which are then linked to the optimization techniques described in the subsequent sections. Section 3 analyzes the two optimization techniques discussed in this paper, namely the use of a nonlinear chirp and the processing of a variable power beamwidth. Section 4 discusses important processing aspects that must be taken into account as a consequence of the techniques introduced. Finally, Section 5 concludes the paper, summarizing the main outcomes and findings of this research, and also delineating the outlook for further work.

2 F-Scan Background

The fundamental principle behind F-Scan is an antenna operating with different pointing angles for different frequencies. This effect, known as frequency dispersion, is a common issue in wide band systems using phased arrays [17]. For F-Scan, conversely, this effect is exploited to implement a sort of analogue beam steering, and scan over a wider swath than what is seen by the static antenna footprint on ground. A relatively well-controlled frequency dispersion of interest can be achieved by making

use of phase shifters and time delay lines. The objective is to point toward far range with the first frequencies of the transmit chirp, and near range with the last frequencies. The scan is said to be relatively well-controlled, because the scan starting and ending points can be defined, but the exact pointing by frequency behavior is, although well-known and almost linear, hard to control [16]. A wide swath is then imaged by transmitting a frequency modulated chirp.

One compelling characteristic of F-Scan is the reduced length of the required receive echo window that allows for the imaging of wider swaths. This effect is a direct consequence of starting the transmission at far range, and ending at near. In contrast, the main drawback is the distribution of frequencies across the swath, which inevitably leads to a lower effective bandwidth for each point on ground than the total transmit bandwidth.

Two F-Scan acquisition modes are considered in the analyses presented in this paper. The first mode is a more conventional F-Scan Stripmap imaging scheme with a swath width of 80 km at a ground range and azimuth resolution of 2 m. The second mode is the MEB F-Scan with two-burst ScanSAR, a technique previously introduced in [14] that can achieve a very wide swath of 300 km at a resolution of 5 m. The wide-swath mode has a more significant variation in range and incidence angle, and is, therefore, the one which benefits most from the performance equalization.

The system assumed for the numerical results shown in this paper is the mission proposal HRWS [6]. The main system and imaging parameters are summarized in **Table 1**. For the MEB F-Scan case, the pulse repetition frequencies (PRFs) should be slightly different for each ScanSAR burst, but here we analyze just one of them, as the performance difference is negligible.

Table 1 Summary of the main system and imaging parameters.

Antenna size	1.4 m (El.) / 6.0 m (Az.)
Center frequency	9.8 GHz
Maximum bandwidth	1200 MHz
Orbit height	519 km
Peak transmit power	7680 W
Duty cycle	30 %
Losses	5.7 dB
PRF	2560 Hz
Swath width	80 km / 300 km
Ground range resolution	2 m / 5 m

3 F-Scan Optimizations

The motivation for equalization methods for F-Scan emerge from two main characteristics. First, due to the wide-swath nature of F-Scan imaging, and the spreading

of a large bandwidth across the scene, large variability in performance is expected from near to far range. Second, F-Scan is an imaging scheme which is intrinsically very flexible. One can, to name a few possibilities, adjust the scanning rate, the scanned area, the transmit bandwidth, the waveform and the processing. Putting these two characteristics together, it can be of great benefit to manipulate the flexibility of F-Scan to tailor the performance to be more uniform across the swath.

This section describes two approaches to equalize the imaging performance in F-Scan acquisitions, namely the processing of a variable power beamwidth, and the use of a nonlinear frequency modulated chirp. The fundamentals behind each technique are described, the resulting performance is presented, and the trade-offs are analyzed.

3.1 Variable power beamwidth

Typically in F-Scan, the useful part of the antenna main lobe is assumed to be the region within the -3 dB points of the one-way power pattern in elevation, i.e., within the half-power beamwidth (HPBW). Therefore, during the first processing steps, those frequencies falling outside the HPBW are filtered out. As a consequence, the range resolution is defined by how wide the HPBW is compared to the angular aperture of the whole scene [11]. In terms of ground range resolution, which is the one of interest in detected products, there can be variations of even 100 % or more depending on the swath width.

An additional consideration relevant to the range resolution is that, due to the relatively large fractional bandwidth, the HPBW has a considerable variation across range of up to 12 % in X band. Therefore, having the equalization of the performance in sight, it can be meaningful to not restrict the signal to the HPBW, but to assume a more general variable power beamwidth (VPBW). This allows, to some extent, for a tailored range resolution profile across the scene. The design of the VPBW in this paper aims at equalizing the ground range resolution.

The main trade-off that emerges from processing beyond the HPBW is the degradation of the average signal power, and, as a consequence, of the signal-to-noise ratio (SNR) and the noise-equivalent sigma zero (NESZ). However, the opposite is also true, i.e., processing less than the HPBW would lead to improvements of the SNR, but naturally at the cost of resolution. For the targets at near range, it is of interest to process a larger bandwidth, as the ground range resolution is degraded by the disadvantageous slant-to-ground projection. At the same time, the SNR at near range tends to be better, such that some degradation in exchange for resolution would potentially be acceptable. A similar logic can be derived for far range, where processing less than the HPBW would potentially be meaningful.

The relevant NESZ component in this analysis is given by

$$\frac{\int_{B_{\text{eff}}} \frac{W^2(f)}{|C_{\text{el}}(f, \beta)|^4} df}{\int_{B_{\text{eff}}} W^2(f) df}, \quad (1)$$

where W is the Hamming window with $\alpha = 0.6$, C_{el} is the one-way amplitude pattern in elevation, f is frequency, β

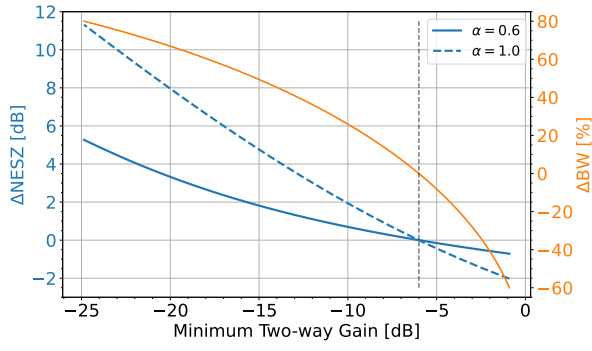


Figure 1 Trade-off between NESZ and bandwidth. The x -axis represents the antenna pattern loss, i.e., how much of the main lobe is processed. The two blue curves represent different Hamming window parameters α . $\alpha = 1$ represents a rectangular window, as if no window were applied. $\alpha = 0.6$ is the parameter considered in the paper.

is look angle, and B_{eff} denotes the effective bandwidth of each target [15]. The term (1) considers the correction of the spectrum by the antenna pattern, to make it rectangular, followed by the application of the Hamming window for good control of the side lobe levels. The trade-off between bandwidth and NESZ is depicted in **Figure 1** having the processing of the HPBW as baseline (vertical dashed line). It is clear that using a Hamming window strongly reduces the NESZ degradation, as it attenuates the increased noise at the edges of the antenna pattern.

Applying this idea to the two scenarios of interest, the bandwidth profile in range is derived from the desired ground range resolution: $B_{\text{eff}} = \frac{c_0}{2\delta_{\text{gr}} \sin \theta_t}$. An additional degree of freedom that emerges is the total transmit bandwidth. With the possibility of processing a variable power beamwidth, one can achieve the same range resolution by transmitting different bandwidths. The selection of the transmit bandwidth can be carried out by minimizing the NESZ across the scene.

The left axis of **Figure 2** depicts the ground range resolu-

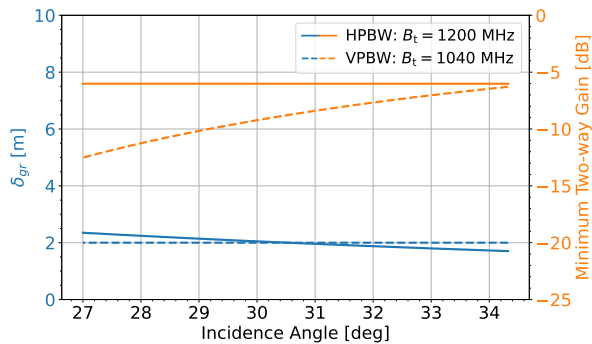
tion for both swaths of interest, considering the traditional processing of the HPBW only (with maximum transmit bandwidth), and of a VPBW with optimized transmit bandwidth. On the right axis, it shows the minimum two-way gains needed to achieve the respective resolutions. For both swaths now it is possible to achieve the target resolutions across the whole swath. This is something not previously possible, even using the full transmit bandwidth. For the 80 km swath, also a 13 % smaller bandwidth can be employed, leading to some NESZ improvement. The behavior of the minimum two-way gain is as expected: using a wider portion of the beamwidth at near range to maximize resolution, and a lower portion at far range to preserve NESZ. Due to the processing of a larger portion of the antenna pattern, the NESZ is degraded at near range, but within acceptable levels. The numerical evaluation of the NESZ is discussed in the next sections.

3.2 Nonlinear chirp

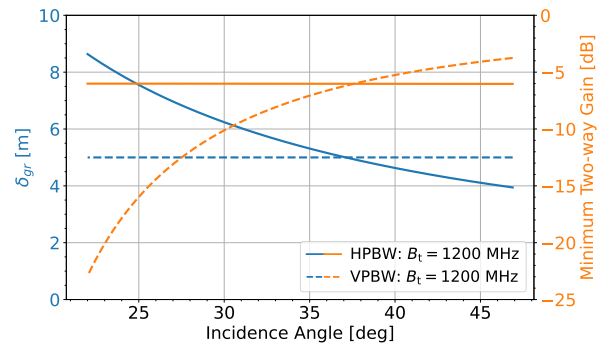
The previous section introduced an effective way of equalizing the ground range resolution across the scene. This section aims at elucidating an approach to equalize the SNR or the NESZ by means of a nonlinear chirp. These metrics are key performance parameters that define the quality of the acquisition, and equalizing them can be of interest to achieve a more uniform product.

Especially for wide swaths, these parameters can exhibit a very significant variation from near to far range due to a number of factors. Namely, the variation in slant range, incidence angle, wavelength, effective bandwidth, illumination time (also known as dwell time) and radar backscatter can lead to an SNR variation of up to 15 dB.

The main idea is to tailor the distribution of the transmitted energy across the swath by adjusting the F-Scan scanning speed on transmit. The pointing by frequency behavior is fixed for a given antenna configuration (delay line and phase shifter setting), i.e., for a certain frequency, the antenna will still point to the same place. However, by changing the local FM rate of the chirp, one can adjust the dwell time of each target, and, therefore, regulate the SNR.

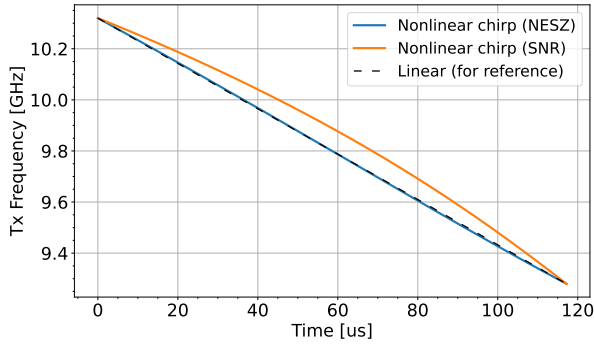


(a) F-Scan Stripmap 80 km

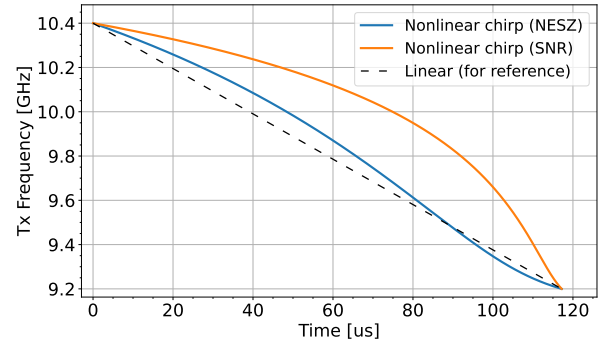


(b) MEB F-Scan 300 km

Figure 2 Ground range resolution and minimum two-way gain profiles achieved by processing either a constant HPBW or a variable power beamwidth. The results are shown for two imaging scenarios. The 80 km F-Scan Stripmap is shown on the left, and the 300 km MEB F-Scan on the right. It is shown that resolutions previously unreachable can be obtained by processing beyond the -6 dB points of the antenna pattern.



(a) F-Scan Stripmap 80 km



(b) MEB F-Scan 300 km

Figure 3 Nonlinear transmit chirps needed to equalize the NESZ and the SNR for the two scenarios of interest. It can be seen that stronger nonlinearities are needed to equalize the SNR and for wider scenes.

Due to the variation of the aforementioned parameters, the NESZ is typically worse at far than at near range. From an SNR perspective, combining the NESZ and the backscatter behaviors, the variation is then even stronger. Therefore, equalizing the SNR by means of a nonlinear chirp requires a stronger nonlinearity of the chirp. For either purposes, the design follows the same procedure of adjusting the dwell time to follow a predefined profile.

Assuming a constant ground range resolution, the dwell time to equalize the NESZ and the SNR need to obey the following conditions respectively:

$$\begin{cases} [t_d(f)]_{\text{NESZ}} \propto \lambda R^3 \text{APC}_{\text{el}} \\ [t_d(f)]_{\text{SNR}} \propto \frac{\lambda R^3 \text{APC}_{\text{el}}}{\sigma_0} \end{cases}, \quad (2)$$

where λ is the wavelength, R is the slant range, APC_{el} is the antenna pattern correction in elevation (taking into account the Hamming window), and σ_0 represents the backscatter coefficient. In the analyses presented in this paper the scenes are assumed to be flat and to have a backscatter profile given by the X-band soil and rock model in HH polarization [18]. In more realistic scenarios with the presence of significant topography and backscatter variations, one can aim at correcting for the average case, but naturally a perfect equalization will not be achieved.

Finally, knowing that the dwell time is proportional to the local FM rate, the transmit chirp can be derived. For the 80 km and the 300 km scenes, the nonlinear transmit chirps to equalize the NESZ and the SNR are derived and depicted in **Figure 3**. The required nonlinearity is more pronounced for the 300 km scenario due to the larger variation of backscatter and range. Down chirps are considered in order to have a wider antenna beam at near range, where a wider bandwidth is needed.

3.3 Discussions

The effect of the derived chirps can be observed by comparing the NESZ and SNR curves for each of the chirps. First, the traditional processing of the HPBW and the use of a linear chirp is considered as the baseline performance. Then, the processing of a variable power beamwidth, but

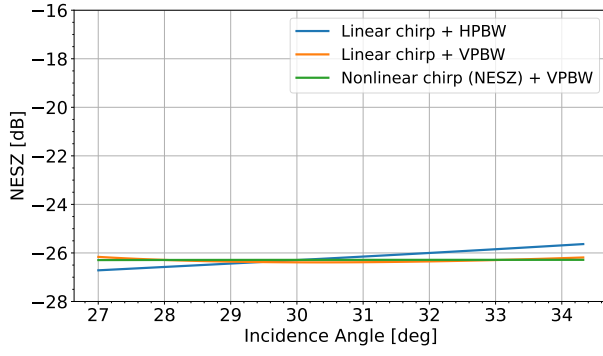
still using a linear chirp is also simulated. Finally, putting the two techniques together, the last scenario of interest is using both VPBW and nonlinear chirps. **Figures 4 and 5** depict the results for the NESZ and the SNR equalization, respectively, for both scenes and all the scenarios aforementioned. The figures show a multitude of interesting characteristics worth discussing in more detail.

Initially, for the 80 km swath case, the effects of these techniques are smaller in amplitude, as the scene is shorter. Nevertheless, still an almost 2 dB improvement of the worst-case SNR can be achieved with the SNR equalizing chirp. The VPBW, as previously discussed, leads to a direct trade of resolution for NESZ. As seen in **Figure 2a**, at near range, the resolution improves from 2.35 m to 2.0 m for a 0.5 dB NESZ degradation. An improvement at far range by the same 0.5 dB in NESZ arises as a consequence of the possibility of using the lower transmit bandwidth.

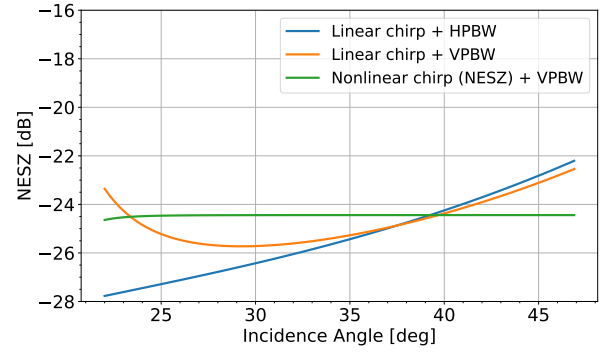
For the 300 km swath case, the effects of the techniques are quite significant, as the scene exhibits more notable performance variation. As it was highlighted by **Figure 2b**, a very relevant and desired resolution improvement from about 8.5 m to 5 m can be obtained at near range. The trade-off can be seen in **Figures 4b and 5b** as a degraded NESZ and SNR by a factor of about 4.5 dB, which, although relevant, is acceptable in comparison to the rest of the swath. The effects of the two nonlinear chirps are also relevant, allowing for additional improvement of the worst-case NESZ and SNR by 2 dB and 4.7 dB, respectively. It is important to bear in mind that a roughly 8 dB backscatter variation is expected from near to far range, and, therefore, even after equalizing the NESZ, still the SNR would show this pronounced variation across the scene. In conclusion, the techniques introduced in this paper are capable of equalizing both the ground range resolution and the NESZ or SNR even for wide swaths, bringing very significant improvements to the worst-case performance.

4 F-Scan Processing

For the techniques introduced, the relevant considerations in the processing and image formation are worth investigating. This section aims at briefly discussing and show-

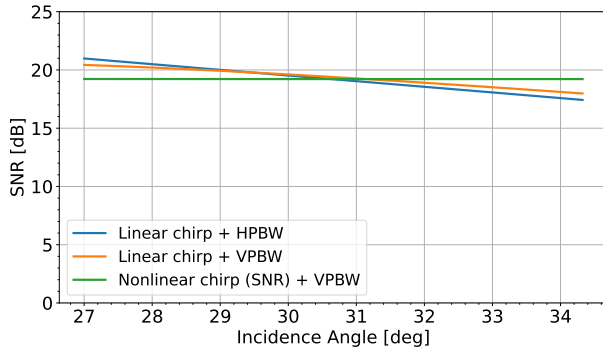


(a) F-Scan Stripmap 80 km

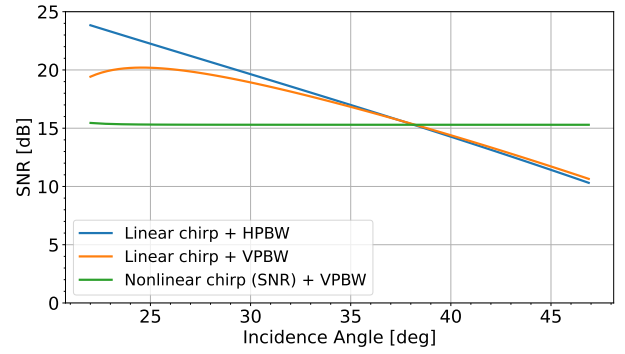


(b) MEB F-Scan 300 km

Figure 4 NESZ achieved by employing VPBW and the nonlinear chirp to equalize NESZ.



(a) F-Scan Stripmap 80 km



(b) MEB F-Scan 300 km

Figure 5 SNR achieved by employing VPBW and the nonlinear chirp to equalize SNR.

casing that the signal processing is not a problem, and can be straightforwardly tackled.

The F-Scan data (one range line) has the intrinsic characteristic of having a variable center frequency across the swath. One of the first suggestions for processing F-Scan data consists in first deramping the echo by a time domain multiplication of the SAR data with a chirp. Next, a low-pass filter is applied, and the signals are whitened (antenna pattern correction) and windowed (for instance with a Hamming window). Finally, the signal can be reramped, and focused [10]. This approach is not suitable for processing variable bandwidths across the swath, as the low-pass filter in frequency leads to a constant bandwidth.

In order to filter the exact bandwidths needed at each region of the scene, a time-variant low-pass filter is needed. The exact implementation can be done in different manners. Here we suggest filtering directly the spectrogram, skipping the deramping step. Likewise, in the same domain, one can generate a map to correct for the antenna pattern, which is also time variant, and apply the Hamming window.

Concerning the focusing, the conventional matched filtering using the replica of the transmit pulse can be applied. This approach also works for the nonlinear chirp, being the main difference the phase profile of the matched filter which differs from that of a linear chirp. An additional effect that arises with nonlinear chirps is that the spectrum

of the targets might no longer be rectangular. However, the nonlinear chirp is seen as (almost) locally linear, so that this effect would just be observable in strongly nonlinear chirps. In any case, this can also be easily corrected, and would ultimately just make the noise become colored.

Figure 6 depicts a 1D simulation of point targets for the 80 km case with a constant ground range resolution of 2 m and a nonlinear chirp for constant SNR. Figure 6a shows the spectrogram of the raw data, highlighting the area to be processed by the lower (blue) and upper (orange) limits. After whitening and applying the Hamming window, the filtered echoes are shown in Figure 6b; the center frequency locus is highlighted by the red line. The variation of the FM rate in range due to the nonlinear chirp is also visible. Finally, Figure 6c shows the focused targets. All the targets achieve the expected resolution and sidelobe ratios, demonstrating that the processing approach is effective.

5 Conclusion

This paper showed that the equalization of the ground range resolution and of the SNR or NESZ is feasible in F-Scan acquisitions. The processing of a variable bandwidth and the employment of nonlinear chirps are shown to be effective ways of achieving these equalizations. For the wide MEB F-Scan mode, significant improvements of the

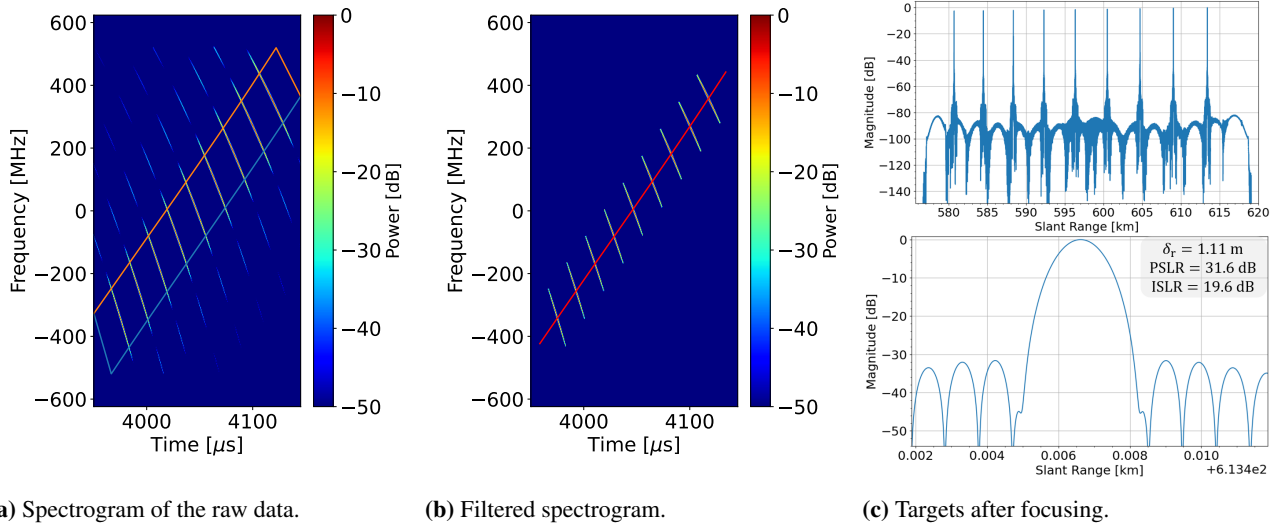


Figure 6 F-Scan point-target simulation with VPBW and nonlinear chirp. The scene has a swath of 80 km at an incidence angle of 27° to 34° . Nine point targets are simulated and processed to a ground range resolution of 2 m.

worst-case performance are obtained, namely the ground range resolution at near range can be improved from 8.5 m to 5 m, and the SNR at far range can be improved by about 5 dB with the adequate nonlinear chirp. The respective processing aspects were discussed and demonstrated to be unproblematic by means of the simulation of point targets.

6 Literature

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