Experimental Demonstration of a Novel End-to-End SAR Range Ambiguity Suppression Method

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***Abstract*—This work demonstrates a novel end-to-end method for suppressing the nadir and the other range ambiguities in Synthetic Aperture Radar (SAR) systems. The proposed method is based on a waveform diversity technique that is locked to the estimated ambiguity number of nadir. Nadir is a point like target and is smeared with Up and Down Chirps (UDC) and extended targets are filtered out with the Azimuth Phase Coding (APC) techniques. The residual nadir echo is suppressed with a novel post processing algorithm. A nadir detection algorithm is developed to eliminate the unwanted signal while preserving the useful signal. The proposed technique is verified by various acquisitions with the current ICEYE SAR satellites. The comparison of the SAR images shows that the proposed technique is promising for range ambiguity suppression.**

***Index Terms*—SAR, Range Ambiguity, Waveform Diversity, Small Satellites**

I. Introduction

A spaceborne Synthetic Aperture Radar (SAR) transmits mostly a chirp pulse and samples the returning echoes coherently to store the data for future processing. An inherent consequence of the pulsed operation of SAR is the range ambiguity that is caused by the echoes of the previous and latter transmitted pulses scattered from undesired regions [1]. In this case, the SAR image is a combination of the unambigous image, the partially focused ambiguous image and the nadir as it is shown in Figure 1.

One way to overcome this problem is to increase the size of the antenna in elevation direction to extract a narrow beamwidth so the received signal backscattered from the ambiguous region is filtered out. However increasing the size of the antenna contradicts with SWAP requirements of small satellites and the demanded wide swath imaging.

Another way to suppress the nadir is to fine tune the PRF so that the nadir echo time is out of the receive window of the radar. In most cases this is impractical and results in additional constraints on PRF that is already optimized to maximize the swath width and minimize the azimuth ambiguity to signal ratio. In addition, no suppression can be achieved with PRF tuning for the ambiguous targets that are out of the blind range region. Instead of applying a fixed PRF, another method is using the staggered SAR system that the ambiguities are located at different ranges for different range lines, as the time distance to the preceding and succeeding pulses continuously varies [2]. The ambiguous energy is therefore incoherently integrated in Doppler domain and as a result smears. Unfortunately, the suppression rate of the range ambiguity is quite limited with the system parameters and additional signal processing algorithms are required to achieve equidistant sampling in azimuth direction.

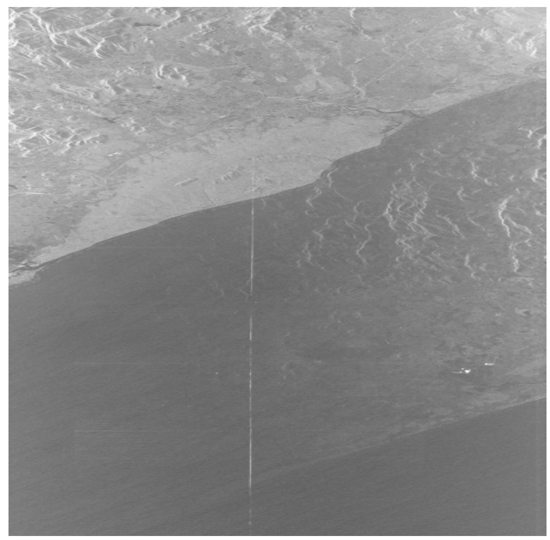


Fig. 1: SAR Image as a combination of the unambigous image (strong in the up and left), ambiguous image (strong in the mid right) and nadir (bright stripe in azimuth direction). Horizontal axis is the range direction. (The width of the image is extended for better visibility.)

The range ambiguity suppression methods are focused on applying waveform diversity [3] and suppressing the residual ambiguity by dual focusing [4], [5]. The basic idea behind waveform diversity is to gain the ability to mark the pulses.

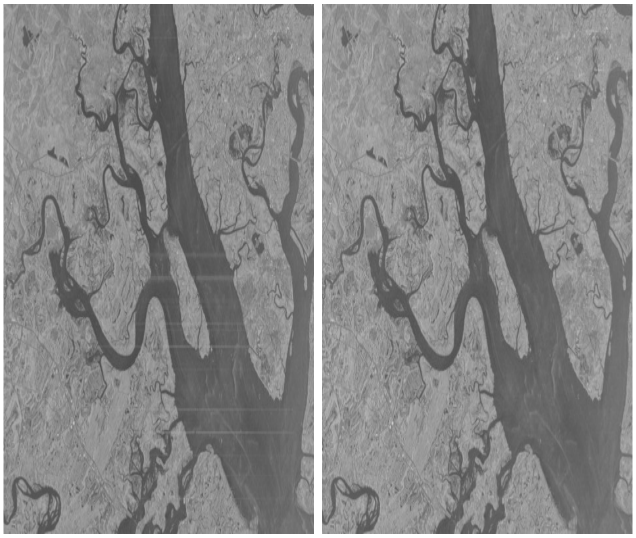


Fig. 2: SAR Images. Left is with the range stripes, Right is without the range stripes

The system must be able to transmit signals with different marks and to identify the scattered signals respectively [6]. There are at least three different waveforms proposed in the literature: Up and Down Chirps, (UDC) [3], Azimuth Phase Coding (APC) [7], [8] and Cyclic Frequency (CF) [9].

The UDC sequence results in an unfocused signal for the ambiguous target so the peak signal power of a point target is theoretically smeared at the level of time bandwidth product. Unfortunately, the energy of the signal is unchanged for an extended target and suppressed only 3dB for a point target. Another waveform diversity method is the APC which the phase of each transmitted chirp is alternated to shift the Doppler bandwidth of unambiguous target signal out of the processing band [8]. The idea is based on setting the PRF high enough such that the unambiguous and ambiguous Doppler bandwidth of the signal is separated. Obviously, this results in narrow swath widths or worse azimuth resolution. CF is a novel method that relies on shifting the transmitted chirp cyclically to generate orthogonal waveforms. However in this case, the required rapid frequency hop results in practical problems like abrupt power drift, complexity in the hardware implementation and the increased calibration burden. SAR systems might have limited memory for storing distinct waveforms, e.g., the TerraSAR-X can store up to eight different waveforms for an acquisition.

There are some recent efforts for combining UDC with the APC to improve the suppression performance. In [10], combinations of a sequence of D, U, D with -$\pi/2$ and U with -$\pi/2$ are discussed in terms of suppression ratio. In [11] UUDD waveform with some arbitrary phase coding is described. None of these waveforms are designed to deal with the suppression of both nadir and range ambiguity. In addition, to the best of our knowledge, these combinations are not assessed with a collection of real data.

In most cases, the nadir suppression that is achieved with UDC waveform diversity is sufficient to extract a high quality SAR image. However the energy is smeared in range direction with a width of twice the pulse length and may result in range stripes for a target that has a strong backscattering as it is shown in Figure 2. Another problem is with the extended targets. The uncompressed summation of adjacent scatterers of an extended target may result in a strong reflectively. In fact, if the total signal power of a specific target is considered, the suppression capability of UDC is only 3dB for a point target and 0dB for an extended one [1]. To overcome this problem post processing algorithms that are based on dual focusing techniques are proposed [5], [12]. In these techniques, raw data is focused according to the ambiguous region. The image of the ambiguous region is then thresholded and complex data is suppressed; so the higher backscattering is assumed to represent ambiguous targets although useful signal may also be lost. The next steps is defocusing back to raw data and then focus the raw data according to the unambiguous region.

To the best of our knowledge, most of the state of the art rely on simulating the range ambiguity case. There is only one very recent work in the literature that uses real SAR data collected specifically to assess the performance of nadir suppression [13]. Unfortunately, this collection is limited to nadir suppression with UDC modulation.

In this work, a combination of UDC and APC is proposed to suppress not only the nadir but also the range ambiguity. For this purpose, the ambiguity number of nadir is estimated and the waveform is defined accordingly. The post processing algorithm steps are the focusing according to the nadir, then detection and at last suppression of the nadir while preserving the useful signal. Instead of defocusing and refocusing, a delta focusing method is proposed to improve the computational efficiency. The experimental results show that the algorithm have promising results for suppressing the range ambiguity. In addition, the ambiguous image is extracted to verify how well the nadir and the ambiguous features are suppressed.

II. Waveform Diversity

In this section, the UDC and APC waveforms will be explained briefly. Simulation results are given to give more insight.

A. UDC

The transmitted signal neglecting the initial phase and power terms can be written as follow:

$$st_U = exp(j\pi\alpha t^2)rect[\frac{t}{T_p}] \tag{1}$$

$$st_D = exp(-j\pi\alpha t^2)rect[\frac{t}{T_p}] \tag{2}$$

where α is the chirp rate, t is the fast time and T_p is the pulse width. The matched filter output of the down chirp with the reference signal of up chirp is [3]

$$r(t) = \frac{1}{\sqrt{2}}[rect(\frac{1}{2T_p})]exp(-j\pi\frac{\alpha}{2}t^2) \tag{3}$$

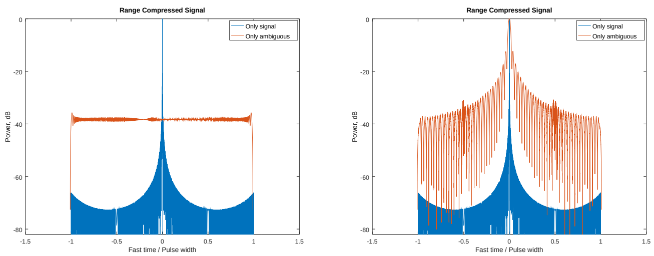


Fig. 3: Range Compressed Data. Blue plot in both images is the unambiguous point target. Red plot in left figure is the point target at the ambiguous region. Red plot in right figure is the extended target (80m long target with point targets at each range sampling spacing) at ambiguous region

and the opposite case has an opposite phase sign. So the focusing according to the unambiguous reference signal makes the ambiguous signal unfocused and still a chirp with twice the pulse width and half the chirp rate. This property is used to improve the computational complexity of the post processing algorithm as it will be described in section III-B. In Figure 3, the matched filter output of the unambiguous point target is compared with the ambiguous point target in the left and ambiguous extended target in the right. The simulation parameters are given in Table I. It is seen that UDC waveform can suppress the point targets by smearing the energy. However if the target backscattering is strong enough, one may expect the range stripes. For the extended target case, UDC may have no contribution depending on the size of the target.

TABLE I: Approximate parameters for Simulation and Data Acquisition

Parameter Name	Value	Unit
Chirp Bandwidth	116	MHz
Sampling Rate	137	MHz
Pulse width	33	us
Slant range to first pixel	687.7	km
Incidence Angle	>35	Degree
PRF	4000	Degree

B. Azimuth Phase Coding

The principle idea of APC is to shift the Doppler spectra of range ambiguity so that it is mitigated during the SAR focusing operation [8]. In order to shift the Doppler spectra for PRF/2, the received signal shall be modulated with: $0, \pi, 0, \pi....$ To achieve this sequence, the transmitted signal shall be $0, 0, \pi, \pi, 0, 0, \pi, \pi, ...$ for odd ambiguities and $0, 0, 0, \pi, 0, 0, 0, \pi, ...$ for an ambiguity number of 2.

C. Proposed Waveform

The waveform is defined to achieve suppression of nadir and decreasing the power of other ambiguous regions. The nadir scattering is a quite bright target within a couple of pixels. As a result, nadir can be defined as a point target (in range direction) that UDC is known to be successful to suppress. The remaining range ambiguous region can be suppressed with the APC. The number of ambiguity, assuming a flat Earth, can be expressed as:

TABLE II: Proposed Waveform Diversity

No	Nadir No	Range Amb No	Waveform Sequence
1	Odd	2	U, D, U+π,D+π,...
2	2	Odd	U, U, D+π,D+π,...
3	4	Odd	U, U, U+π,U+π, D, D, D+π,D+π...

$$N_{amb} = \left\lfloor \frac{R - R_n}{c/2PRI} \right\rfloor \tag{4}$$

where R is the slant range to the far extent of the planned scene, R_n is the estimated range to the ambiguous point, c is the speed of light, PRI is the pulse repetition interval and $\lfloor\rfloor$ is the floor operator. Considering the current ICEYE SAR configuration, the elevation antenna pattern is dominating the received signal power more than the range. Hence, the strongest range ambiguity (other than nadir) is the first number of ambiguity, $N_{amb} = 1$ as the range is closer than the unambiguous one and antenna gain is higher than the other ambiguities. In Table II, the three different waveform sequence are defined. In these sequences, the UDC sequence is defined to suppress the nadir ambiguity while APC is defined to suppress the range ambiguity. The number of ambiguity is limited to 5 and for sure can be increased with the same rationale.

The definition of U and D were already given in Equations 1 and 2. For the sake of completeness the definition of U+π and D+π can be given as:

$$st_{U_\pi} = exp(j\pi\alpha t^2 + j\pi)rect[\frac{t}{T_p}]$$
$$st_{D_\pi} = exp(-j\pi\alpha t^2 + j\pi)rect[\frac{t}{T_p}]$$

III. Residue Range Ambiguity Suppression

The post processing algorithm flow is presented in Figure 4 by a comparison with the state of the art. There are two improvements of the proposed flow. The first is that instead of dual focusing that includes the inverse focusing and refocusing, a method that is called the 'delta focusing' is defined. The basic idea is that after focusing the SAR raw data according to the nadir parameters, data is still a SAR data with a different configuration and can be focused with the proper parameters to extract the unambiguous SAR image. As a result, the computational burden is approximately halved. The second advantage of the proposed algorithm is that the nadir is detected and suppressed so that the useful signal that is not within the nadir region is preserved and, in addition, the plot of nadir is extracted. The details of the nadir detection and delta focusing are given in the following sections.

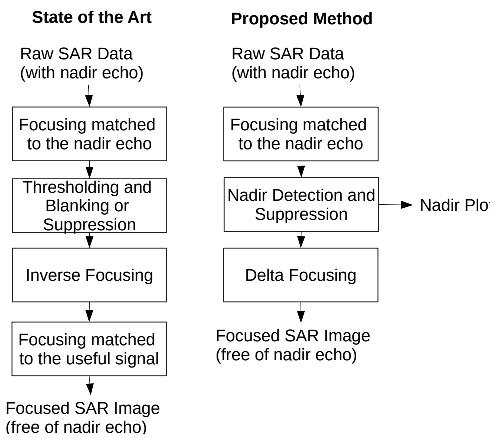


Fig. 4: Algorithm flows of state of the art [4], [5] and the proposed method

A. Nadir Detection

The SAR image that is focused according to the nadir is extracted. There are two major features of the nadir within an image. The signal power is high and the range is deviating within a narrow region in azimuth time and even mostly in the same range bin for successive azimuth bins. In Figure 5, the detection plots of a SAR image is presented. It is clearly seen that nadir range bins are between [6200 - 6500] while plots outside of this region maybe useful signal. In order to detect the nadir, a range sliding window is applied to extract the ratio of the cell under test to the background. This ratio is summed up for each range bin to detect the nadir as it is presented in Figure 5(b).

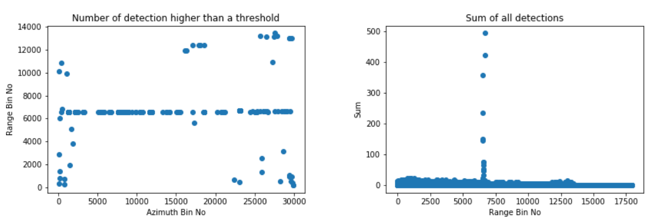


Fig. 5: Left: Detection in Nadir focused image, Right: Sum of Signal Power vs Range Bin

Nadir detection has two advantages: The first is that it is less likely to suppress the useful signal. Second is that above the ground altitude of the satellite is measured and this can be used for radar altimetry purpose. Last step is to suppress the nadir by dividing data with the time bandwidth product.

B. Delta Focusing

In this section, the mathematical background for the proposed refocusing algorithm will be explained. Here the algorithm is derived for the low squint case and can be generalized to the more general case. The baseband received signal for the unambiguous target can be approximated by [14]:

$$s_0(t,\eta) = A_0\omega_r(t - \frac{2R(\eta)}{c})\omega_a(\eta-\eta_c)exp(-j\frac{4\pi R_0}{\lambda}) \\ exp(-j\pi K_a\eta^2)exp(j\pi\alpha t^2)rect[\frac{t-\frac{2R(\eta)}{c}}{T_p}]$$

where ω_r and ω_a represents the antenna pattern in azimuth and elevation respectively, η is the slow time, K_a is the azimuth chirp rate, $R(\eta)$ is the range to the target, R_0 is the minimum range to the target, λ is the wavelength and c is the speed of light.

The first step for focusing according to the ambiguous chirp rate doubles the pulsewidth while halves the chirp rate for the unambiguous signal. After range compression and Fourier Transform in azimuth direction; Range Doppler data can be expressed as:

$$s_{rc}(t,f_\eta) = A_0A_1\omega_r(t - \frac{2R(f_\eta)}{c})\omega_a(f_\eta - f_{\eta c})exp(-j\frac{4\pi R_0}{\lambda}) \\ exp(-j\pi\frac{f_\eta^2}{K_a})exp(j\pi\frac{\alpha}{2}t^2)rect[\frac{t-\frac{2R(f_\eta)}{c}}{2T_p}]$$

The Range Cell Migration (RCM) term in the range envelop is expressed according to the nadir distance:

$$\Delta R(f_\eta, R_n) = \frac{\lambda^2 R_n {f_\eta}^2}{8{v_r}^2} \\ = \Delta R(f_\eta, R_0)\Delta R(f_\eta, -N_{amb} * \frac{c}{2PRF})$$

RCM can be corrected in Range Fourier Domain with a linear phase multiplication:

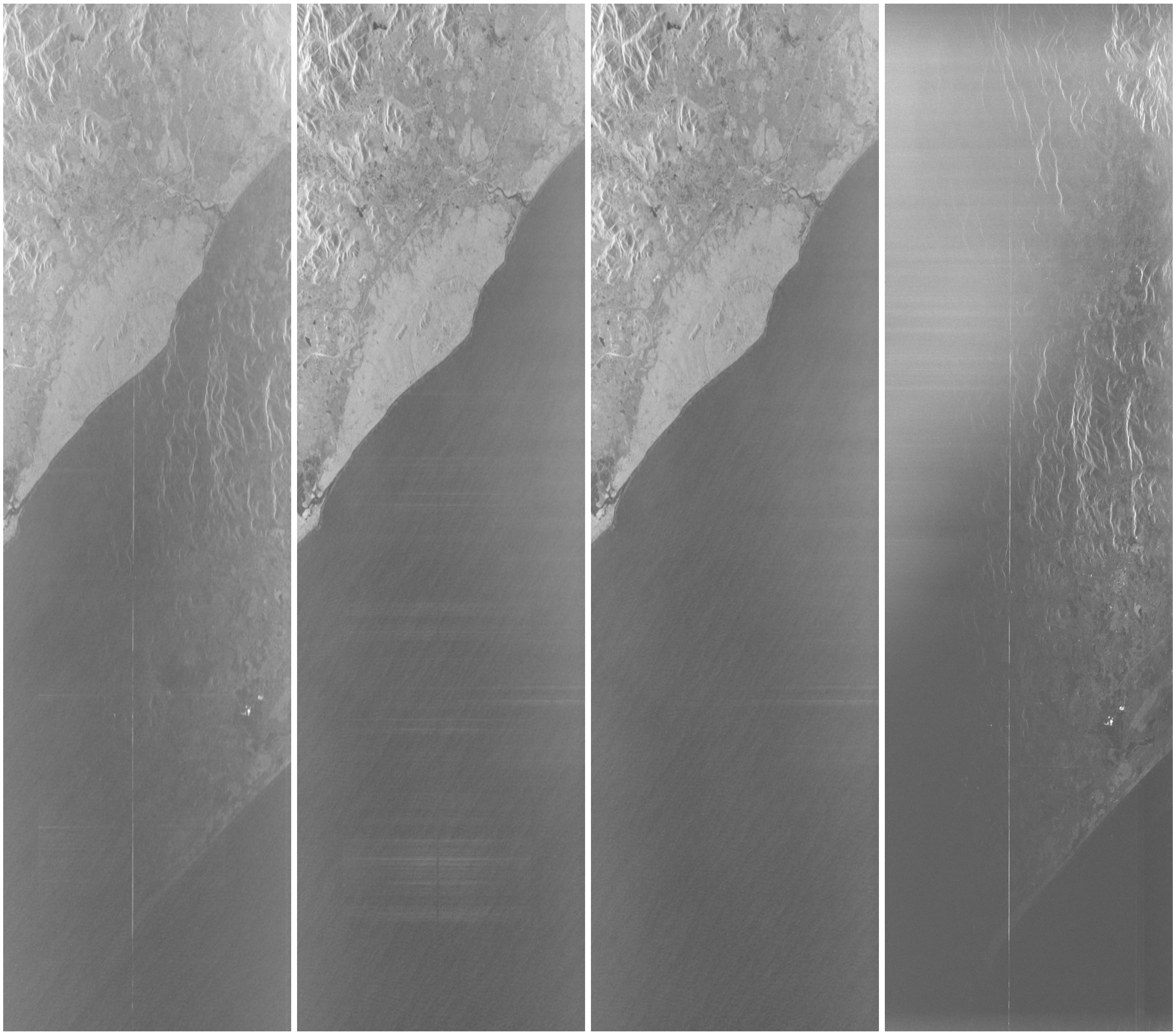
$$G_{rcmc}(f_t) = exp(j\frac{4\pi f_t}{c}\Delta R(f_\eta, R_n)) \quad (5)$$

After RCMC the signal can be written as follows:

$$s_{rcmc}(t,f_\eta) = A_0A_1\omega_r(t - \frac{2\Delta R(f_\eta, -N_{amb} * \frac{c}{2PRF})}{c}) \\ \omega_a(f_\eta - f_{\eta c})exp(-j\frac{4\pi R_0}{\lambda}) \\ exp(-j\pi\frac{f_\eta^2}{K_a})exp(j\pi\frac{\alpha}{2}t^2) \\ rect[\frac{t-\frac{2R(f_\eta)}{c}}{2T_p}]$$

Last step is the azimuth compression with respect to the nadir range. In this case the azimuth chirp rate can be expressed as:

$$K_{a,N_{amb}} = K_a\frac{R_0}{R_0 - N_{amb} * \frac{c}{2PRF}} \quad (6)$$



(a) Only Up Chirp (b) Waveform Diversity (c) After Nadir Suppression (d) Ambiguous Image

Fig. 6: SAR images. The horizontal and vertical axes represent slant range and azimuth, respectively.

Finally extracted image of an unambiguous target after azimuth compression can be written as:

$$
\begin{aligned}
s_{im,amb}(t,\eta) = A_0 A_1 \omega_r (t - \frac{2\Delta R(R0, -N_{amb} * \frac{c}{2PRF})}{c}) \\
\omega_a(\eta - \eta_c) exp(-j\frac{4\pi R_0}{\lambda}) \\
exp(-j\pi K_a \frac{2R_0 PRF}{cN_{amb}} t^2) exp(j\pi \frac{\alpha}{2} t^2) \\
rect[\frac{t - \frac{2R(f_\eta)}{c}}{2T_p}]
\end{aligned}
$$

As a result, the unmabiguous signal after focused according to the ambiguous parameters is a SAR raw data that can be considered as collected with a different configuration and the signal is not needed to be defocused and then refocused

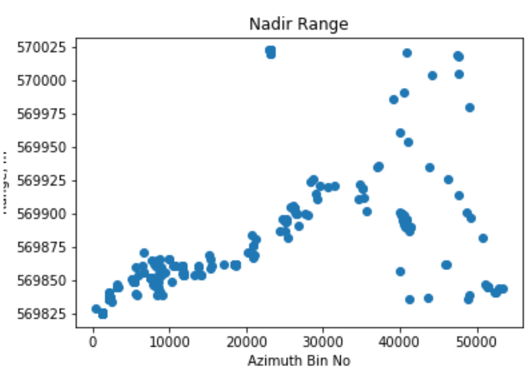


Fig. 7: Nadir range detection

but instead can be directly focused to extract the unambigous image. That is why this method is named as "Delta Focusing".

IV. Results

To verify the proposed range ambiguity suppression method, a series of SAR acquisition is performed by using ICEYE satellites with the parameters in Table I. The scene includes a calm water surface that is expected to coincide with the strong nadir echo and ambiguous region return and a mountainous area with strong scatterers, as illustrated in Figure 6)(a). SAR image is collected without waveform diversity to assure the existence of the expected features. The mission planning is done to obtain a nadir line nearly the middle of the swath. Incidence angle is selected as 37.3 degree that is higher than the ICEYE standards to guarantee to observe an exaggerated range ambiguity. In this image, it is clear that unambiguous signal, nadir and ambiguous signal are all included within the SAR data. The ambiguity number of nadir is 5. Waveform diversity according to Table II is applied for the same scene and resulting SAR image is presented in Figure 6)(b). As it is seen, the nadir and the range ambiguous region is substantially removed. The quality of the image is much more superior than the previous one. However, there are some range stripes where the nadir echo is strong.

Post processing is applied to suppress the residual nadir ambiguity like the range stripes. Firstly the nadir is detected as it is presented in 7. The estimated nadir was 570005.8m that is very close to the measured. The strong scatterers labeled as nadir are suppressed by simply dividing the sample to the time-bandwidth product, then nadir free raw data is focused to extract the unambiguous image. In Figure 6(c), the result of both the waveform diversity and the post processing are presented. It is clear that those range stripes in the middle of the image are related with nadir and fully suppressed.

For some reason, the two acquisitions that are with and without waveform diversity may not be identical and a fortunate collection may not be corrupted by the nadir and/or the range ambiguity for the data collected with waveform diversity. To be sure that raw data include the ambiguity, raw data is focused according to the ambiguous region. The ambiguity number for the dominant ambiguity is 1. This value is set first intuitively and then the image that is focused to this ambiguity number is extracted and the features on the image is verified with the Google Earth to validate the ambiguity number. This image is the most right one in Figure 6(d). In this case, as it is seen, the unambiguous region is unfocused while the ambiguous region is focused. This image also can be used to assess the performance of the proposed method.

V. Conclusion

In this work, a novel range ambiguity suppression method is proposed. Waveform diversity is tuned to the estimated nadir. A novel post processing method is developed. The nadir is detected and suppressed to retain the useful signal that is distributed to the whole scene as is. A delta focusing method is proposed to halve the computational burden comparing with the dual focusing. The current ICEYE SAR systems are used to acquire various data with waveform diversity. The results are quite promising.

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