Comparison of range migration correction algorithms for range-Doppler processing

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Comparison of range migration correction algorithms for range-Doppler processing

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Abstract. The next generation digital radars are able to provide high-range resolution by the advancement of radar hardware technologies. These systems take advantage of coherent integration and Doppler processing technique to increase the target’s signal-to-noise ratio. Due to the high-range resolution (small range cells) and fast target motion, a target migrates through multiple range cells within a coherent processing interval. Range cell migration (also known as range walk) occurs and degrades the coherent integration gain. There are many approaches in the literature to correct these unavoidable effects and focus the target in the range-Doppler domain. We demonstrate some of these methods on an operational frequency-modulated continuous-wave (FMCW) radar and point out practical issues in the application. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JRS.11.036023]

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1 Introduction

In range-Doppler processing, the target is assumed to stay in the same range bin during the coherent processing interval (CPI), and a Fourier transform along the slow-time dimension is used to focus the target signature. Range migration occurs when the target passes into multiple range bins over the CPI. As a result, the Doppler signature of a target smears (also known as blurring) in both the range and Doppler domains, which is undesirable. The effect of moving targets on a range-Doppler map is discussed in detail in Ref. 1.

There are different methods available in the literature to address the range cell migration problem in pulse-Doppler radars. The basic method for correcting the range walk is compensation by range shifting, which assumes that there is a single target and its velocity is known. In practice, there might be multiple targets (with unknown velocities) present in the area of interest. To overcome the multiple target issue, a search for each range gate and each speed hypothesis is introduced in Ref. 2.

A well-known method—the Keystone algorithm—was first introduced to focus moving targets in synthetic-aperture radar (SAR) images.3 It was then extended to focus targets in pulse-Doppler radar4,5 and ultrawideband radar.6 Unlike the compensation by the range shifting method, the Keystone method does not depend on any prior knowledge regarding the number of targets and target velocities. The principle of the transformation consists of one-dimensional interpolation of the received signal in the slow-time domain to remove the cross-coupling terms created by the range walk (Keystone is the interpolation version of coherent integration introduced in Ref. 2). Li et al.7 showed how the Keystone algorithm can be used to focus a target in wideband pulse-Doppler radar, when the target velocity is ambiguous. A Keystone-like algorithm in the slow-frequency (Doppler) domain was proposed for fast coherent integration (Fast-CI) of targets.8 Practical limits of Keystone transform and extension to second-order corrections are discussed in Ref. 9.

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It has been known that the Keystone algorithm suffers from the effects of interpolation. The first and last few slow-time samples cannot be fully interpolated because the interpolation filter impulse response extends beyond the ends of the available data. This will result in a slight loss of Doppler resolution that will become more severe for longer interpolation filters. Moreover, depending on the application domain (such as the slow-frequency domain), interpolation errors may yield ghost targets and requires extensive oversampling to avoid these unwanted effects.

An alternative focusing algorithm that does not use any interpolation in slow-time, but instead uses convolution (or frequency domain multiplication) is proposed in Ref. 10. A back projection based coherent summation algorithm for pulse-Doppler radar to focus the moving target signature is proposed in Ref. 1.

Unfortunately, most of these methods1,4,5,8 are illustrated by simulations and application of these methods to a real radar data sets has not been presented or not been discussed in detail. This paper (which is an extension of our previous work in Ref. 1) demonstrates the application of a range-Doppler back-focusing algorithm1 for the first time in a real radar data set. Moreover, we analyze other range cell migration methods and discuss their pros and cons in real-world applications.

The rest of this paper is as follows. First, a brief introduction to range cell migration is provided together with the signal model and Doppler processing. Following, different range-cell migration algorithms are revisited. In Sec. 4, the application of a range cell migration algorithm to operational radar is demonstrated. We conclude our paper with a discussion of the advantages and disadvantages of each method.

2 Background

In this section, we briefly mention the signal model and Doppler processing after discussing under which conditions the range cell migration occurs.

2.1 Range Cell Migration

The combination of three factors, target line-of-sight velocity \( \nu \), range resolution \( \delta r \), and the coherent processing time \( T_c \), contributes to the degradation of the coherent integration gain. To achieve a well-focused target signature in Doppler processing, a target must stay in the same range bin during the CPI. In another word, a target range change \( \nu T_c \) within a CPI should be less than one range cell resolution

\[
\nu T_c < \delta r, \tag{1}
\]

to avoid range cell migration.

Note that this results in limiting either the range resolution or Doppler resolution of the radar.5 Condition (1) usually is not satisfied in practice. As in a wideband pulse-Doppler radar, target range walk is unavoidable during a CPI due to the high-range resolution (small \( \delta r \)) of the system. Therefore, range cell migration compensation is needed to achieve a better coherent integration gain along with a well-focused target signature.

2.2 Signal Model and Doppler Processing

Let a Doppler radar transmits pulses with a pulse repetition time \( T \) at a carrier frequency \( f_c \), to detect a point target with a constant line-of-sight velocity \( \nu \) at an initial range \( R_0 \). If the fast-time matched filter output of this system is defined as \( y(t) \), the pulse-compressed signal on the \( k \)'th pulse is in the form of

\[
s(t_f, t_s) = \gamma y(t_f, \tau) e^{-j2\pi f_c \tau}, \tag{2}
\]

where \( \gamma \) is the complex attenuation due to propagation and the round trip delay is

\[
\tau = 2(R_0 - \nu t_s)/c, \tag{3}
\]
where $c$ is the speed of light. Note that the received signal for the $k$’th pulse $s(t_f, t_s)$ is two-dimensional (2-D), namely “fast-time” (range) and “slow time” domains where $t_f = t - kT$ and $t_s = kT$. In traditional-Doppler processing, Fourier transform is applied in the slow-time domain to achieve range-Doppler (or velocity) information of the target

$$s(t_f, t_s) \xrightarrow{\text{slow-time FFT}} s(t_f, f_d).$$

To achieve range–velocity information of targets, Doppler frequency $f_d$ needs to be converted into the velocity information $\bar{v} = c/(4Tf_d)$, which is bounded by

$$-\frac{c}{4Tf_c} \leq \bar{v} \leq \frac{c}{4Tf_c}.$$  

These limits are also known as the unambiguous velocity interval. Special attention (unfolding and correction) is needed to focus the targets out of this ambiguity limit.

### 3 Range Cell Migration Correction

In this section, we give a brief overview of different methods that can be used to correct range cell migration in pulse-Doppler radars.

#### 3.1 Keystone Formatting

It has been shown by Perry et al. that there is a direct relationship between the target’s Doppler and linear range migration. The first step in removing the linear range migration is to transform the received signal $s(t_f, t_s)$ into the fast-frequency/slow-time domain

$$s(t_f, t_s) \xrightarrow{\text{fast-time FFT}} s(f, t_s).$$

Then, the time axis for each frequency is rescaled by the transform

$$t_s = \alpha \tau \text{ where } \alpha = \frac{f_c}{f + f_c},$$

(7)

to remove the linear range migration. Finally, the corrected signal can be represented as

$$s(f, \tau) = s(f, t_s)|_{t_s = \alpha \tau}.$$  

(8)

Range migration correction using Keystone formatting can still be done even if the data are undersampled. Basically, an extension of the Keystone algorithm makes it possible to focus a target even if its velocity is ambiguous. If the ambiguity region (number of folds) that needs to be corrected is $F$, then the under-sampled data $s(f, \tau)$ are modified for foldover correction as

$$s_c(f, \tau) = \sum_F s(f, \tau)e^{i2\pi F \tau/T}.$$  

(9)

Note that the foldover correction can also be applied before the Keystone formatting. The transform in Eq. (7) results in reversed isosceles trapezoid spectral shapes as shown in Fig. 1, so-called Keystone transform. Since range-Doppler information of targets is embedded in fast-time $t_f$ and Doppler $f_d$ domains, such as shown in Eq. (4), one may apply the Fourier transform in both domains (2-D Fourier transform)

$$s_c(f, \tau) \xrightarrow{2\text{-D FFT}} s(t_f, \hat{f}_d).$$

(10)

to achieve a range-Doppler map of the data, which can be written explicitly as
3.2 Fast Coherent Integration

A Keystone-like algorithm in the slow-frequency domain was proposed by Bidon et al. for Fast-CI of targets; it consists of four main steps.

First, the fast-frequency/slow-time signal \( s(f, t_s) \) is upsampled in the slow-time domain by \( F \) to repeat the folded signal spectrum. Then, a slow time Fourier transform is applied to achieve the fast-frequency/slow-frequency signal \( s(f, f_s) \). Note that \( f_s \) is the repeated version of \( f_d \) in the frequency domain due to the upsampling. If the number of folds \( F = 0 \), then \( f_s = f_d \) such as that in Eq. (4).

The next step of the algorithm aims at realigning the target spectrum in the slow-frequency dimension. Thus, an inverse Keystone transform

\[
\beta = \left( 1 + \frac{B}{K f_c} \right),
\]

is applied to the slow-frequency axis regardless of the target features. In this formulation, \( K \) and \( B \) represent the number of range bins and the bandwidth of the transmit waveform, respectively. Finally, after applying the inverse-Keystone transform Eq. (12) to the fast-frequency/slow-frequency signal \( s(f, f_s) \), the corrected signal in the fast-frequency/slow-frequency domain can be shown as

\[
s(f, f_d) = s(f, f_s)|_{f_s = \beta f_d},
\]

The last step of the algorithm is just an inverse Fourier transform in the fast-frequency domain

\[
s(f, f_d) \overset{\text{fast-time IFFT}}{\rightarrow} s(t_f, f_d),
\]

to achieve the range-Doppler map of the data.

The application of Fast-CI to the real data has been demonstrated in Ref. 11, however, its comparison with other methods and practical limits are not discussed.

3.3 Range-Doppler Back-Focusing

We introduce an alternative focusing method to correct range cell migration by using the backprojection algorithm in Ref. 1. The backprojection-based focusing algorithm is inspired by the backprojection algorithm that has been used in different fields, such as tomographic and synthetic aperture radar imaging.

Backprojection and back-focusing are similar, but are two different methods whose aims and outputs are different. In radar fields, the backprojection technique focuses the stationary targets for SAR imaging, whereas the proposed “back-focusing” method focuses only the moving target in the range-Doppler domain. In other words, the backprojection corrects the range cell migration due to the motion of the platform for SAR imaging and focus of the stationary target. On the contrary, the back-focusing method corrects the range cell migration due to the motion of targets and the focus of any nonstationary targets.
In the back-focusing approach, contribution of data to every range bin is computed under the assumption of point targets with constant line-of-sight velocities and is appropriately compensated. This method is similar to compensation by the range shifting method except this method does not need any prior information such as the number of targets and target velocities.

For every pulse and all range gates over a span of potential target velocities $\nu_s$, the time delays are given as

$$t_k = \frac{2(R_0 - k\nu_s T)}{c}, \quad (15)$$

where $k$ is the pulse index and $R_0$ is the initial range of the target. Motion compensation and phase correction are applied to the pulse-compressed received signal [Eq. (2)] on each pulse, such that the compensated signal $s_k(t_f, t_s)$ on the $k$'th pulse is

$$s_k(t_f, t_s) = s(t_f, t_s + t_k) e^{j2\pi f_c t_k}. \quad (16)$$

The summation over all compensated pulses is then computed to create the focused velocity cut for each selected velocity $\nu_s$ according to

$$d(t_f, \nu_s) = \sum_k s_k(t_f, t_s). \quad (17)$$

The summation of all pulses forms a peak when the search velocity ($\nu_s$) matches the actual target line-of-sight velocity ($\nu$). This procedure is repeated for all search velocities $\nu_s$ to create the full range–velocity map. The selection of the range and velocity search vectors determines the final range-Doppler map coverage and grid spacing. The bounds of the velocity search vector can be set by the user. Thus, this method is able to focus velocities from outside the ambiguity limits without any modification, which is similar to the technique used for target detection in Ref. 2. Moreover, a modified version of this method is able to correct the second-order errors due to the high tangential velocity, which is not discussed in this paper.

4 Experiment

This section mainly explains the data collection process and demonstrates the application of four different methods on an operational radar system.

4.1 PARSAX Radar

Polarimetric Agile Radar in the S- and X-bands, also known as PARSAX (shown in Fig. 2), is an agile full polarimetric continuous wave (CW) S-band (3.315 GHz) radar, which is operated by Delft University of Technology (TU Delft). The analog-to-digital conversion on intermediate frequency (IF) provides a wider dynamic range, linearity, and freedom to use any pairs of orthogonal waveforms with different durations and bandwidths up to 100 MHz. The IF sampling is done at 400 MHz with 14-bit resolution; the embedded fast field-programmable gate array (FPGA)-based digital processing board with a large memory buffer and multiple graphics processing units (GPUs) in an interconnected PC give the possibility to implement complicated real-time algorithms for signal and data processing. In ground moving target indication mode (such as the data presented here), it uses a pair of synchronous linear frequency modulated continuous signals with opposite frequency excursions of (up to) 50 MHz and duration (sweep time) of 1 ms. The standard deramping processing technique provides range profiles up to 15 km with a resolution around 3 m for further Doppler processing.\(^{12,13}\)

4.2 Data Collection

The aforementioned data were collected February 6, 2017, when PARSAX was oriented through the A13 Motorway (near Delft in the Netherlands) as shown in Fig. 3. The bandwidth of the received signal after preprocessing is 45 MHz, which yields a 3.33-m range resolution. Pulse
repetition time is 1 ms, thus the ambiguous velocity is $22.6244 \text{ m/s}$. Only the horizontal polarization (horizontal transmit, horizontal receive) data are illustrated in this figure.

It should be noted that PARSAX is not a pulse-Doppler, but is a frequency-modulated continuous-wave (FMCW) system that can directly sample data in the fast-frequency/slow-time domain. Thus, it does not need any fast-time fast Fourier transform (FFT) processing, such as in Eq. (6), to achieve fast-frequency data.

### 5 Results

Four different methods, FFT, Keystone algorithm, Fast-CI, and backprojection range-Doppler focusing (back-focusing), are applied to the collected data to achieve range–velocity plots.
The velocity of interest is set to $\sim 45$ m/s (two times the unambiguous velocity). Thus, the unfolding operation is applied where applicable. For fair comparison, data are upsampled by 2 (to address the folding) in the slow-time domain for all cases. No additional zero padding is applied. Thus, the Doppler resolution is $0.0442$ m/s, whereas the range resolution is $3.33$ m. It should be noted that upsampling is used to focus the targets whose velocities are greater than the maximum detectable unambiguous velocity. Unfolding operation does not recover any lost information by itself, but with the help of range cell migration, a better focused target signature can be achieved in the correct Nyquist zone.

Consecutive 2048 pulses ($\sim 2$ s of data) are used to form the range–velocity plots that are shown in Fig. 4. However, the PARSAX’s radar can process up to 512 pulses in real time. In our figures, 2048 pulses are used to clearly illustrate the severe effect of range walk.

5.1 Comparison and Discussion

As seen from Fig. 4, basic FFT processing cannot provide any extra information for a folded spectrum where most of the moving targets are present. Instead, FFT processing results in a blurred signature of targets with incorrect velocity information. To solve the ambiguity problem in FFT processing, pulse-Doppler radar system typically uses PRF stagger, which is not considered here since PARSAX is an FMCW radar. Keystone, Fast-CI, and back-focusing algorithms are able to focus moving targets even though they are in the second Nyquist folding zone. It is obvious that there are still unfocused target signatures in the first Nyquist zone. These methods do not solve the ambiguities, but can focus the multiple targets in different ambiguity regions without knowing the targets’ correct velocities (without solving the ambiguity).

To thoroughly research the success of each method in focusing, we concentrate on the finer details in the range–velocity map. For instance, Fig. 5 shows a special case when a target’s velocity is approximately equal to the maximum unambiguous velocity, such as $v_T \approx -c/(4T f_c)$. As seen from this figure, the Keystone algorithm has difficulty in focusing the target at the edge of the spectrum due to the discontinuities in frequency, whereas the Fast-CI and back-focusing algorithms successfully focus the target signature.

In this specific example (Fig. 5), target location is changed $\sim 46$ m during the CPI (which can easily be seen in this figure as range walk). Note that there might be a small bias between the range information of the focused target for each algorithm. This is due to the fact that each algorithm has a different focus point. It is possible to focus a target back to its initial, middle, and final positions in the CPI. During the course of this experiment, it has also been observed that Fast-CI’s results are distorted by ghost targets, such as the case shown in Figs. 5 and 6. Ghost targets and unwanted effects of interpolation are well known and are reported in Ref. 8. To
Fig. 5 Zoomed range-Doppler plot of a special case where target velocity is approximately equal to the radar maximum unambiguous velocity. Keystone algorithm is unsuccessful focusing the target.

Fig. 6 Zoomed range-Doppler plot where ghost targets appear in Fast-CI plot. Top left figure points out the range walk as it appears in FFT processing where the velocity of target is incorrect due to the foldover.
overcome the unwanted effects of interpolation, zero-padding the slow-time signal at least 4 times is suggested. Note that zero-padding factor will improve the interpolation accuracy, however, it increases the number of slow-frequency points, hence it will increase the computational complexity of the algorithm.

The back-focusing algorithm has superior success in focusing the targets without using any interpolation. However, it is computationally expensive compared to the other methods due to the nature of the algorithm.

Once again, for fair comparison, we do not oversample the data more than the number of folds ($F$) and do not zero-pad the signals before Fourier transforms. With oversampling and zero padding, it is possible to increase the accuracy of the Fast-CI and Keystone algorithms at the expense of higher computational complexity.

5.2 Execution Time

Since all algorithms are highly parallelizable, we take advantage of massive parallelization. Execution time for each algorithm in a MATLAB environment that is supported by Nvidia K20 GPU is 4 ms, 0.4 s, 0.1 s, and 1.5 s for FFT, Keystone, Fast-CI, and back-focusing algorithms, respectively, for 512 pulse (PARSAX’s FPGA can process up to 512 pulses in real time). As expected, FFT processing is the fastest approach but cannot provide a well-focused target signature due to the range walk. The Fast-CI algorithm provides range cell correction within a reasonable time, but it suffers the effect of interpolation.

To satisfy the real-time requirements, the processing time for 512 pulses should be less than 0.512 s. Thus, the back-focusing algorithm is not a practical option for the current setup. Keystone and Fast-CI algorithms can be adjusted (zero-padded and oversampled) accordingly to minimize the unwanted effects of interpolation while keeping the execution time inside the limits.

Overall, Table 1 summarizes the comparison of each algorithm under the same conditions.

<table>
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<th>FFT</th>
<th>Keystone</th>
<th>Fast-CI</th>
<th>Back-focusing</th>
</tr>
</thead>
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<tr>
<td>Focusing (integration gain)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Better</td>
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<td>Unfolding</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
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</table>

6 Conclusion

This paper serves as a benchmark for range cell migration algorithms and guides researchers to select the best algorithm according to their needs (speed versus quality). Thus, the practical issues in range-Doppler focusing are illustrated with real world examples.

Mainly in this paper, we demonstrate the application of the range-Doppler back-focusing algorithm for the first time in a real-radar data set. Furthermore, we revisit the well-known range cell migration methods and demonstrate their application to the PARSAX radar. We compare the recently proposed back-focusing algorithm with previous methods and discuss its pros and cons.

We conclude that the back-focusing algorithm yields the best coherent processing gain and can be preferred for offline processing to focus fast moving targets. On the other hand, the Fast-CI algorithm is an alternative for real-time application since Fast-CI makes possible to minimize the unwanted effects of interpolation by zero-padding while keeping the execution time inside the real-time application limits.
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References


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