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Analysis of Signal Processing Methods for Formation of Radar Range Profiles

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Abstract. A range profile (RP) is a vector of reflected powers from a target by the range direction and is used for the purpose of target recognition. In this paper, a problem of formation of RPs is investigated. The well-known difference operator and window-based methods are analyzed with data from a coastal surveillance radar. The drawbacks of those methods are shown. Then, a new method is presented to improve the performance of formation of RPs.

Keywords. Radar signal processing, radar range profile, difference operator method, window-based method, automatic target recognition

1. Introduction

Radar signal processing contains the consecutive algorithms that focus on target detection and formation of target profiles (range or azimuth). A range (or azimuth) profile of a target is a power vector reflected from the target along the radial (or azimuth) direction (see, Figure 1).

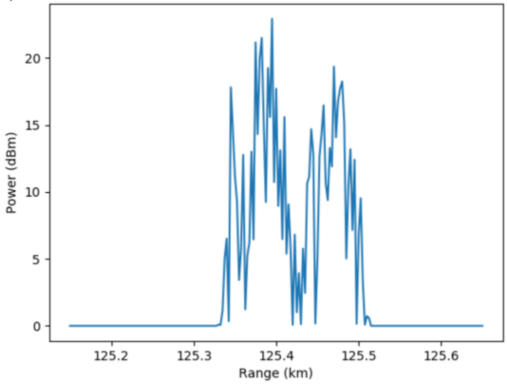

Figure 1. A RP of a cargo ship of length 225m, which is approaching directly in a clear environment region

From RPs important features (such as ship length and width, structure of dominant scattering ...) can be extracted and used for the target recognition [1],[5],[6]. However, for targets moved in a sea clutter environment, the signal-to-clutter ratio (SCR) is low, and therefore, the RPs of a target will be longer than normal (see Figure 2).

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In this paper, we deal with the problem of formation of RPs of a target in case of low SCR. Two common approaches for the formation of RPs of a target are considered and analyzed. The tests with data from a coastal surveillance radar show that the window-based method is more accurate than the difference operator method. However, the original window-based method has many disadvantages which are highly sensitive to low SCR. Then, a proposed method on improving the original window-based method is given.

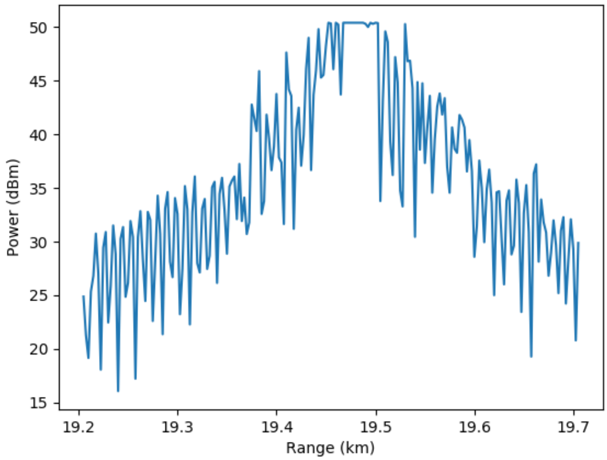

Figure 2. A RP of a cargo ship, which is approaching directly in a sea clutter region. The RP has a length of 500m while the true length of the ship is 181m.

The paper is organized in the following way. In the next section, we give a brief description of the difference operator and window-based methods. The tests and analysis are given in Section 3. In section 4 a modification of the original window-based method is presented. The last section deals with the conclusion and future works.

2. Related works

First of all, let us recall the basic steps of radar signal processing [2],[3],[4]. Figure 3 represents the radar block diagram with Doppler processing.

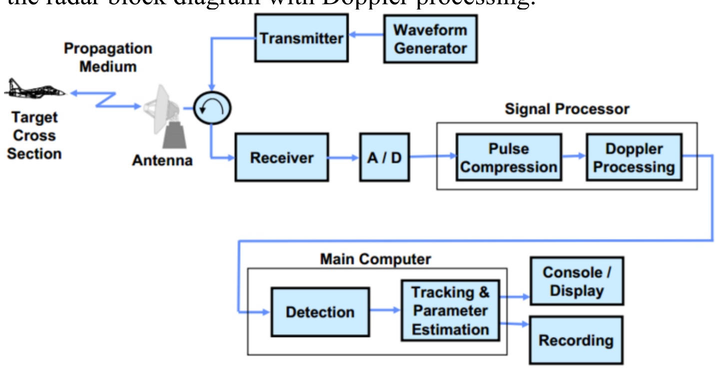

Figure 3. Radar block diagram [4]

The Doppler processing is done by using FFT (Fast Fourier Transform) and its output is considered as the *target's raw range profiles*.

A simple method of formation of RPs is the thresholding method [5]. However, this method is highly sensitive to noise and interference [6]. Then, an adaptive difference operator method is introduced to improve the thresholding method [6]. The idea of the difference operator method (see Figure 4) is the following [6]:

Let $X = [x_1, x_2, \cdots, x_N]^T$ be a raw RP of a target, where N denotes the number of reflected sampling points (the number of range cells in the same radial direction that reflect the radar transmitted signal). Set

$$W[k] = \begin{cases} -1, & -M \le k < 0 \\ 1, & 0 \le k < M \\ 0, & others \end{cases} \tag{1}$$

The RP of the target is a vector $Y = [y_1, y_2, \cdots, y_{N-2M+1}]^T$ defined as:

$$y_i = \begin{cases} \left(\frac{E_{i2}}{E_{i1}}\right) \times (E_{i2} - E_{i1}), & E_i \ge 0 \\ \left(\frac{E_{i1}}{E_{i2}}\right) \times (E_{i1} - E_{i2}), & E_i < 0 \\ (i = 1,2,\cdots, N-2M+1) \end{cases} \tag{2}$$

where,

$$E_i = \sum_{j=0}^{2M-1} x_{i+j} \times W[-M+j] \tag{3}$$

$$E_{i1} = \left|\sum_{j=0}^{M-1} x_{i+j}\right| \tag{4}$$

$$E_{i2} = \left|\sum_{j=M}^{2M-1} x_{i+j}\right| \tag{5}$$

$$\begin{cases} M = m_1, & SNR < S_1 \\ \frac{SNR-m_1}{S_2-S_1} = \frac{M-m_1}{m_2-m_1}, & S_1 \le SNR \le S_2 \\ M = m_2, & SNR > S_2 \end{cases} \tag{6}$$

$$SNR = 10 \times log_{10}\left\{\frac{(\max(x_i)_{i=1}^{N})^2}{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2}\right\}, \quad \bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{7}$$

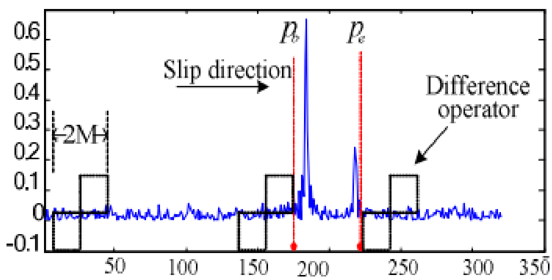

Figure 4. Illustration of difference operator method [6]

Another approach for formation of RPs of a target is the window-based method [1],[7]. This method starts with N_{st} windows, each of them is a range cell containing one of the N_{st} strongest peaks of a raw RP. For each window, at each step, the power sums of three adjacent cells on the left and right side of the window are estimated. Then, the window is extended by the next adjacent cell on the side with the higher power sum. Moreover, the relative power

$$\Delta_i = \frac{p_i}{p_i + \sum p_{win}} \tag{8}$$

is determined, where p_i is the power in the next adjacent cell and $\sum p_{win}$ is the power sum of all cells in the window. The process is repeated until the value Δ_i stays permanently below a certain threshold:

$$\Delta_i < \Delta_{thres} \tag{9}$$

The value of certain threshold $\Delta_{thres} = 0.01$ was found to be effective [1]. So, the classical window-based method is characterized by the number of created windows, the rule for extending the window and the ending condition:

- *Creating the windows:* from N_{st} strongest peaks of a raw RP of a target, N_{st} windows (one range cell for each window) are created.
- *Extending the windows:* for each window, step by step the window is extended by the next adjacent cell on the side with the higher radar-cross-section.
- *Ending condition:* The process is repeated until the inequality

$$\Delta_i = \frac{p_i}{p_i + \sum p_{win}} < \Delta_{thres}$$

stays permanently.

3. Analysis of methods

For analysis of the methods mentioned above we will use the AIS information as ground truths to find the relative errors of estimated lengths of vessels and their standard deviation:

$$Err = \frac{1}{N}\sum_{j=1}^{N}\left|1 - \frac{L_{estj}}{L_j}\right| \tag{10.a}$$

$$Std = standard\ deviation\left\{\left|1 - \frac{L_{estj}}{L_j}\right|\right\} \tag{10.b}$$

where, *Err* is the relative error; *Std* is the standard deviation of the relative error; *N* is the total number of RPs using for evaluation; L_j is the true length of the target corresponding to the *j*-th RP and L_{estj} is the estimated length of target estimated from the *j*-th RP:

$$L_{estj} = \frac{length\ of\ j\text{-}th\ RP}{\cos(aspect\ angle)} \tag{11}$$

The data for the analysis (see Table 1) is collected from a coastal surveillance radar with the following parameters:

Table 1. Radar parameters

Parameter	Value
Frequency	X-band
Range resolution	3m
Sanpling frequency (*f*)	120MHz

Two tests are investigated.

Test 1: The dataset contains 53 ships (32 cargo ships and 21 tanker ships) with 5600 profiles (3263 profiles of cargo ships and 2337 profiles of tanker ships). All ships moved in the area of radius of 90km slant range and with the aspect angles in the interval *aspAngSet* (see Figure 5):

$$aspAngSet = [0^0; 60^0] \cup [120^0; 240^0] \cup [300^0; 360^0]$$

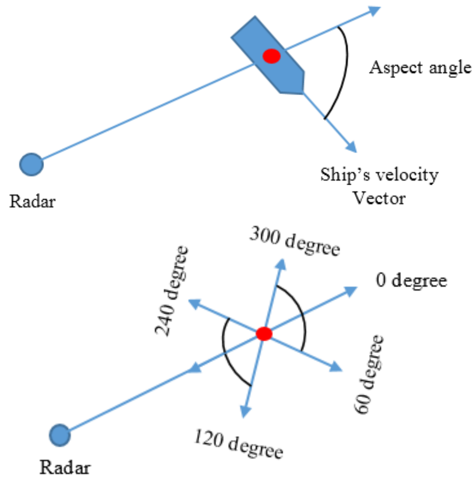

Figure 5. Aspect angle of a ship (above) and considered aspect angles (*aspAngSet*) for Test 1 (below)

The parameters for the difference operator method are obtained by the same way as given in [6], i.e.

Table 2. Parameters for difference operator method

Parameter	Value
S_1	10
S_2	30
m_1	$= 15f/c = 6$ (c is the speed of light)
m_2	$= 7f/c \approx 3$

The parameters for the window-based method are the same with that one given in [1, p.94], i.e.

Table 3. Parameters for window-based method

Parameter	Value
N_{st}	X-band
Δ_{thres}	3m

The test results are given in Table 4.

Table 4. Test result

Difference operator method		Window-based method	
Err	*Std*	*Err*	*Std*
1.5	1.97	0.229	0.21

Test 2: The dataset contains 8 ships (4 cargo ships and 4 tanker ships) with 619 profiles (218 profiles of cargo ships and 401 profiles of tanker ships). All ships moved in the area of 90km slant range and with the aspect angles in the interval *aspAngSet*:

$$aspAngSet = [0^0; 10^0] \cup [170^0; 190^0] \cup [350^0; 360^0]$$

This test is taken for the case when the ships moved directly toward to the radar station or moved directly far away from the radar station. The parameters for difference operator and for window-based methods are the same as given in Tables 2 and 3. The test results are given in Table 5.

Table 5. Test result

Difference operator method		Window-based method	
Err	*Std*	*Err*	*Std*
0.88	0.4	0.175	0.194

The above tests show that the window-based method has a better performance than the difference operator method. However, the original window-based method has some drawbacks that are:

- The use of N_{st} ($N_{st} > 1$) strongest peaks of the RP for "Creating the windows" may lead to the wrong result due to the case of multiple targets or the case of low SCR. In these cases, selected peaks may be clutter or different closed targets (see Figure 6).

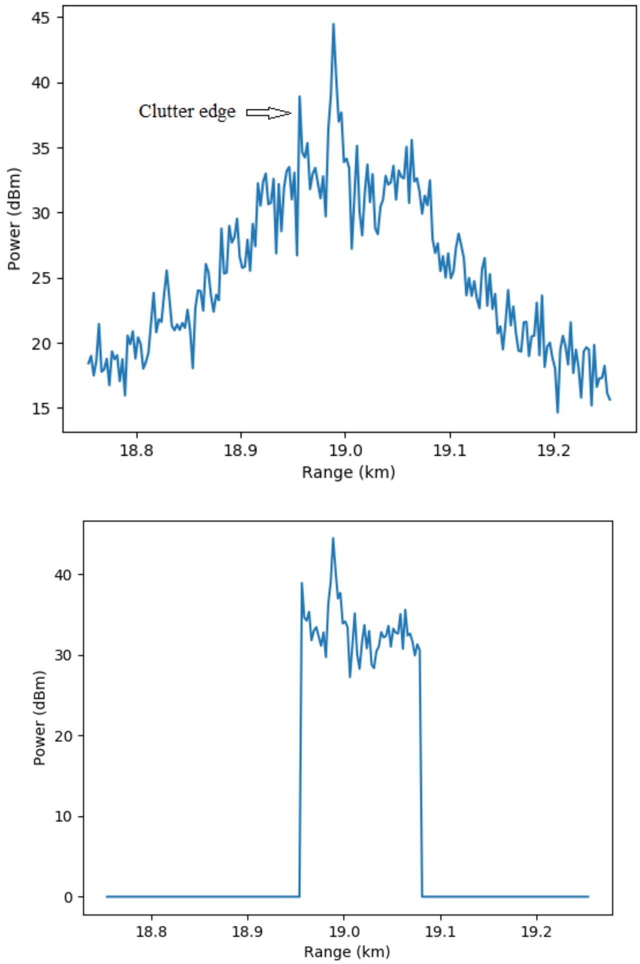

Figure 6. A raw RP of a tanker (length = 127m and aspect angle ≈ 304°) in a non-homogenous clutter region (above) and the RP formated using the window-based method (below) with $N_{st} = 3$. In this example, one of the selected peaks is the clutter edge and therefore the estimated length of the target is approximately 225m. Relative error ≈ 77.16%.

- The use of power sum of three cells in the left and the right sides of the window to extend the window size. This drawback in case of non-homogeneous clutter may lead to extend the window size into the clutter region (see Figure 7).

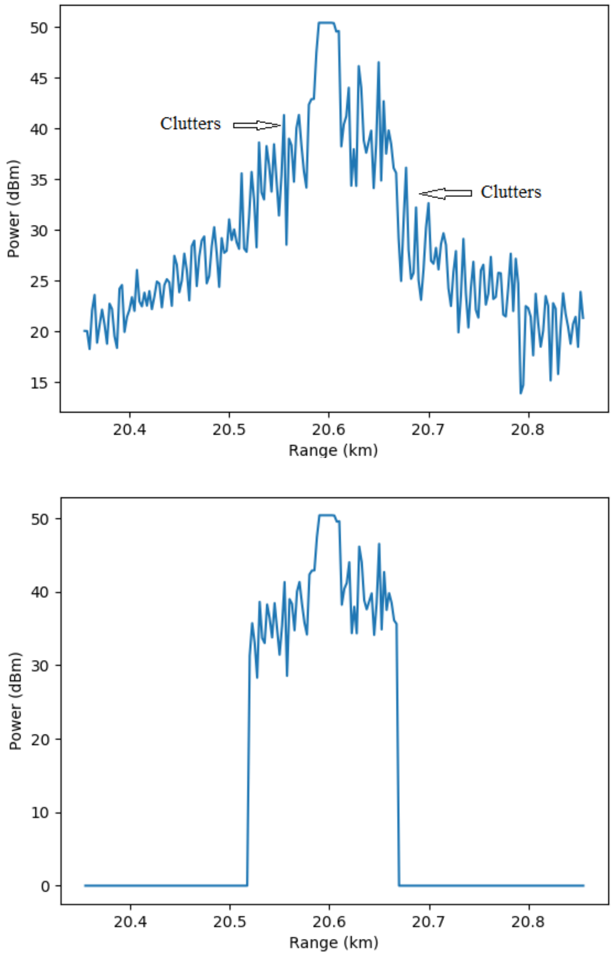

Figure 7. A raw RP of a tanker (length = 127m and aspect angle ≈ 321°) in a non-homogenous clutter region (above) and the RP formated using the window-based method (below). The estimated length of the target is approximately 183m. Relative error ≈ 44%.

- The use of a constant value Δ_{thres} for ending condition for all types of ships. This problem may lead to the extension of the estimated length of target (see Figure 8).

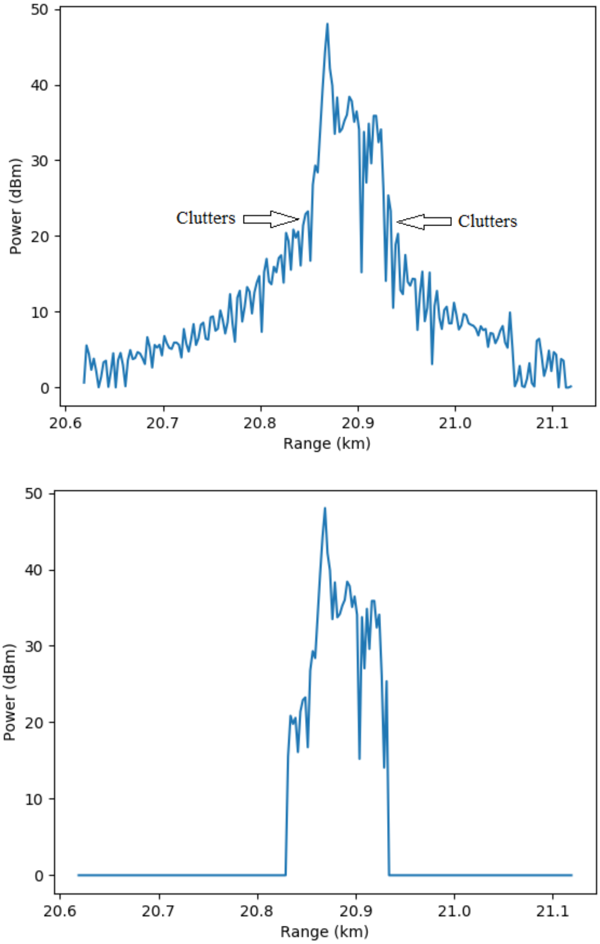

Figure 8. A raw RP of a tanker (length = 63m and aspect angle ≈ 20º) in a clutter region (above) and the RP formated using the window-based method with $\Delta_{thres} = 0.02$ (below). The estimated length of target is approximately 109m. Relative error ≈ 73%.

4. Proposed method and test result

4.1. Proposed method

To overcome the drawbacks analyzed above we propose a modification of the window-based method which contains the following steps:

Step 1: *Create a window* with only one range cell at target's centroid (i.e. $N_{st} = 1$). Let $X = [x_1, x_2, \cdots, x_N]^T$ be a raw RP of a target, where x_i is the power reflected from i-th range bin (or equivalent from a range r_i) . Then, the target's centroid range $r_{centroid}$ is defined by (see Figure 9):

$$r_{centroid} = \frac{\sum_{i=1}^{N} x_i * r_i}{\sum_{i=1}^{N} x_i} \tag{12}$$

The target's centroid bin ($centroid_{bin}$) is the bin i_* such that $r_{i_*} \approx r_{centroid}$.

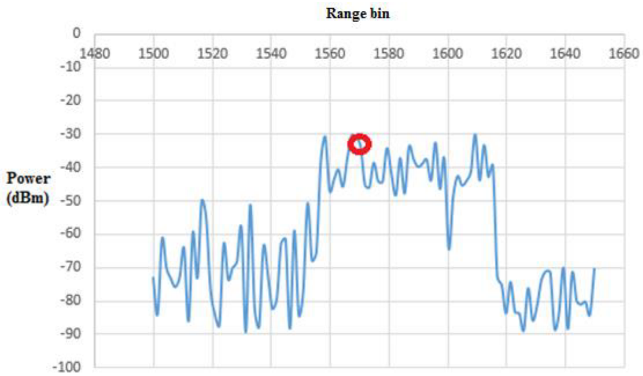

Figure 9. Example of a target's raw profile and its centroid range bin (at the circle position)

Step 2: *Extend the window*

- Take 2M cells near the $centroid_{bin}$ (M adjacent cells on the left and M adjacent cells on the right of the window). The value of M depends on the radar range resolution ΔR and can be chosen by the rule:

$$M \approx \frac{15(m)}{\Delta R\ (m)} \tag{13}$$

For example, if a radar has range resolution 1,5m we can take M = 10. The distance of 2M bin is 30m. This distance is suitable for almost marine targets. If we take less range cells, statistics are not guaranteed. If more range cells are taken, the lengths of many types of marine targets may be exceeded.

- Find the means M_{left} and M_{right} of the left M adjacent cells and right M adjacent cells near the $centroid_{bin}$, respectively.

- Calculate the means: λ_{left} and λ_{right} of the bins $[x_1, x_2, \cdots, x_M]$ and $[x_{N-M+1}, x_{N-M+2}, \cdots, x_N]$, respectively.

- Calculate the values: $M_{left} - \lambda_{left}$ and $M_{right} - \lambda_{right}$. These values show the power level of the target relative to the background noise on the left and right sides of the window (see Figure 10).

- Extend the window one adjacent cell to the left of the window if:

$$M_{left} - \lambda_{left} \geq M_{right} - \lambda_{right} \tag{14}$$

Otherwise, extend the window one adjacent cell to the right of the window.

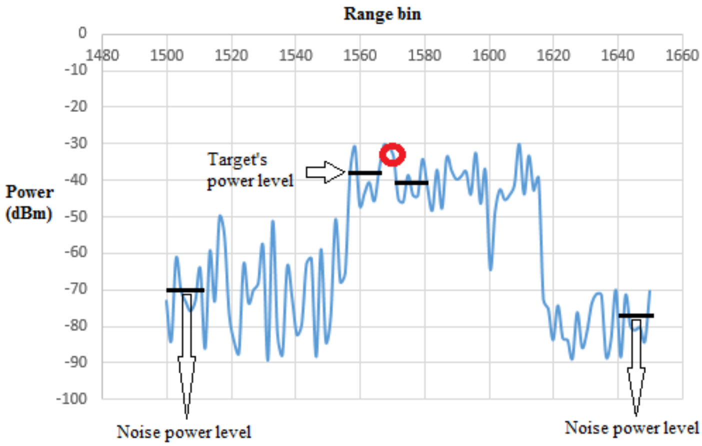

Figure 10. Example of power levels of the target relative to the background noise on the left and right sides of the window

Step 3: *End of the process*

- The process of extending the window is ended when condition

$$M_{left}\left(respectively, M_{right}\right) < \Delta_{thres} \times \sum p_{win} \qquad (15)$$

always satisfies, where $\sum p_{win}$ is the sum of powers in all cells of the window; Δ_{thres} is a threshold which depends on the length of the window $l(win)$:

$$\Delta_{thres} = \begin{cases} 0.02 & for\ \ l(win) < \frac{60}{\Delta R} \\ 0.01 & for\ \ l(win) < \frac{120}{\Delta R} \\ 0.005 & for\ \ l(win) > \frac{120}{\Delta R} \end{cases} \qquad (16)$$

The formula (16) means that for targets of small and medium sizes (target's length $\leq$ 60m) the threshold $\Delta_{thres} = 0.02$ is used, for targets of large size (60m<target's length≤120m) the threshold $\Delta_{thres} = 0.01$ is used and for targets of extremely large size (target's length > 120m) the threshold $\Delta_{thres} = 0.005$ is used.

4.2. Test results

We use the same datasets and parameters used in Test 1 and Test 2 in section 3 for the test and comparison of the proposed method. The test results are given in Tables 6 and 7, respectively.

Table 6. Test result

Window-based method		Proposed method	
Err	*Std*	*Err*	*Std*
0.229	0.21	0.113	0.112

Table 7. Test result

Window-based method		Proposed method	
Err	*Std*	*Err*	*Std*
0.175	0.194	0.069	0.06

As given in (10.a) the value *Err* is the mean value of all relative errors estimated from all test RPs. Figure 11 represents the cumulative probabilities of relative errors of the window-based and proposed methods.

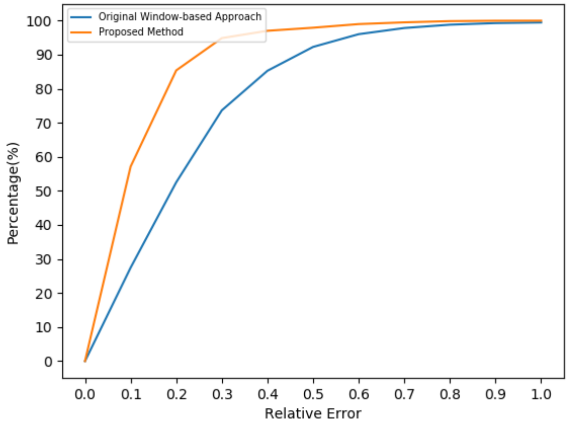

Figure 11. Cumulative probability of relative errors. The curve above corresponds to the proposed method.

5. Conclusion and future works

The paper presented the detailed analysis of two popular signal processing methods for range profile formation that are the difference operator method and the window-based method. The tests shown that although the window-based method has a better performance than the difference operator method, it contains some disadvantages such as the use of $N_{st} > 1$ peaks, the use of reflected powers in three cells in the left and the right sides to extend the window size and the use of a constant value Δ_{thres} for the end of process.

To avoid these drawbacks, we proposed a modification of the original window-based method that uses only one peak (at the target's centroid) for creating a window; uses more statistical information of the reflected powers for extending the window size and uses an adaptive threshold for ending process. The tests shown that the proposed method achieves better performance than the original window-based method.

In future works we will investigate the problem of formation of RPs in case of low SNR (signal-to-noise ratio), multiple closed targets and other interferences.

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