An Improved Technique for Single-Channel Video-SAR Based on Fractional Fourier Transform

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In the field of synthetic aperture radar (SAR), a lot of researchers have tried to study an improved application beyond the conventional two-dimensional image. Video-SAR (ViSAR) is one of the hot issue in the SAR application. The main purpose of ViSAR is to monitor various targets in the area of interest in time order. It can offer video images to detect not only the fixed target but also the moving target. For the signal processing of ViSAR, this article introduces the improved performance by the Doppler shifting technique with fractional Fourier transform. And also, it shows that the proposed method can separate the unexpected signal of the moving target within each frame of single-channel ViSAR. Furthermore, the overall algorithm can increase efficiency and reliability in ViSAR processing. To verify the improvement of our method, we carry out the practical experiments by an X-band chirp pulse SAR system, mounted on an airplane.

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I. INTRODUCTION

In the study of synthetic aperture radar (SAR), a lot of researchers try to develop the various application of SAR to more accurately monitor the target scene without the influence of various nature condition. One of hot issue in the applications is video-SAR (ViSAR). It can generate the sequential images of SAR in time order and detect the interested target in video image [8]. Different from the conventional SAR image, which focuses on a specific area at a time, ViSAR shows the video image using continuous SAR measurement for a desired period of time. Furthermore, we can detect and monitor the moving targets with the signal processing of ViSAR. Conventionally, it has been operated at the airplane platform of flying a circular orbit and processed on spotlight mode. In the state of art, research to implement ViSAR on stripmap mode is also being studied to compensate for the shortcomings of the conventional method. In this article, we use the one of the recent ViSAR techniques, called Doppler shifting technique for generating the video frames [14]. The Doppler shifting technique extracts ViSAR frames at a high-frame rate by separating multiple superimposed chirps on a wide range of received signals. It has the advantage to generate the frames from the extended Doppler band (slow-time dimension) without a fixed coordinate system. Using the additional information of signal other than the main aperture, subapertures method [6], [7] has been conventionally used to improve the quality of SAR image. In this article, using the expended Doppler band from the main aperture to the subaperture, the Doppler shifting technique helps to extract each frame of the ViSAR. If the wide-angle antenna is used, which has low side lobe level, we can expect more increased Doppler band. And also, it can reduce the computational amount of ViSAR process, based on range doppler algorithm (RDA). However, in this ViSAR technique, it is important how we extract each Doppler chirp pulses in a received band, effectively and accurately. Moreover, it still has to be improved in the extraction technique of each frame of ViSAR. This technique creates each frame by shifting the Doppler frequency band of the azimuth filter, and is used without distinction technique of surrounding signals. It can lead to inaccurate Doppler estimation and degrades image quality by the interference from unexpected signals. Thereby, it can lead to reducing the quality of the ViSAR images. Therefore, it needs to be developed by the advanced method to escape from surrounding interference. Furthermore, in the above condition, it can be difficult to distinguish the signal of a moving target in the state of overlapping with different signal components, which become the frames of ViSAR.

In this article, we try to improve the performance of ViSAR using the characteristics of the fractional Fourier transform (FrFT) method with the original Doppler shifting technique. In other words, the received signals, which have each unique Doppler band, are separated by the rotation of angle on FrFT domain. After the overall process, it can be the frames of ViSAR with more clear focusing. And also, we can find an expected moving target between each frame. According to the rotation angle of the *x*-*y* axis on FrFT, each separated signal is concentrated at each angle. With the windowing of each signal, we can obtain an accurate and efficient separation of frames in ViSAR, significantly, than before. Moreover, the proposed method on FrFT can be applied to simultaneously discriminate the Doppler information of a moving target. Different from the conventional multichannel model for ground moving target indication (GMTI), we can extract the phase information of a moving target even in the single-channel SAR system. To verify the improvement of the extraction method on FrFT, we obtained the raw data from the experiment with an X-band radar system. From the results by the proposed method, we accurately generated the successive frames in time order. It is processed to the accurate separation of each chirp for each frame of video, which allows accurate estimation and calculation. Furthermore, it can detect the moving targets in the raw data with distinguish the Doppler information of moving targets along to FrFT rotation in video frames.

This article is organized as follows. Section II introduces a novel approach scheme based on the Doppler shifting technique. In addition, it shows the improvement of the proposed technique on FrFT for ViSAR. Section III presents and analyzes the processed results of the proposed technique by raw data of the practical experiment. Finally, Section IV concludes this article.

II. IMPROVED EXTRACTION METHOD OF VISAR

A. Overall ViSAR Algorithm Process

In this article, we use the Doppler shifting technique, which is one of the processes for ViSAR. To use the above technique, we utilize the wide beam angle antenna, which has a low side lobe level, to receive a wide Doppler band. It is suitable for application to our proposed process.

Based on multilook frames by Doppler shifting technique, Doppler data can be introduced as several superimposed chirp pulse signals (3 dB beam width) from the wide beam width, shown as Fig. 2. Thus, it is important to separate each signal from the received wide band and to utilize the separated signals for generation of multiple frames. Therefore, we need to estimate and define an accurate Doppler parameter of each 3 dB Doppler band. Each Doppler parameter becomes one of the frames for the successive image of ViSAR. In the proposed algorithm, based on the Doppler shifting technique, we can extract the frame of the ViSAR algorithm in the expanded Doppler band. In other words, we need to extract more frames of ViSAR in the expanded band accurately. To increase the accuracy of extraction, the algorithm for SAR should have the additional process to compensate for the diverse interference and ambiguity of Doppler signals. In particular, it is critical for airborne-SAR due to an unstable environment than other representative platforms (auto-SAR, spaceborne-SAR). Therefore, to remove various unexpected interference factors in the practical experiment, the additional Doppler estimation method is included in our proposed algorithm. Among the various

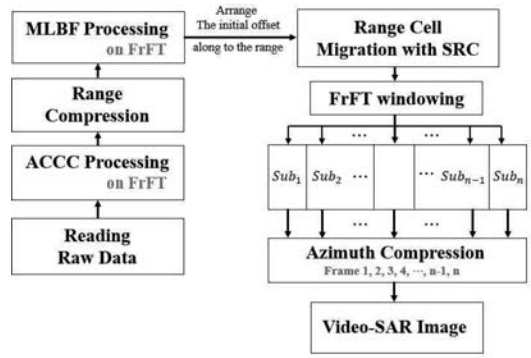

Fig. 1. Flow chart of the proposed algorithm for ViSAR.

estimation methods for Doppler parameters, the proposed method is based on average cross-correlation coefficient (ACCC) and multilook beat frequency (MLBF) algorithm. The received signals of SAR [1] can be modified and represented as sum of the superimposed Doppler signals shown as

$$s_{\text{azimuth}}\ (\tau,\ \eta) = \sum_{n=1}^{m} A_a \omega_a\,(\eta - \eta_c)\, e^{j2\pi f_{\eta c}(\tau,n)} e^{j\pi K_a(\tau,n)\eta^2}$$
$$n = 1, 2, 3, 4, \ldots \text{(look order along the azimuth direction)} \tag{1}$$

where τ and η are the range and azimuth time, respectively. The subscript a indicates azimuth direction and c indicates center of each parameter, A is the amplitude, ω is the window function, f is frequency, and K is the chirp rate of the pulse signal. Chirp pulse signal in Doppler frequency is defined as approximation with exponentials of two important parameters (Doppler center frequency and Doppler chirp rate). The relative range between the target and radar depends on the observed angle of measurement. Theoretically, the Doppler center frequency and the chirp rate in each signal are defined as (2) according to the observed angle of SAR platform, respectively

$$f_{\eta_c}\,(\tau, n) = \frac{2V_s \sin\left(\theta_{s(n)}\right)}{\lambda}, K_a\,(\tau, n) \cong \frac{2V_s^2 \cos^3\theta_{s(n)}}{\lambda R_0\,(\tau)}$$
$$n = 1, 2, 3, 4, \ldots \text{(look order along the azimuth direction)} \tag{2}$$

where $R_0(\tau)$ is the range between the target and radar. It is simple and efficient to immediately extract each Doppler information by utilizing the (2). However, due to unexpected interference, more sophisticated approaches should be required in addition to the ACCC and MLBF methods. Therefore, in order to extract accurate Doppler information suitable for the above equation, it is necessary to separate the Doppler signals in the extended Doppler band. Using the FrFT method, which is a mathematical technique of rotation axis, we not only estimate but also separate each Doppler signal from the received signal band. After the separation, these signals, which have different Doppler information, can generate a number of frames for ViSAR. In addition, the superimposed signals are separated into the same size

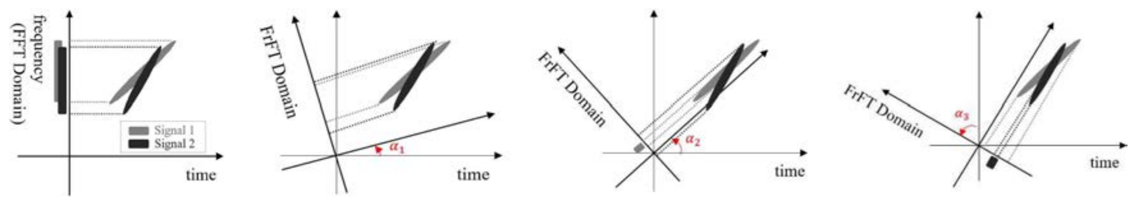

Fig. 2. Illustration for the principle of FrFT rotation.

of Doppler bandwidth without resolution loss, as shown Fig. 2(b). Overall, to obtain ViSAR images without the unexpected interference, we need to improve the accuracy and performance of the Doppler shifting technique. Applied FrFT technique can be the best solution to isolate the expected signal as an interfering signal. We will describe this process in detail in the next section. Furthermore, from the accurate Doppler information, the modified range cell migration (RCM) with secondary range compression (SRC) and azimuth compression is processed.

B. Generating Frames of ViSAR on FrFT Domain

As mentioned above, it is important to separate and estimate each Doppler frequency within the received signals. Therefore, we propose the improved process to generate the video frames for ViSAR. As shown in Fig. 1, we propose five steps as follows:

1) **ACCC processing**: Estimating Doppler center frequency of each separated signal by FrFT rotation (α).
2) **Range compression**: Convolution between raw data and range matched filter's impulse.
3) **MLBF processing**: Estimating the ambiguity of Doppler frequency for each separated signal by FrFT rotation (α).
4) **RCM with SRC**: Range compensation of each target according to squint direction through RCM with SRC.
5) **FrFT windowing and azimuth compression**: Convolution between the data, after step 4, and the azimuth matched filters, defined by the FrFT rotation.

At first, based on the received signals, the superimposed signals are indicated by sum of the Doppler chirp signals

$$s\ (\tau, \eta) = A\omega_r e^{\frac{j4\pi f_0 R(r,\eta)}{c}} e^{j\pi K_r\left[\tau - \frac{2R(r,\eta)}{c}\right]^2} \times \sum_n \omega_n e^{j2\pi f_{\eta c}(\tau,n)} e^{j\pi K_a(\tau,n)\eta^2} \tag{3}$$

where f_0 is center frequency of transmitted chirp pulse signals. The subscript r stands for range direction. The squinted equivalent model, as shown in (4), is applied for reducing the error of image focusing between radar and target [4]. Therefore, since the distances of each separated frame are different, we can organize the slant ranges according to the beam angle. The final model between airplane and target can be expressed as

$$R\ (r, \eta) = \sum_n \sqrt{r^2 + (V\eta)^2 - 2rV\eta\cos\theta_n} \tag{4}$$

where r is the relative distance between center of each aperture and target, θ_n is the corresponding equivalent squint angle, V is the equivalent velocity of an SAR radar. From (3), ACCC algorithm has been conventionally used for estimating the center frequency of Doppler band. In overlapped frequency band, FrFT method can improve the accuracy of ACCC algorithm for separating each Doppler chirp signal. As one of the applications for the Fourier transform, the FrFT method finds the strongest signal that matches its characteristics by rotating two orthogonal axes in a time-frequency coordinate system. In other words, the superimposed signals have each point where the energy of each signal is concentrated according to the FrFT rotation of the x and y axes, respectively. The calculated results of signal $s(t)$ on FrFT with rotation angle α is defined as follows [13]:

$$S_\alpha\ (u) = \begin{cases} \sqrt{\frac{1-j\cot\alpha}{2\pi}} e^{j\frac{u^2}{2}\cot\alpha} \int_{-\infty}^{\infty} s\,(t)\,dt & \text{if } \alpha \neq n\pi \\ \quad e^{j\frac{t^2}{2}\cot\alpha} e^{jutcsc\alpha} & \\ s\,(t) & \text{if } \alpha = n\pi \\ s\,(-t) & \text{if } \alpha = (2n+1)\,\pi \end{cases}. \tag{5}$$

The parameter α introduces the rotation angle of time and frequency domain. To understand the term of rotation on FrFT, the transform kernel is defined as [13]

$$K_\alpha\ (t, u) = \begin{cases} \sqrt{\frac{1-j\cot\alpha}{2\pi}} e^{j\frac{1}{2}\left(u^2+t^2\right)\cot\alpha - jutcsc\alpha} & \text{if } \alpha \neq n\pi \\ \delta\,(t-u) & \text{if } \alpha = 2n\pi \\ \delta\,(t+u) & \text{if } \alpha = (2n+1)\,\pi \end{cases} \tag{6}$$

where n denotes an integer and α indicates the rotation angle in FrFT domain. When the rotation angle α corresponds to $n\pi/2$, the FrFT generates the same result as a generalized Fourier transform. Therefore, the FrFT of signal $s(t)$ is summarized as

$$S_\alpha\ (u) = \int_{-\infty}^{\infty} s\,(t)\,K_\alpha\,(t, u)\,dt. \tag{7}$$

Thus, we apply the extracted signal $S_\alpha(u)$ into the accurate estimation of Doppler parameters. In the previous method, it is difficult to distinguish each signal because the received signals share the same frequency bands in the fast Fourier transform (FFT) domain. Fig. 3 illustrates the principle of FrFT [13]. Two signals, which have the

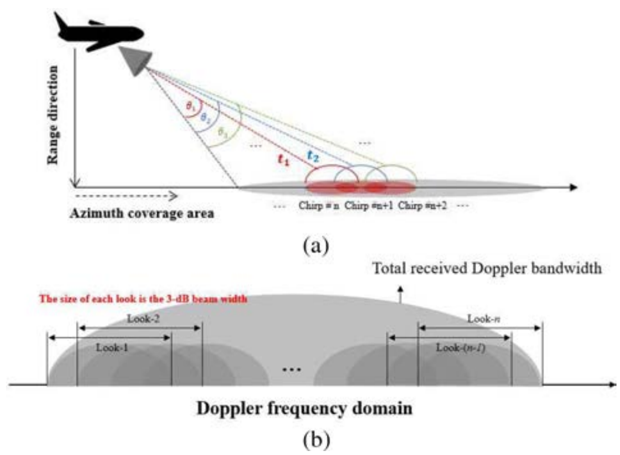

Fig. 3. (a) Concept of Doppler shifting technique for ViSAR [14] and (b) illustration of overlapped multilook frames.

same power, are overlapped. By the rotation of axis, α_2 and α_3 lead to the high magnitude of "signal 1" and "signal 2," respectively. Therefore, the overlapped signals can be separated into each signal.

Based on the above characteristic of FrFT, we can improve the performance for the extraction of frames than the previous technique. It leads to decreasing uninterested interference and increasing the accuracy of estimation. In previous technique, each desired signals are extracted from the wide frequency band through the matched filtering. If the matched filter can be simultaneously integrated with the undesired parts of the surrounding signal, the quality of the target signal is degraded, significantly. Thus, in order to compensate and improve the image quality of the previous ViSAR technique, the FrFT technique should be applied to our proposed algorithm. The rotation of axis on FrFT helps to separate each signal and easy to analyze the information of this signal from the unexpected interference. Due to the high resolution performance described above, each separated signal on FrFT can keep a good quality from the other interfering signals.

Based on the results from FrFT rotation, we can accurately extract each signal for ViSAR frames from the received frequency band. Furthermore, to generate a high-quality image of ViSAR, we need to analyze and estimate the information of each separated signal. It constructs the shape of a Doppler chirp pulse in the condition of SAR measurement (fixed target and moving radar). To generate the accurate matched filter in the azimuth direction, the information of Doppler chirp pulse should be estimated, exactly. Estimation errors have increased in the previous method due to the interference signals, but the accuracy of the proposed method has been further strengthened. Therefore, in this article, the center frequency and chirp rate of each Doppler chirp pulse signal can be classified accurately for focusing high quality of each SAR image of ViSAR. From each separated signal by FrFT rotation, the ACCC formulation can define the Doppler center frequency by the sum of cross-correlation between two successive azimuth signals at the same range time. For subsampled data, we construct the rotated signal on FrFT as initial concept

$$S_n\ (\eta) = \mathrm{FrFT}_{\alpha(n)}\ \{\mathrm{s}\,(\eta)\} \times \left(n\ = \theta_1\ , \theta_2, \ldots,\ \theta_{n-1}\theta_n\right) \tag{8}$$

where $\alpha(n)$ is the rotation angle of FrFT domain and n indicates the number of beam angle in our designed antenna. In addition, the received Doppler chirp pulse signals are separated along to the look angle in antenna beam width, as shown in Fig. 2(a) and (b). Thus, (8) defines the total Doppler chirp signals in the received frequency band, which can section by the rotation angle on FrFT.

Based on each separated signal on the FrFT rotation, these Doppler chirp pulses are analyzed to estimate each respective center frequency by the ACCC algorithm. The estimated center frequency is defined with the correlation phase ($\phi(\eta)$) of each received signal, which indicates the average phase increment [1]. Moreover, to calculate the difference of phase in slow time, the phase increment of several signals can be defined by the rotation angle, according to the center of exposure time of each signal

$$\sum_n \phi_{\mathrm{accc},\ \alpha(n)} = \frac{d\phi\,(\eta)}{d\eta}\ |_{\eta\ =\eta_1\ ,\eta_2,\eta_3\ldots\eta_n}\ \Delta\eta$$

$$\sum_n f'_{\eta_{c,\alpha(n)}} = \frac{\mathrm{PRF}}{2\pi}\ \sum_n \phi_{\mathrm{accc},\ \alpha(n)} \times \left(n = \theta_1\ , \theta_2, \ldots,\ \theta_{n-1}\theta_n\right) \tag{9}$$

where f'_{η_c} is baseband Doppler center frequency and PRF indicates abbreviation of "pulse repetition frequency." η_n is the center of exposure time in azimuth direction. $\Delta\eta$ is a sampling interval, ϕ_{accc} is the average phase increment, wrapped within the interval $(-\pi, +\pi]$. However, some results cannot be estimated only by the ACCC algorithm because these are beyond the bandwidth of PRF, called ambiguous signal. Therefore, to solve the problem, we derive the accurate ambiguity number to compensate for the incorrect signals into accurate signals, based on MLBF technique [1] and [3]. In the proposed algorithm, we apply the MLBF algorithm of FFT type [5] into the FrFT domain. It also leads to an increase in the accuracy of estimating the ambiguity number. Processing MLBF algorithm, we determine a beat frequency from the received signals to introduce the absolute Doppler center frequency shown as

$$\sum_n f_{\mathrm{absolute},\ \eta_{c,\alpha(n)}} = -\sum_n \frac{f_0}{\Delta f_r} f_{\mathrm{beat},\alpha(n)} \times \left(n\ = \theta_1\ , \theta_2, \ldots,\ \theta_{n-1}\theta_n\right) \tag{10}$$

where $f_{\mathrm{absolute},\eta_c}$ is absolute Doppler center frequency, Δf_r is a look size of bandwidth in chirp pulse signal, and f_{beat} is the beat frequency. To obtain the beat frequency in MLBF, we separate Doppler chirp signal into two looks. In the conventional model, the accuracy of difference between the angles of two looks decreases because of the interference of surrounding signals and inaccurate center point. Thus, it needs to calculate the accurate cutoff size to guard the desired signal against above problems. The size of the guard window must be accurately calculated so that it minimizes

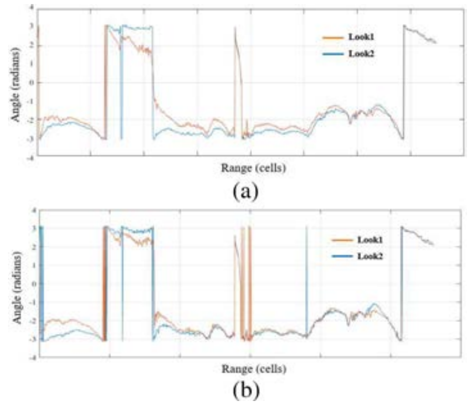

Fig. 4. Angle difference between two looks (a) on FFT and (b) on FrFT in the measured data of the practical experiment.

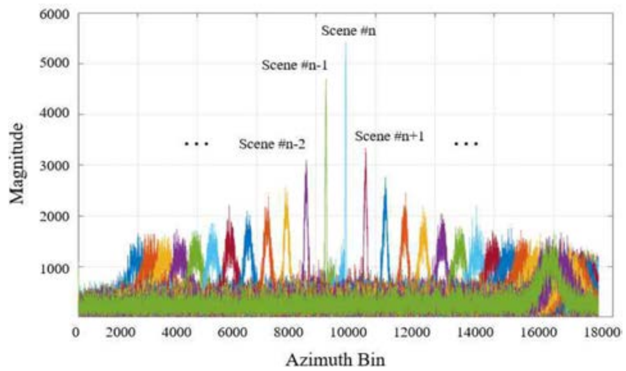

Fig. 5. Separated Doppler signals by the rotation of FrFT angle.

the affection by unexpected signals. Otherwise, it generates an inaccurate estimation of the Doppler information from the desired signal. It is important to guarantee the parameter of Doppler ambiguity number in the MLBF process for azimuth matched filtering. Therefore, we try to apply the FrFT technique into our proposed algorithm of ViSAR. This analysis derives the beat frequency between two looks from the peak energy on FrFT rotation as a weighted window for each signal. Because FrFT rotates the axis and concentrates the energy of the expected target from the overlapped signals, it can take over the same role of the weighted windowing. Accordingly, we can estimate the Doppler information of each desired signal. Fig. 4(a) and (b) shows the difference of angle between two looks with/without FrFT, respectively. In the MLBF process, when the above angles are constant (without interference), a reliable beat frequency is extracted from the two looks of Doppler signal [1]. When FrFT is applied in the estimation, the difference error between the two looks of the interested Doppler signal decreases than the conventional process without FrFT. Thus, it shows that the estimation on FrFT can extract the information with high accuracy without a specific windowing to guard original signal. Moreover, the proposed technique is easy to modify the estimation method in specific condition and simplify the overall process without unnecessary process. In Fig. 5, the extracted signals on the rotation of FrFT are accurately distinguished from the received frequency band. Based on

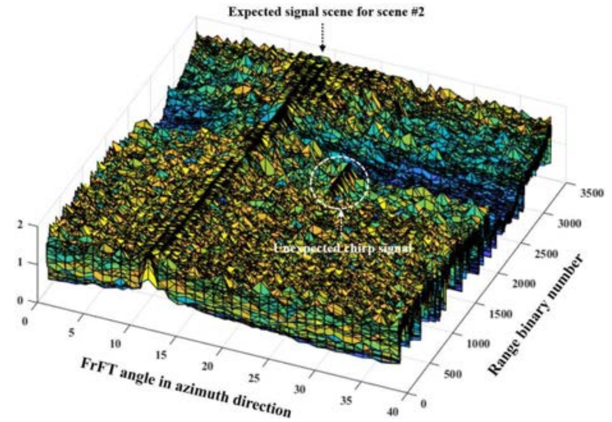

Fig. 6. ViSAR data on 2-D FrFT domain after the second step of the proposed algorithm.

the above results, the difference of "baseband and absolute" Doppler center frequency can derive the Doppler ambiguity number [1]. With the accurate ambiguity number, we can estimate each Doppler center frequency of each separated chirp pulse signal

$$\sum_n f_{\eta_{c,\alpha(n)}} = \sum_n \left(f'_{\eta_{c,\alpha(n)}} + M_{amb,\alpha(n)}\mathrm{PRF}\right) \times \left(n = \theta_1, \theta_2, \ldots, \theta_{n-1}\theta_n\right) \qquad (11)$$

Therefore, each exact Doppler parameter of each superimposed signal in a received band can be separated with FrFT rotation. Based on the Doppler estimation results, we apply the Doppler shifting technique into our method. As shown in Fig. 2(a), the elapsed time of the signal returning from the target increases to the larger steering angle of the antenna due to the travel distance. It means that the elapsed time (t_1 to t_2) increases according to the beam angle (from ϑ_1 to ϑ_2). That is, when the chirp signals in the whole aperture of antenna can be accurately separated according to the angle, a time-ordered SAR image can be obtained, called by ViSAR. From this phenomenon, the Doppler center frequency, varying with the observed angle, also follows the time sequence. In other words, each chirp signal is superimposed in a received frequency band of the antenna, which has different look-angle along to the elapsed time. Thus, we can apply the Doppler center frequency and chirp rate of (2) into the time-ordered angle, defined as

$$f_{\eta_c}(\tau) = \sum_n f'_{\eta_c}(r, \theta(t_n)) = \sum_n \frac{2V_s \sin(\theta(t_n))}{\lambda},$$
$$K_a(\tau, n) \cong \frac{2V_s^2 \cos^3\theta(t_n)}{\lambda R_0(\tau)}$$
$$n = 1, 2, 3, 4, \ldots (\text{shift order}). \qquad (12)$$

The above proposed method on FrFT improves the accuracy of the estimation by using a function that classifies the desired signal from the overlapped signals. Furthermore, it can generate the results with reducing the interference of

Fig. 7. Photograph of the mounted SAR system on airplane. (a) Airplane appearance. (b) Inside view. (c) Outside view.

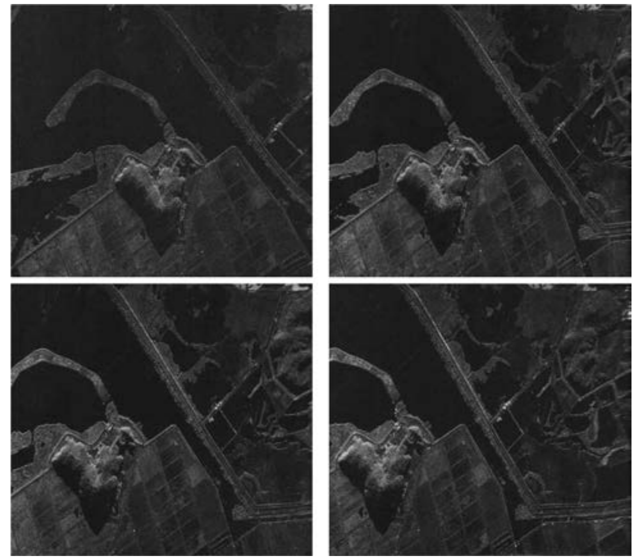

Fig. 8. Final processing frames of video-SAR.

unexpected signals. Therefore, we need to use the characteristic of FrFT, which can differentiate signals with different information (center frequency and chirp rate). It can generate the frames of ViSAR by separating the desired signal between the superimposed signals. In our concept, each chirp signal has each different Doppler information along to the elapsed time. Thus, it leads that each has the maximum energy at a different location. Based on the principle of FrFT rotation, we can separate the interested signals from the received band effectively. In Fig. 5, we can find that each individual signal is separated from the superimposed signals in real raw data. In addition, because the magnitude of some signals decreases in insufficient antenna gain, the proposed method should be performed within a range of the guaranteed gain of an antenna. To summarize, the Doppler band construct as a wide Doppler band from the receive antenna. And then, the Doppler information of each signal can be estimated on our proposed FrFT domain. Furthermore, these separated signals are generated into the frames of ViSAR through FrFT rotation. Therefore, we propose an advanced technique to improve the quality of the video frames in Doppler shifting technique.

C. Ground Moving Target Indication in Single Channel

In addition, our proposed method has another advantage to apply it into ViSAR technique. When moving targets are in the measured raw data of ViSAR, we need to distinguish the unexpected signal between each of the sequential Doppler signals. In conventional SAR processing, moving targets can be detected in a single SAR image by the rotation on FrFT [15], [16]. As mentioned in the previous section, signals, overlapped in the same frequency band, can be separated by FrFT. Nevertheless, in ViSAR, it is difficult to find the signals of moving targets hidden in the received Doppler band because multiple frames are also separated by the rotation on FrFT. In other words, in the conventional SAR, it is possible to detect only by discriminating between a chirp signal of the fixed SAR image and a chirp signal of the moving target. However, in the ViSAR method, since multiple frames are also distinguished by FrFT, several chirp signals are extracted at each FrFT angle. It is difficult to extract only the signal for a moving target at a specific angle. Thus, an advanced classification method should be proposed in this article. In order to classify the desired moving target in ViSAR images, we design "FrFT windowing" in our proposed algorithm, using the sequence of the shifted frames by Doppler and two-dimensional (2-D)-plot of the rotation on FrFT domain. Video frames are processed in chronological order according to the measurement angle within the antenna beam width. In addition, the measurement angle has a sequential Doppler shifting phenomenon. As mentioned above section, the extracted signals for each frame can be arranged in Fig. 5. These signals are separated at each rotation angle of FrFT. However, when we generate the frames of ViSAR with a moving target, we find the unexpected situation that the separated chirp signals by the rotation on FrFT cannot be arranged in time order. It means that an error occurs in the middle between successive separated signals due to an unexpected signal, which is a moving target. Therefore, we need to analyze and define the moving target in a specific part of the image within the frames of ViSAR. To detect it more accurately, we analyze 2-D plots of each scene on FrFT domain. Based on the proposed FrFT method in the previous section, each separated Doppler signal along with the range bin shares the same rotation angle because each Doppler signal is received in the same look angle of the antenna. Thus, we try to arrange the same Doppler signal to generate a frame of ViSAR. Based on the measured raw data for ViSAR, we analyze the signal processing in two dimensions with the x- and y-axis, which are the rotation angle on FrFT and range bin, respectively. In the 2-D analysis, the desired signal in each frame, fits the angle of rotation on FrFT, should be aligned along to the range. However, the FrFT rotation

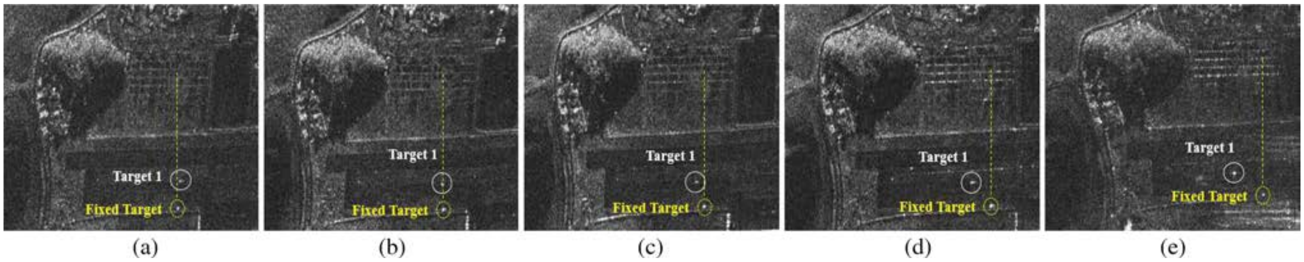

Fig. 9. Moving target in the frames of the proposed ViSAR process. (a) Frame #1. (b) Frame #13. (c) Frame #34. (d) Frame #55. (e) Frame #90.

TABLE I
X-Band SAR System Specification

System Parameter	Value
Center Frequency	X-band
Chirp signal Bandwidth	200MHz
PRF	2000 Hz
Measurement Velocity	< 320 km/h
Flying height	1.2 km
Squint angle	≈ 7°

for each frame is sequentially performed, and an irregular signal is found in a specific range. As you can see in Fig. 6, it is confirmed that the unexpected signal is measured at 1500–2000 range bin in the 2-D plot. As mentioned above, a moving target causes a new unexpected signal due to the different moving in SAR measurements. In other words, the different moving of the target leads to different Doppler parameters, contrary to the original frames of ViSAR. Thus, this unexpected signal is separated at its own angle of FrFT rotation. From the proposed FrFT technique, we can detect moving target, using the sequential frames of ViSAR along to the measurement angle on FrFT domain. In summary, the chirp signal of the moving target can be extracted by the characteristics of sequential frames in Doppler shifting technique for ViSAR and by the separation method from the rotation in the FrFT domain. In addition, when a number of moving targets are monitored in the frames of ViSAR, it is possible to detect the desired moving targets with a low amount of computation by the iteration of the algorithm with the rotation on FrFT. In the end, through the convolution with the azimuth-matched filter (14), these unexpected signals of moving targets are processed in each frame of ViSAR. These steps calculate the azimuth matched filter, matched with the specific angle of FrFT with a high-order model [1], [13]. From the rotation angle parameter, we can also estimate the specific velocity of the interested moving target

$$\alpha = -cot^{-1}\left(f_d\right) = \cot^{-1}\left\{2(V_a - V_x)^2/\left(\lambda R_0\right)\right\}$$
$$V_x = V_a - \sqrt{\left(\lambda R_0 ctg\alpha\right)/2}. \quad (13)$$

From the separated signal of the moving target by proposed FrFT method, we will show the focused result in next section. After above process, to generate the well-focused ViSAR frames, the azimuth-matched filters, defined by FrFT, are derived in the following equation:

$$H_{\text{mov}}\left(f_\eta, t_n\right) = \sum_{\alpha(n)} e^{j\frac{4\pi R_0(\tau) D\left(f_\eta(t_n), V_x(\tau)\right) f_c}{c}} \quad (14)$$

where f_η is the frequency in Doppler domain, f_c is center frequency, c is light speed, and $D(f_\eta(t_n), V_x(\tau))$ is migration factor [1]. From the results of the convolution between each matched-filter and each separated target signal in undesired points, we can focus the moving target and generate the frames in time order as a continuous ViSAR. In the next section, we will show the processed results with the practical experiment of airborne-SAR and prove the improved performance of the proposed method.

III. EXPERIMENT AND RESULTS

To verify the proposed method with the practical experiment, we design the X-band chirp pulse radar system, which is conventionally used for military and government policy. The experiment was done on strip-map mode. And also, we operate the designed radar on an airplane platform to monitor the interested terrain. The airplane model name is “Citation jet 1+c525,” as shown Fig. 7. The system specifications of the radar are shown in Table I.

The stop-and-go measurement technique is applied for ViSAR. Based on the proposed algorithm in Fig. 1, the received raw data are range-compressed and compensated with RCM and SRC technique. In the previous section, the accuracy of Doppler estimation was demonstrated with real raw data by the proposed FrFT method. Based on the estimated Doppler results, we can analyze the accurate azimuth filter and obtain the video frames for ViSAR as shown in Fig. 8. It shows that the SAR images of the interested area flow according to the time order. Comparing the previous Doppler shifting technique, we can secure high accuracy in Doppler estimation and it leads to generate a number of the frame in a wide-received Doppler band. Moreover, data processing complexity is also reduced because it is easier to distinguish each frame. In Table II, we analyze the improvement of our proposed technique. In one of the processes, we can compare the error rate of Doppler estimation between the existing MLBF and the modified MLBF algorithm. The error rate can be decreased from 5% to 1%. Moreover, based on the decreased unexpected interference,

TABLE II
Processing Performance Comparison for ViSAR

	Doppler Accuracy of each signal	Extraction for Frame rate	Data Processing Complexity
The previous technique[14]	Vulnerable to interference (Error rate: 5%)	Low	Medium
The proposed technique	Accurate Performance (Error rate: 1%)	High (20% increase)	Low

we can find the increased frame from 100 to 120 and it leads to increasing the frame rate up to 20%. Comparing the loop-back process of the previous technique, the number of re-estimations is significantly reduced. And, the amount of calculation can be also reduced because the desired Doppler parts are compressed through FrFT windowing, which can concentrate the interested area.

As explained in the previous section, our method extracts the desired signal more accurately than the conventional Doppler shift technique. The chirps extracted by FrFT could be intuitively identified, and video frames could be obtained without any additional algorithm. From the results of our proposed process so far, it can generate high-quality video frames in better performance than the previous ViSAR technique. Furthermore, for detecting a moving target in this experiment, we filmed one of the airfields in Korea and shot the scene of vehicle, which was moving on the airfield runway. Fig. 9 shows the processed results by our proposed method. In each frame of the ViSAR, we can see a scene where the moving target moves on a track relative to a fixed target. From Fig. 9 (a)–(e), a target is running from right side to left side on the track. In the previous technique, it was difficult to distinguish clearly the ghost phenomenon of a moving target, which interferes with the focusing within a low-quality image. As a result of accurate separation in the 2-D-FrFT domain, a moving target image can be obtained with a good quality image.

IV. CONCLUSION

In this article, we propose the improved method how to generate lots of frames for high-quality ViSAR. To introduce the proposed technique, we estimate accurate Doppler parameters and apply them into the Doppler shifting technique with FrFT rotation. Thus, it is easy to handle the extraction of each Doppler band along to the angle of FrFT and generates each frame of ViSAR in chronological order. In the end, our proposed method secures the reduced complexity in terms of computational amount of overall process and helps to simplify the operating SAR system with FrFT method. Furthermore, the proposed 2-D-FrFT method makes it easy to distinguish intuitively when the desired signal and an unexpected signal share the same frequency band. From the extraction on 2-D-FrFT, an unexpected signal, which is a moving target, is well focused on video scenes. The experiment on real raw data also proves the improved results with the airborne-SAR platform. In future article, the proposed method with FrFT can be applied to detect the moving targets in two-channel model of ViSAR, which has special Doppler information. In order to increase the performance of the FrFT technique, we will study to apply the advanced FrFT into our technique [17]. By efficient numerical computation, it can promote the practical implementation of FrFT in a radar system. Furthermore, the Doppler shifting technique on FrFT for ViSAR could offer diverse synergy, which is attractive for other SAR platforms (e.g., auto-SAR and spaceborne-SAR).

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