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ISAR Motion Compensation based on Accumulation and Limitation of Consecutive Radar Returns

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ABSTRACT

A new motion compensation method for ISAR is presented in this paper. It employs amplitude limiting and integration of consecutive range profiles to improve the range and phase alignment accuracy, and to alter the propagation properties of compensation errors. These allow the image quality to be significantly improved. It is shown from the imaging results that the new motion compensation algorithm can get images of targets in field situations with much better quality than the traditional cross-correlation algorithm.

I. Introduction

An Inverse Synthetic Aperture Radar [1-3] (ISAR) relies on equivalent target rotation to synthesize the equivalent of an extremely long antenna aperture, capable of achieving an azimuth range resolution independent of target altitude or distance. This characteristic makes ISAR a valuable instrument for imaging of non- cooperative targets. ISAR has found many applications for target recognition.

An ISAR obtains target images based on Range/Doppler imaging. The imaged target, such as an aircraft, moves with respect to a coherent radar which is normally stationary on the ground. High range-resolution cells on the target could be obtained by transmitting a signal with large bandwidth. Resolution in the cross-range direction can be obtained when the equivalent rotation of the target causes significant differential Doppler frequencies between different points on the target in the same range cell.

In general, there are three causes of defocusing in ISAR imaging : phase and range drifts caused by target movement along the radial direction, phase and amplitude distortions in transmit waveform, and non-uniform rotation rate of the target. Without stringent calibration, the phase and amplitude distortions in the transmitted waveform that spans a wide bandwidth would degrade image quality mainly in range direction. The non-uniform rotation rate of target during integration interval leads to image blurring in the cross-range direction. However, the range drift of targets in the slant range direction can cause defocusing in both directions. The motion compensation algorithm [4-7] removes the effects of range drift. It is regarded as the basis of an ISAR imaging algorithm, and plays an essential role in solving other defocusing causes.

The motion compensation algorithm discussed here is based on the cross-correlation of consecutive radar profiles. This method assumes that the radar pulse repetition interval (PRI) is small enough. The target attitude remains almost unchanged during this time span, leading to little variation between textures of consecutive radar returns except for the effect of range drift. Hence, the cross-correlation of consecutive radar returns can be used to estimate the slant range movement.

This algorithm has gained considerable popularity due to largely its simple assumption that target echoes, as demonstrated in chamber

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experiments, might be suited to most radar systems. However, for imaging targets in field situations, the image qualities suffer severely from the real echo fluctuations and error propagation properties inherent in the algorithm. In fact, the fluctuation, as well as the propagation properties, have put an extreme burden on any motion compensation system since the subwavelength knowledge of target movement has to be maintained during the aperture generation time. In order to obtain high quality images, the effects of the fluctuations and error propagation have to be further evaluated.

This paper presents an improved motion compensation method based upon the method mentioned above. The new algorithm utilizes limiting and integration of consecutive range profiles to eliminate the fluctuating portion of the range profiles, and enhance the relatively stable portion. Amplitude limitating of range profiles can reject strong scintillation in target echo; Integration can depress small perturbations and, furthermore, alter the propagation of compensation errors. After accumulation, the large compensation errors do not propagate to the next profiles, and as such the propagation rate of small compensation errors has been depressed. Therefore, accumulation and limitation of adjacent range profiles can improve the alignment accuracy of both range and phase drifts caused by target movement along the radial direction, and alter the propagation properties of alignment errors as well. This paper first describes the principle of cross-correlation for motion compensation as well as its drawbacks. Then the improved method, based on limiting and integration of aligned range profiles, is presented. The experimental results of four types of aircraft in field situations are shown in the last section.

Ⅱ. Cross-correlation for motion compensation

The fundamental concept of cross-correlation for ISAR motion compensation is to make an estimation of range drift based on two adjacent range profiles (or range images). The estimation process exploits the textural similarity between consecutive range profiles that is independent of the underlying range drift. Choosing range profiles as the beginning of the process implies that we need not know how the range profiles were formed, only that the range image should be phase coherent over the aperture generation interval.

Let us denote $e_i(r)$, $e_{i+1}(r)$ as progressive range profiles, $S_i(k)$, $S_{i+1}(k)$ are the corresponding spectra, respectively. In addition, suppose that during this PRI, the target moves Δr_i. Then we have

$$S_i(k) = W_i(k) \tag{1}$$

$$S_{i+1} = \exp(j\varphi_i - j2\pi\Delta r_i)\, W_{i+1}(k) \tag{2}$$

$$e_i(r) = \int S_i(k)\exp(j2\pi kr)dk \tag{3}$$

where, $W_i(k)$ is the spectrum of target image in range direction, k is the wave number, $k = 2\pi/\lambda$, λ is the wavelength of the transmitted signal, and φ_i is the Doppler phase drift caused by target movement during this PRI

$$\varphi_i = -4\Pi f_0 \Delta r_i / C \tag{4}$$

The f_0 in Eq. 4 is the carrier frequency of radar transmitted signal, and C is the velocity of light. Eq. 2 shows that the effects of target movement result in an exponential term between the spectra of adjacent range profiles. The cross-correlation function (CCF) of the profiles is given by

$$\begin{aligned} R_{i(s)} &= \int e_{i+1}(r+s)e_i^*(r)dr \\ &= e^{j\psi_i}\int |W_i(k)|^2 \exp[j2\pi k(s-\Delta r_i)]dk \end{aligned} \tag{5}$$

where the asterisk denotes conjugation. Let us suppose that usually the radar sampling rate in azimuth direction, PRI, is small enough, and that little change occurs in adjacent range profiles except the phase and range drifts. Based on the assumption we have, $W_{i+1}(k) \cong W_i(k)$. Eq. 5 can then be approximately rewritten as

$$R_i(s) \approx e^{j\psi_i} \int |W_i(k)|^2 \exp[j2\pi k(s-\Delta r_i)]dk \quad (6)$$

It is shown that the $R_i(s)$ reaches a peak at $s=\Delta r_i$. Therefore, we may obtain the estimated range drift by looking for an amplitude maximum point in the detected CCF. Note that the phase of CCF at peak point is just φ_i, which is the constant phase shift between the two range profiles caused by target movement. So we can estimate the value of the range and phase drifts, $\widehat{\Delta r_i}$ and $\widehat{\varphi_i}$, from the same estimation function. Based on the estimated results we may form a compensation factor

$$comp(k) = \exp(-j\,\widehat{\varphi}_i + j2\pi k\Delta\,\widehat{r}_i) \quad (7)$$

$S_{i+1}(k)$ can then be compensated by multiplying it with the compensation factor. Thus the effects of range drift have been removed from the radar returns.

Ⅲ. Problems of common motion compensation method

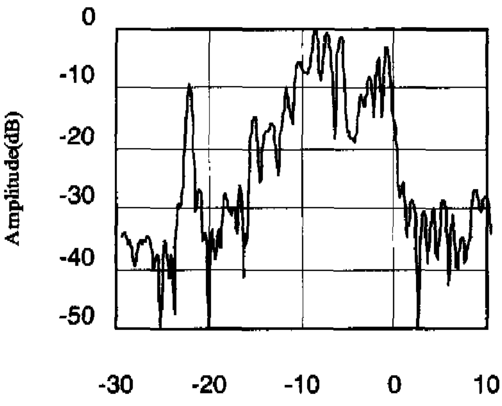
The motion compensation algorithm based on cross correlation stems largely from its simplicity, the efficiency of computation, and its applicability to almost all kinds of targets. Nevertheless, in real applications, the variations of adjacent range profiles have a strong impact on the compensation accuracy. When the radar returns are stable, high quality images can be obtained from this method. On the contrary, when the returns, or parts of them, vary drastically during the integration interval, the images will be seriously degraded.

ISAR relies on the rotation of the target to discriminate scattering points in the azimuth direction, but rotation of the target causes fluctuations of the target echoes. The varying rate of the echoes from one scattering point on the target depends on the distance between the point and a nominal rotation center on the target, or Doppler centroid. If the point were far from the Doppler centroid, Doppler phase would drift drastically between adjoining range profiles, degrading the estimation accuracy. Target rotation may also cause some rapid variations between pulses because of shadowing by other parts, and the resonant phenomena that are very sensitive to incident angle.

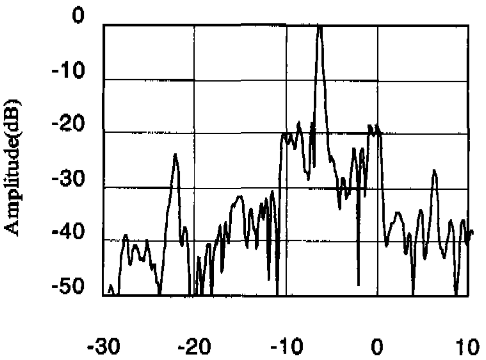
Moving parts of the target, such as jet engine turbine blades, also cause significant fluctuation of range profiles. If deramp range compression or stretch is adopted in some ISAR systems to reduce sampling rate and ease the implementation of ISAR systems, the fluctuation becomes more severe because of the nature of range-Doppler coupling inherent in such systems. Due to these reasons, it is very difficult for the compensation algorithm based on cross-correlation to align properly the range profiles when the fluctuation parts of echoes become too strong.

Fig.1 illustrates two sequential range profiles of a jet aircraft along with reflections from the engine turbine. The actual change in range between them is about 0.06m. The correlation result is shown in Fig. 2 (a). Due to the effects of turbine blades at the central part of the profiles, the correlation has a peek at 2.15m. That is, the alignment error is 2.09m. One cannot expect high quality images in this case.

The traditional motion compensation method based on cross-correlation of consecutive range



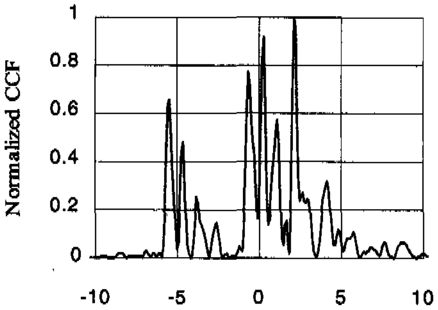
(a) Range(Meter)



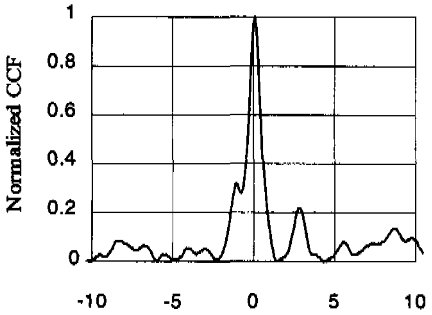
(b) Range(Meter) r)

Fig. 1 Adjacent range profiles of turbine aircraft.

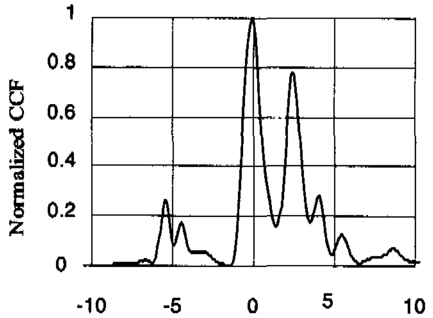
profiles utilizes only two neighboring range profiles. When the procedure of estimation and compensation is used, the previous range profile serves as a reference, aligning the current profile with the previous one. Unfortunately, the previous one is also aligned through the same procedure, so that it may also contain some alignment errors. If errors were induced during the alignment process of the previous range image, such errors surely would propagate to the following aligned range profiles.



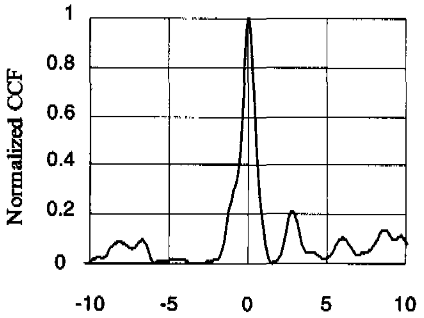
(a) Range(Meter)



(b) Range(Meter)



(c) Range(Meter)



(d) Range(Meter)

Fig. 2 CCF of range profiles.
(a) CCF of two range profiles.
(b) CCF with limitation.
(c) CCF with accumulation.
(d) CCF with limitation and accumulation.

Suppose the misalignment of $e_i(r)$ is δ_{r_i}. When we estimate the range walk of $e_{r+1}(r)$, a new misalignment may be induced. Due to the propagation properties of the compensation procedure, the compensation error in *i+1st* range profile would be

$$\Delta r_{i+1} = \sum_{n=1}^{i+1} \delta r_n \qquad (8)$$

Therefore, the traditional cross- correlation method has a drawback of error propagation properties. Once an estimation error is caused in a single step, it would spread to all of the succeeding range profiles. Step by step, the compensation errors soon become intolerable, severely defocusing two- dimensional target images.

Ⅳ. Dynamic range compression of target echoes

If we carefully examine Fig. 1, we can see that the echoes of turbine blades cause strong modulations in the central portion of the range profiles, but the rest of the target echo is relatively stable. Because the echoes from the turbine blades fluctuate drastically, large estimation errors are incurred especially when the blade echoes become too strong. By the way, if the scintillations could be depressed with the stable part enhanced, the alignment accuracy would be improved. Limiting the amplitude of complex range profiles can serve for this purpose. But jet engine modulation depends on head-on or near head-on viewing of the aircraft. By limiting the amplitude of the echoes from the turbine blades becomes relatively similar to that from the rest of the target. Because the area where blade scintillations are generated occupies a small portion compared to the whole target echo extent, the fluctuation level can then be depressed through the amplitude limitation, consequently enhancing stable parts of range profiles.

Fig. 3 shows two sequential range profiles that are the same as in Fig. 1 except dynamic range compression in logarithmic scale. At this time, the two range profiles now become more alike. Hence, the estimation accuracy based on the cross-correlation of dynamic compressed profiles can be improved. From now, we will analyze the consequences and impacts of magnitude limitation. Let us also suppose, as mentioned above, that $e_i(r)$, $e_{r+1}(r)$ are the adjacent range profiles, respectively, and that the range change between them is Δr_i. To compress the dynamic range of the adjoining range profiles, each range profile should be limited as

$$\overline{e}_i(r) = \begin{cases} e_i(r) & |e_i(r)| < H_i \\ e_i(r)H_i/|e_i(r) & |e_i(r)| \geq H_i \end{cases} \tag{9}$$

where $\overline{e}_i(r)$ is the output range profile of the limiter, Hi is a threshold. Since $\overline{e}_i(r) \cong \overline{e}_{i+1}(r)$, their complex CCF can be approximately written as

$$\begin{aligned} e_i(s) &= \int \overline{e}_{i+1}(r+s)\overline{e}_i^*(r)dr \\ &\approx e^{j\varphi} \cdot \int |\overline{W}_i(k)|^2 \exp[j2\pi k(s-\Delta r_i)]dk \end{aligned} \tag{10}$$

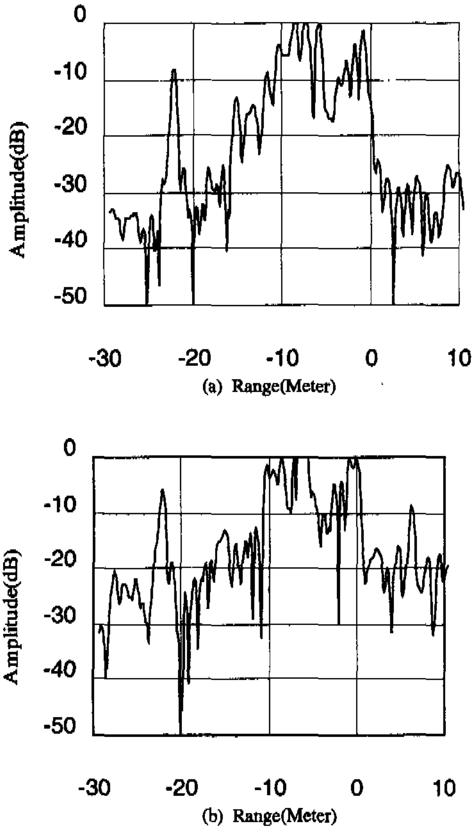


Fig. 3 Profiles of turbine aircraft after dynamic range compression

where, $\overline{W_i}(k)$ is the amplitude- limited spectrum of $\sigma(r)$ target reflectivity function, obtained in the *i-th* PRI. From Eq. 9 we can get the estimations, $\widehat{\varphi}_i$ and $\Delta\widehat{r}_i$, of φ_i and $\Delta\widehat{r}_i$ based on the same principle described before. Then the estimated value can be used to compensate for the effects of range drift. Note that the scintillation in $\overline{e}_i(r)$ has been depressed through limiting, so consequently the estimation accuracy can be improved. Fig. 2 (b) is the correlation function of the compressed range profiles. It can be seen that the effect of the blade scintillation has been rejected and the correlation function has already reached a peak at the correct position.

The selection of the threshold of the limiter. Hi is very important. If Hi is too low, the shape information of the range profile is probably lost and signal to noise ratio also suffers from heavy limitation, leading to increasing alignment error. Whereas if Hi is too high the echo is not sufficiently compressed, which also degrades the alignment performance. The rationale is that different range profiles with various dynamic ranges should have similar dynamic range after limitation. Therefore, for a particular range profile, there exists a most suitable threshold for dynamic range compression, and the selection of the threshold must be adaptive in order to perform the motion compensation automatically. An adaptive method has been justified by the returns from turbine aircraft targets. It first identifies three maximal peaks in every range profile. Two of them may be the turbine blade echoes that degrade the compensation accuracy when they exceed a criterion. The amplitude of the third peak is taken as the limiting threshold. This selection method can depress strong blade echoes and meanwhile can maintain the main features of range profiles. It is also found that the estimation accuracy is not very sensitive to the selection of threshold within an acceptable range.

Many other approaches of dynamic range compression have been adopted to improve the estimation accuracy, but the limiting method mentioned above proves to be the best. This method can give a cross-correlation function with the sharpest mainlobe, whereas all the other approaches broaden the mainlobe of the cross-correlation function, hence decreasing the estimation accuracy.

V. Accumulation of consecutive range profiles

Limiting can only depress strong scintillation, but cannot cope with smaller perturbations occupying large scope. Moreover, the compensation algorithm still retains the drawback of error propagation properties, which is very deleterious to obtain high quality images.

One common approach for depressing noise and interference in traditional radar is to adopt coherent integration of radar returns. However, at first glance the accumulation of consecutive range profiles can not be adopted because they are dispersed in slant range direction. If the absolute range from radar to target comes from a tracking radar, and the ISAR system does not record the range values in each PRI, then every range image may scatter randomly in slant range direction. In such a situation, it is very difficult to employ integration to improve estimation accuracy. However, from analysis, we know that accumulation can be used to improve the quality of the reference of the correlation.

In traditional motion compensation procedures, two range profiles are involved in every step. The previous profile serves as a reference to align the current profile. If the reference becomes more stable, the estimation accuracy can be improved. Notice that this reference has already been aligned properly with all the pervious profiles, so the accumulation of some previous profiles can be employed to form a new and better reference. In fact, the accumulation can be further regarded as a low-pass filter in cross range. After low-pass filtering, the fluctuating parts are smoothed and the stable parts enhanced. Next we will analyze the properties of the effects of accumulation in detail.

The spectra of radar returns and their corresponding range profiles can be divided into two parts, the stable and the fluctuating parts

$$\overline{S}_i(k) = \overline{S}_{1i}(k) + \delta\overline{S}_i(k) \tag{11}$$

$$\overline{e}_i(r) = \overline{e_{1i}}(r) + \delta\,\overline{e}_i(r) \tag{12}$$

where, $\overline{e_{1i}}(r)$ and $\delta\overline{e}_i(r)$ are stable and fluctuating parts of the range images after dynamic range compression, $\overline{S_{1i}}(r)$ and $\delta\overline{S}_i(r)$ are stable and variable parts of the spectra, respectively, $i=1,2,\cdots\cdots N+1$. In the motion compensation method based on limiting, the current amplitude-limited range profile, $\overline{e}_{N+1}(r)$, is only correlated with previous one, $\overline{e}_N(r)$. Now it is correlated with the sum of N previous range profiles

$$R_i(s)=\int\Big[\sum_{i=1}^{N}\overline{e}_i^*(r)\Big]\overline{e}_{N+1}(r+s)dr$$

$$\approx R_{1i}(s)+R_{2i}(s) \qquad (13)$$

where, $R_{1i}(s)$ is the sum of cross-correlations between the stable parts of range profiles

$$R_{1t}(s)=\sum_{i=1}^{N}\int\overline{S}_{1N+1}(k)\,\overline{S}_{1i}^*(k)\exp[j2\pi k(s-\varDelta r_N)]dk \qquad (14)$$

$R_{2i}(s)$ is the cross-correlation between stable and variable parts of the range profiles

$$R_{2i}=\sum_{i=1}^{N}\int[\overline{S}_{N+1}(k)\,\overline{\delta}\,S_i^*(k)\,\overline{S}_{N+1}(k)]$$

$$\times\exp[j2\pi k(s-\varDelta r_N)]dk \qquad (15)$$

It can be seen that the CCF consists of two parts. One is the sum of cross correlation between stable parts. Since stable parts do not change dramatically, they can be summed up mainly in phase. Whereas the other is the sum of cross correlation between stable and changing parts. Since the changing parts fluctuate almost randomly in each range profiles, they will be added up mainly in power. So that the accumulation of CCF can depress the effects of fluctuation parts in range images, consequently improving the imaging quality.

Fig. 4 shows the same range profiles as those in Fig. 1 except accumulation. It shows that the fluctuation, near the center of each profile caused by turbine blade rotation has been depressed, so the estimation accuracy can be improved if the accumulated profile is taken as the correlation reference. Fig. 2 (c) is the correlation result based on integration with no limiting. Although the CCF reached a peak at the correct position, it contains a strong sidelobe, which might surpass the mainlobe if the modulation becomes stronger. Fig. 2 (d) is the correlation result with both integration and limiting of adjacent range profiles. Because the strong modulation and the small interference have been diminished significantly through limiting and integration, the CCF has reached a very clear peak at correct position. Such results show that both limitation and accumulation are required to guarantee the alignments of consecutive range profiles.

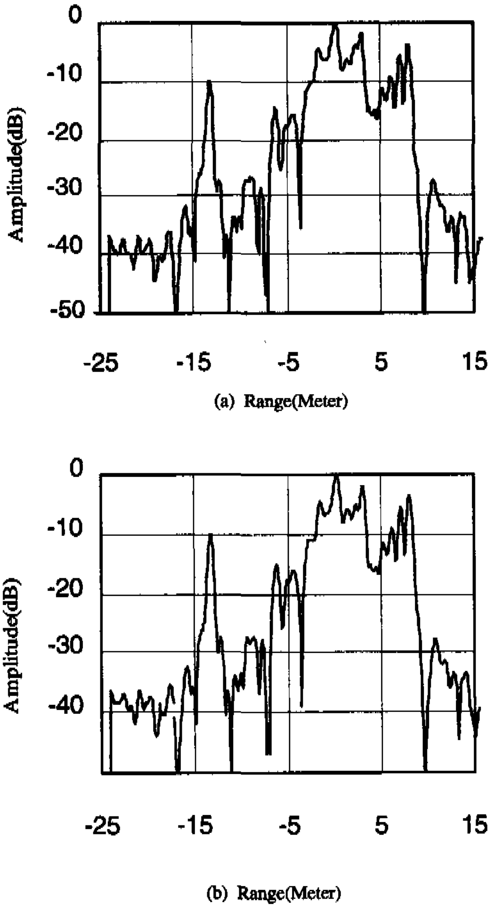
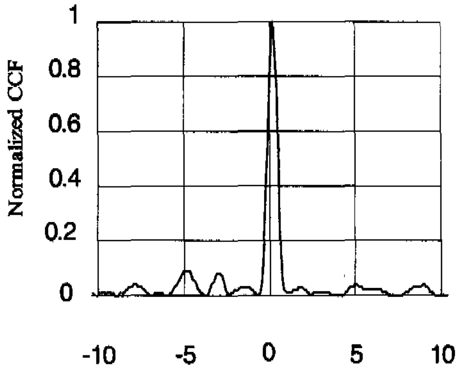


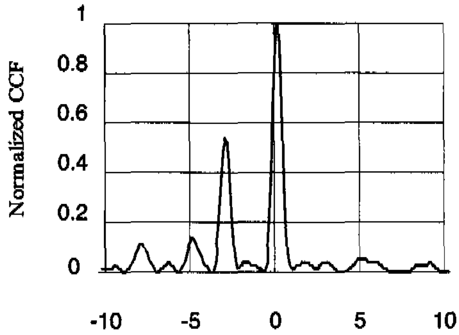
Fig. 4 Consecutive range profiles after accumulation.

Ⅵ. The error propagation properties of integration on cross-orrelation method

The unique merit of integration cross-correlation method is that it reduces the error propagation property. In this method, the combination of N range images, instead of only one, is taken as the correlation reference function. Therefore, if some of the range images have compensation errors, they cannot be dispersed totally to the next profile. Especially when the errors are relatively large, say larger than one range resolution cell, they hardly affect the following estimation accuracy. Fig. 5 (a) is a CCF between the current profile and the combination of 10 previous profiles. Now we deliberately let 4 out of them have an error of 3 meters. Fig. 5 (b) shows the correlation results. The CCF still reaches a peak at correct position. The previous compensation errors only affect the sidelobes of the CCF, Causing few distortions to the mainlobe. That is the essential reason why accumulation compensation method can significantly improve the imaging quality of ISAR.



(a) Range(Meter)



(b) Range(Meter)

Fig. 5 CCF of range profiles. (a) CCF with accumulation of 10 previous profiles. (b) CF, 4 out of 10 previous profiles have3meters alignment error.

The accumulation algorithm also benefits the estimation of Doppler phase drifts based on similar principle as range drift estimation. Moreover, it has some extra benefits to the phase drift estimation. When we integrate the previous range profiles, the echoes from the scattering points far from the Doppler centroid cannot be added up coherently because of the large phase variations between each PRI. Meanwhile, the echoes from the scattering points relatively near the Doppler centroid are mainly added up in phase because their phase drift during one PRI changes only a little. Therefore, such parts of echoes have been enhanced.

In summary, the integration of previous range profiles has improved the performance of cross-correlation motion compensation algorithm from two aspects. First, it can equivalently serve as a low-pass filter in azimuth direction, effectively rejecting the disturbance of Doppler centroid by target rotation in various directions. Second, the integration has altered the error propagation properties of the motion compensation algorithm based on cross-correlation of neighboring range profiles. Through integration, the large error no longer transfers to the next estimation procedure, and the propagation rate of small estimation errors has been decreased as well.

The selection of the number of profiles to integrate is an important issue. If profiles in sequence are all coherent, more profiles may result in better estimation accuracy. However, ISAR discriminates scattering points in azimuth direction based on Doppler phase drifts caused by target rotation. That means the echoes must vary intrinsically between each PRI. If more range profiles contribute to form the correlation reference, the reference will be far away from the current profile that is to be aligned, consequently degrading compensation performance. As mentioned above, integration is equivalent to a low-pass filter. Both filter type (FIR or IIR) and filter bandwidth have to be determined adaptively in accordance with PRI, size of targets to be imaged, and range resolution. So far this complicated issue is beyond the scope of this paper and will be discussed thoroughly in another paper. One filter with finite impulse response has been identified with real target echoes. It makes an adaptive low-pass bandwidth by adjusting the number of range profiles integrated equal to the number of profiles collected during one angular sampling interval. This filter is suitable for most situations since the angular sampling interval is related to the PRI, rotation rate of target, and target size.

Ⅶ. Experimental results and conclusion

The motion compensation method described above has been verified with recorded echoes from real target by using an experimental C-band ISAR. The signal bandwidth of this ISAR is 400MHz, and the rotation angle in each image is 4 degrees. This gives a resolution of about 0.375m in both range and cross-range directions. The targets include four types of aircraft in field situations.

Fig. 6 shows the imaging results obtained with the traditional cross correlation motion compensation method. It is seen at a glance that the imaging quality is not good enough due to target echo fluctuation. The imaging results obtained with the motion compensation algorithm based on integration are illustrated in Fig. 7. These images have much better quality.

Fig. 6 Imaging results by traditional correlation algorithm.

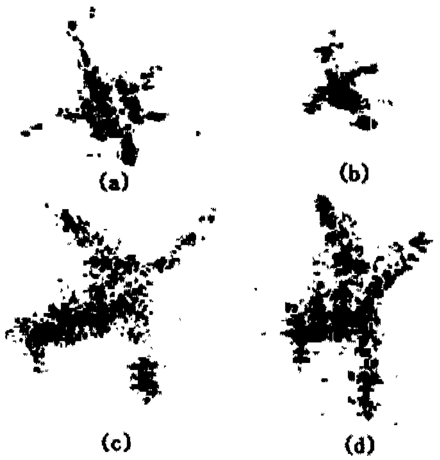


Fig. 7 Imaging results by limitation and accumulation.

In summary, the performance of the motion compensation algorithm with a common signal cross-correlation suffers from target echo fluctuation. The improved algorithm presented in this paper exploits integration to reduce the interference in aligned range profiles. The effects of integration can be regarded as a low-pass filter, forming a correlation reference with better quality, and altering the error propagation property. Thus, the imaging quality can be improved. The imaging results have shown the ability of the motion compensation algorithm described in this paper.

References

[1] C. C. Chen, and H. C. Andrews, "Target-Motion Induced Radar Imaging," *IEEE Transactions on AES.*, AES-16, pp. 2-14, Jan. 1980.

[2] Dale A. Ausherman, A. Kozma, J. L. Walker, H. M. Jones, and E. C. Poggio, "Developments in radar imaging," *IEEE Transactions on AES.*, AES-20. pp. 363-400, July. 1984.

[3] R. Goodman, Nagy W. Wilhelm, "A High Fidelity Ground to Air Imaging Radar System.," *IEEE Record of IEEE National Radar Conference* , 1994.

[4] Xu Rongqing, Cao Zhidao, and Liu Yongtan, "Motion Compensation for ISAR and Noise Effect," Record of ISNCR 89, IN Japan.

[5] Xu Rongqing, Cao Zhidao, Liu Yongtan, "A New Method of Motion Compensation for ISAR," *Proceedings of IEEE International Radar Conference*, 1990.

[6] Gilles Y, Delisle, and Haiqing Wu, "Moving Target Imaging and Trajectory Computation Using ISAR," *AES-30*, pp. 887-899, July 1994.

[7] Haiqing Wu, and Gilles Y. Delisle, " Precision Tracking Algorithms for ISAR Imaging," *IEEE Transaction on AES*, AES-32, pp. 243-254, Jan. 1996.

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