Final Report for EE381K Project

Inverse Synthetic Aperture Radar Imaging

Junfei Li
Electrcial and Computer Engineering
University of Texas at Austin

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Abstract

High-resolution radar images can be achieved by employing SAR or ISAR techniques. It can be shown that SAR and ISAR have the same underlying theory but different configuration. Here the specific problem of aircraft ISAR imaging using ground-based radar is addressed.

Three ISAR imaging scenarios, namely ISAR imaging with the normal motion compensation, ISAR imaging with the EM model, and ISAR imaging with GPS data are studied, with emphasis on GPS-aided imaging.

As motion plays a critical role in ISAR, we study how the motion compensation should be done to focus the echoed data into a 2-D image. Besides the normal motion compensation, which uses the data sets themselves, here GPS-aided motion compensation is proposed and studied in detail, which uses GPS motion data of the aircraft as an additional input. Comparison of these two cases help to expose problems of the normal motion compensation and to form a better understanding of ISAR imaging process. EM model-based imaging results can be regarded as a third reference for the comparison. Neither GPS-aided imaging nor comparison between it and normal motion compensation imaging or EM model-based imaging has been reported, therefore this work is both initiative and difficult in this sense.

After giving problem definition and objectives of the project, this final report presents the underlying theory of ISAR imaging. Then emphasis is on the implementation and results. Conclusions and suggestions on further work are given in the last section.

Key words: ISAR, norm motion compensation, GPS data, EM model

1. Introduction

High-resolution radar imaging is interdisciplinary and has wide application in many different areas [1 and 5]. In radar remote sensing, synthetic aperture radar (SAR) images are usually used to map the terrain. In the defense industry, inverse synthetic aperture radar (ISAR) imaging of moving objects is an important tool for automatic target recognition. The problem of radar imaging of an aircraft using ISAR is addressed in this project, with emphasis on motion compensation.

Although both SAR and ISAR have the same underlying theory, they differ in geometry configuration. In SAR imaging, the radar is flying in space, and the object is stationary, while in ISAR imaging, the object is moving and the radar is stationary. Since only the relative movement between the object and the radar is important, the ISAR imaging problem is found to be equivalent to the more easily understood SAR imaging problem.

From a signal processing viewpoint, radar imaging is a 2-D signal processing problem [2]. To form an image, 2-D resolution must be defined for radar imaging. Here the two-dimensional discrimination is realized by compression in the range direction and synthetic aperture in the cross range direction. Actually, radar echoes are just 1-D time series, but it is convenient to format this 1-D signal into 2-D signal.

Radar images can be called as motion-induced images. Hence, in both SAR and ISAR, motion is the problem and the solution [3]. In ISAR, the motion compensation is more challenging as we have no prior knowledge about the object, and in some case the object like the aircraft can exert complex movement. It can be observed that the normal motion compensation might fail at time during flight.

To assess GPS-aided technique, we compare its results against those from the normal motion compensation and the electromganetic (EM) model. We expect to get a better image with the GPS motion data as an additional input, and improve our understanding the ISAR imaging process.

2. Objectives

The objective of this project is to better understand ISAR imaging by comparing the GPS-aided motion compensation technique with the normal motion compensation technique and the EM model prediction. With GPS data as an additional input, GPS-aided motion compensated image should be better than the normal motion compensated images. If this is not the case, a reason should be given regarding to the accuracy of the GPS data. At the same time, evaluation of the normal motion compensation technique and validation of the EM model can be done.

3. Theory and Algorithm

Fig. 1 illustrates the ISAR concept and geometry [3]. It shows a stationary radar sensor illuminating a passing aircraft. The linear waveform radar has pulse width T_p and pulse repetition time T . The instantaneous frequency is

$$f = f_c + K(t - nT) \qquad (1)$$

where f_c is the radar carrier frequency. $t = nT$ corresponds to the center of the pulse n. The bandwidth B of the pulse is KT_p, where K is called the chirp rate. The spatial resolution in the range dimension achievable by pulse compression is

$$\rho_r = \frac{c}{2B} \qquad (2)$$

The angular interval $\Delta\theta$ is the angle through which the target is viewed during the coherent processing aperture. It is usually no more than a few degrees in ISAR imaging. The spatial resolution in the cross-range dimension achievable by synthetic aperture processing is

$$\rho_a = \frac{c}{2 f_c \Delta\theta} \qquad (3)$$

The transmitted signal in the complex exponential form is

$$s_x(t_n, t) = rect(\frac{\hat{t}}{T_p}) e^{j[2\pi f_c t + \pi K \hat{t}^2]} \qquad (4)$$

where $\hat{t} = t - nT$. For simplicity, the transmitted signal is normalized to have unit magnitude.

Assuming an ideal point at (x_t, y_t, z_t) has complex radar cross-section σ_t, the received signal is a scaled and time-delayed version of the transmitted signal:

$$s_r(t_n, t) = a_t rect(\frac{\hat{t} - t_d}{T_p}) e^{j2\pi f_c (t - t_d)} e^{j\pi K(\hat{t} - t_d)^2} \qquad (5)$$

where $a_t = \sqrt{\sigma_t}$ and t_d is the round trip delay time from the radar antenna to the target.

$$t_d = \frac{2R_t}{c} = \frac{2\sqrt{(x_a - x_t)^2 + (y_a - y_t)^2 + (z_a - z_t)^2}}{c} \qquad (6)$$

where (x_a, y_a, z_a) corresponds to the antenna phase center (APC) position.

The baseband signal in the receiver [4] is:

$$S(f_x, f_y) = e^{(-j4\pi R_t(t)/c)} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} a_t(x_t, y_t) e^{(-j2\pi(xf_x - yf_y))} dx_t dy_t \qquad (7)$$

where the components of the spatial frequency are:

$$f_x = \frac{2 f_c}{c} \cos\theta(t)$$
$$f_y = \frac{2 f_c}{c} \sin\theta(t) \qquad (8)$$

Notice that we have assumed a planar movement of the target in the (x, y) plane and $\theta(t)$ corresponds to the azimuth angle.

If the motion of the target is know exactly, we can determine the term $R(t)$. Then the reflectivity function can be obtained by inverse Fourier transform of the phase compensated frequency signature $S(f_x, f_y)\exp\{+j4\pi fR(t)/c\}$. This is the basic idea of GPS-aided imaging. In contrast, without target movement information, he normal motion compensation can achieve this through the radar data themselves, it usually consists of two steps: range alignment (coarse motion compensation) and autofocus (fine motion compensation) [6].

The azimuth data $\theta(t)$ are used to account for unevenly sampling effects of defocusing in the cross-range direction. In addition, this term is needed for scaling of the ISAR images in the cross-range direction, which is needed to generate EM model-based ISAR images.

4. Implementation and Results

4.1 ISAR imaging with GPS data

First, the GPS data are matched to the radar data in time coordinate since the reference times are different for the two data sets. This can be done by correlating the range from the radar track data with the range from the GPS data. The GPS data is also resampled with spline interpolation as the refreshing time for the GPS time is much smaller than the pulse repetition time of the radar. Fig. 2 shows the time-matched GPS range and radar track range.

Second, coordinates transformation is done to generate azimuth and elevation data of radar wave incident on the aircraft from the GPS attitude data. It is due to the fact that the GPS data is in the reference system of the earth while the needed azimuth and elevation data are in the local system of the aircraft. The azimuth angle is shown in Fig. 3.

Third, range alignment is done with the GPS range. Because the measurement data is acquired by applying range alignment with the radar track data, we need to compensate the range difference between the GPS data and the radar track data. This can be achieved by phase compensation after inverse FFT of the measurement data in the range direction:

$$S(i,n) = \exp(+j2\pi(f_c + f_r(n))\Delta t_r(i) + \pi K \Delta t_r(i)^2) S(i,n), \quad 0 \le i \le N_p - 1, 0 \le n \le N_s - 1 \quad (9)$$

which implies there are N_p samples in the cross range direction and N_s samples in the cross range direction. Δt_r is the associated time difference between radar track range and GPS range. The resultant image is shown in Figure 4.

Although an inverse FFT of the range profile gives a relatively good ISAR image of the aircraft, a fourth step called azimuth resampling is done with the GPS azimuth angle in the cross range direction. By using inverse FFT in the cross-range direction, we assume that the data are evenly sampled in azimuth angle. Observation of Figure 3 shows this is not true. Therefore, the azimuth angle associated with the range profile is fitted into a second order polynomial expression. Then time coordinates for evenly sampled azimuth angle are found. The range profile is resampled in these new time coordinates along the cross range direction. Figure 5 shows the final ISAR image with motion compensation by means of the GPS data.

Finally, a scaling process represents the ISAR image in meters instead of the digital numbers. While the scaling in the range direction is only dependent on the radar system data, the scaling in the cross-range direction relies on the azimuth data, which are derived from the GPS data. The scaled ISAR image is shown in Figure 6.

4.2 ISAR imaging with normal motion compensation

The adaptive joint time-frequency (AJTF) technique [4 and 6] is used for ISAR imaging with normal motion compensation. By using a search and projection procedure, the reference points can be automatically selected and the desired motion parameters can be figured out. Unscaled ISAR image with normal motion compensation is shown in Fig 7.

4.3 ISAR imaging with EM model

The shooting and bouncing ray (SBR) technique [7] is used to form the ISAR image based on the EM model. As a robust electromagnetical computation method, it can predict the complex reflectivity of a complex target. Scaled ISAR image with EM model is shown in Fig. 8.

5. Conclusions

Although only the normal motion compensation can be done in the non-cooperative ISAR imaging scenario, the proposed GPS-aided ISAR imaging in this scenario has been found to be useful in two senses. First, it has generated additional ISAR images, which are independent of ISAR images from the normal motion compensation technique and the EM model. Second, only the GPS-aided imaging method can generate the scaling factor along the cross-range direction, which makes the straightforward comparison between normal motion compensation results and EM model results possible.

The performance of GPS-aided ISAR imaging is satisfactory when it is applied in the measurement data of our project. This is observed by comparing its results with those from the normal motion compensation method and the EM model. The GPS-aided mages are a little less focused than the normal motion compensation images in some cases, possibly owing to the limited accuracy of the GPS data. But the GPS-aided images are more consistent than the normal motion compensation images in that in cases where the normal motion compensation technique completely fails, the GPS-aided method still generates ISAR images retaining the shape of the aircraft. To overcome the enigma of the normal motion compensation, more point scatters are suggested for the autofocusing process whenever the output image is out of focus. After evaluation of the normal motion compensation and validating of the EM model, our further work is on target identification with ISAR imaging.

References

1. D. A. Ausherman, A. Kozma, J. L. Walker, H. M. Jones, and E. C. Poggio, "Developments in Radar Imaging," *IEEE Trans. Aerospace Electron. Syst.*, vol. 20, pp.363-400, July 1984.
2. D. C. Munson and R. L. Visentin, "A Signal Processing View of Strip-Mapping Synthetic Aperture Radar," *IEEE Trans. Acoust, Speech, Signal Processing*, vol. 37, pp.2131-2147, Dec. 1989.
3. W. G. Carrara, R. S. Goodman, and R.M. Majewski, *Spotlight Synthetic Aperture Radar-Signal Processing Algorithms*, Boston: Artech House, 1995.
4. V. C. Chen and S. Qian, "Joint Time-Frequency Transform for Radar Range-Doppler Imaging," *IEEE Trans. Aerospace Electron. Syst.*, vol. 34, pp.486-499, Apr. 1998.
5. D. R. Wehner, *High-Resolution Radar* (2nd edition), Boston: Artech House, 1994.
6. Y. Wang, H. Ling, and V.C. Chen, "ISAR Motion Compensation Via Adaptive Joint Time-Frequency Technique," *IEEE Trans. Aerospace Electron. Syst.*, vol. 34, pp.670-677, Apr. 1998.
7. H. Ling, R. Chou, and S.W. Lee, "Shooting and Bouncing Rays: Calculating the RCS of an arbitrarily shaped cavity," *IEEE Trans. Antennas Propagat.*, vol.37, pp.194-205, Feb. 1989.

Figures

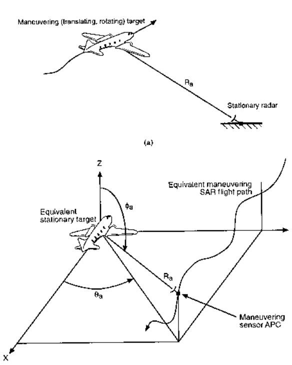

Fig.1 ISAR concept and Geometry perspective [3]: (a) moving target and (b) maneuvering sensor

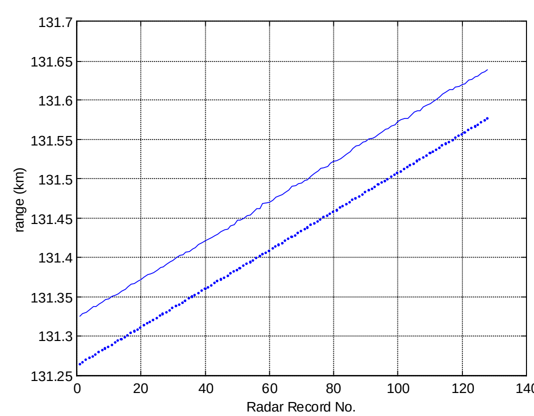

Fig. 2 GPS range (solid) vs. radar track range (dotted)

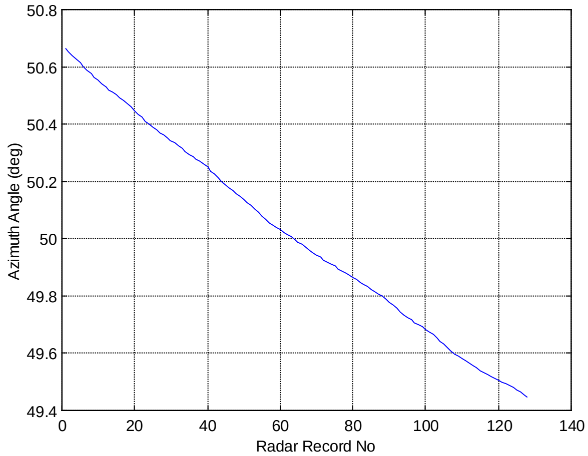

Fig. 3 Azimuth data in local coordinates

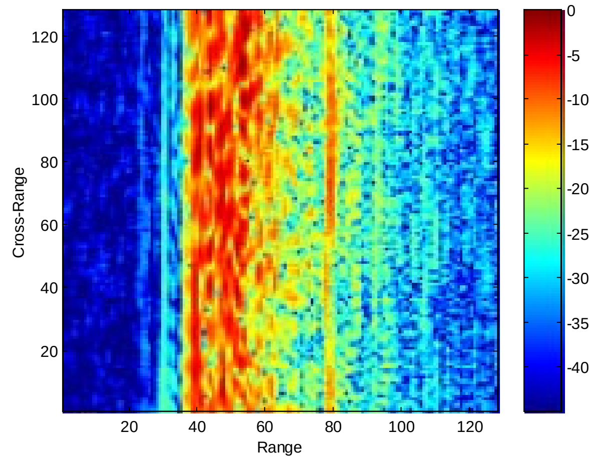

Fig. 4 Range profile with GPS range alignment

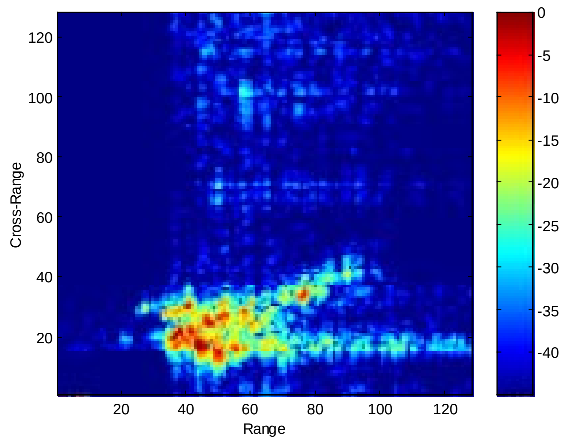

Fig. 5 GPS-aided ISAR imaging: step two

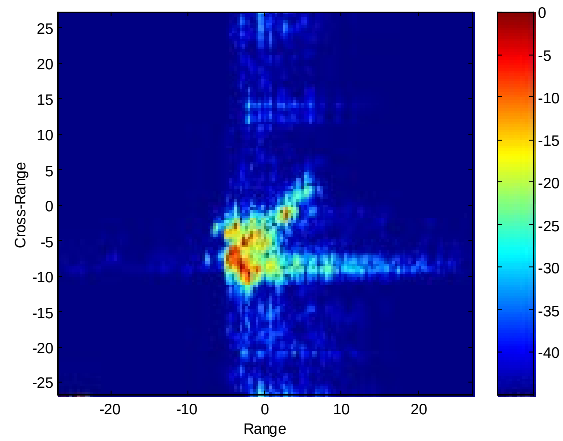

Fig. 6 Scaled ISAR image with GPS data

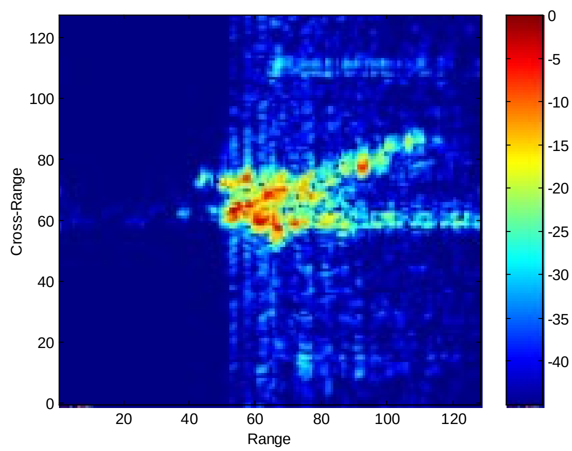

Fig. 7 ISAR imaging from normal motion compensation

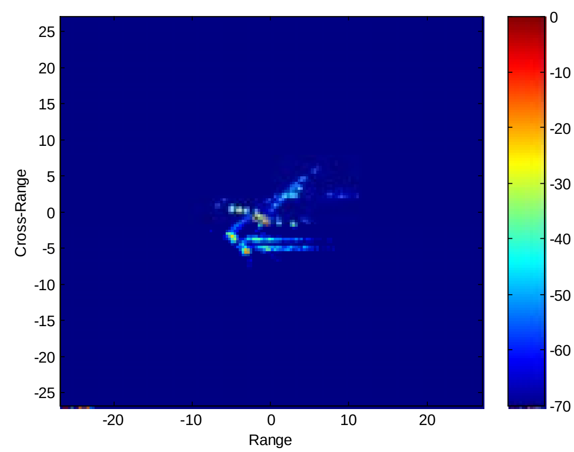

Fig. 8 ISAR image from the EM model