Compressive Sensing Technology for Synthetic Aperture Radar

Author: *Takehiro Hoshino**

1. Introduction

Synthetic aperture radar (SAR) uses sensors installed on satellites and airplanes to monitor the ground day and night in any weather. Although SAR is suitable for observing a wide area, the observation area needs to be expanded to reduce the total observation time. To do this without affecting image quality, Mitsubishi Electric Corporation developed the "DAICHI-2" advanced land-observing satellite-2 with two radar antennas, achieving high-resolution wide swath (HRWS). However, since the number of antennas was increased to two, the amount of data to be downlinked also doubled.

Due to the data volume for HRWS, the downlink faces a shortage of capacity, so the amount of downlink data needs to be reduced. To reduce the data size, compressive sensing technology was proposed in 2006.[1]

Mitsubishi Electric has been developing a compressive sensing technology for SAR that contributes to resource-saving space development[2], [3] and has confirmed in an airplane SAR experiment that even when the data size is halved at regular intervals from the conventional size, the data can be reconstructed. This paper reports the details.

2. Compressive Sensing SAR

Figure 1 illustrates the concept of compressive sensing SAR. In compressive sensing SAR, the observable area is halved and the available extra resource is used to observe another area, thus expanding the coverage.

3. Principle of Compressive Sensing

3.1 Sampling theorem

Compressive sensing is a technology that overcomes the limit of the data size determined by the sampling theorem. The sampling theorem states that to reconstruct data of up to a certain frequency faithfully, it is sufficient to double the sampling frequency. Figure 2 shows an example where, when the sampling theorem is not satisfied, the frequencies cannot be identified. The solid line shows the true wave motion and the circles show signals observed in sampling. The broken line is wave motion (ambiguity) having a high frequency for which the observed values are the same as those in the true wave motion. Whether the solid or broken line is the true wave motion cannot be determined only by observing the circles.

3.2 Random sampling

To solve the problem in Fig. 2, random sampling is used in compressive sensing in general. Figure 3 shows an example of random sampling. In random sampling, the solid line is distinguished from the broken line when

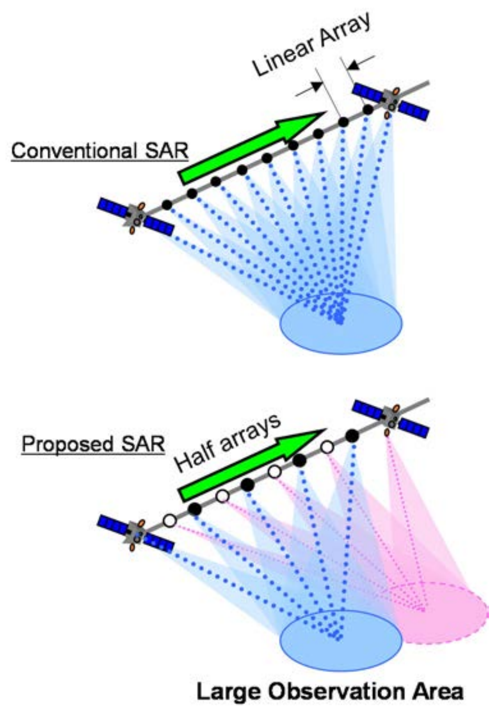

Fig. 1 Concept of compressive sensing SAR

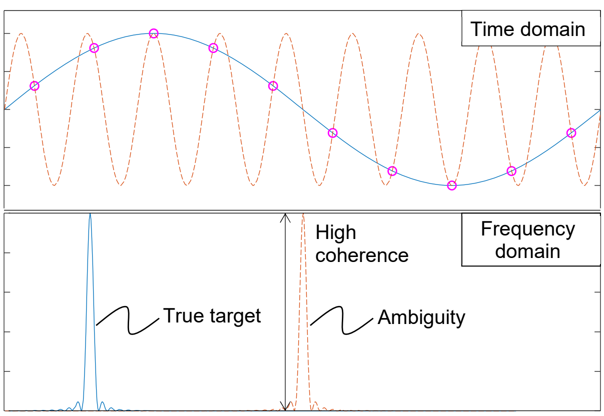

Fig. 2 Two sinusoidal waves on time/frequency domains with sub-Nyquist linear sampling

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observing the circles and so it can be understood that the solid line is the true wave motion. When Fourier transform (FT) is performed on the values observed in random sampling and the frequency domain is analyzed, the high-frequency ambiguity component seen in Fig. 2 is diffused and becomes smaller. This means that the coherence of the ambiguity is reduced.

3.3 Compressive sensing for SAR

In general compressive sensing, random sampling is a solution. However, in SAR, for reflection sources away from the center of observation, changes in distance from the observation point are not even, so the radio waves change as shown by the broken line in Fig. 4 relative to the observation point. Therefore, the solid line can be distinguished from the broken line even in the case of sampling at regular intervals. This means that the coherence of the ambiguity component (broken line) is reduced and the ambiguity's intensity level after FT is lowered. In addition, the solution (SAR image) is extracted on the assumption that the solution is sparse. This is the principle of compressive sensing for SAR developed this time.

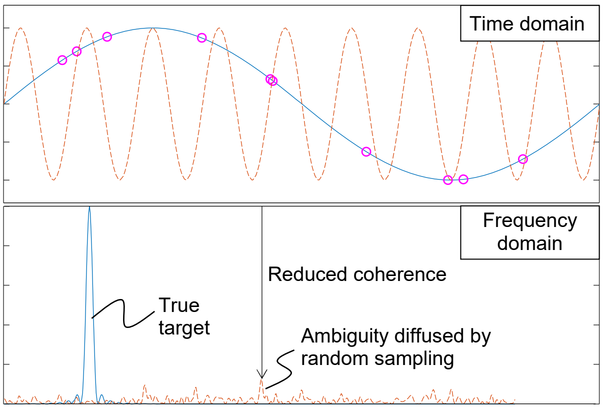

Fig. 3 Two sinusoidal waves on time/frequency domains with sub-Nyquist random sampling

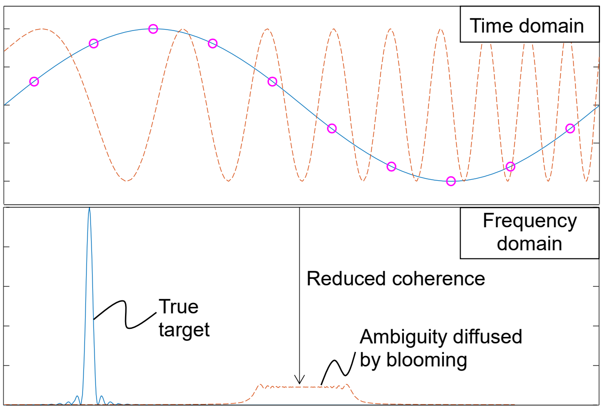

Fig. 4 Two waves of SAR observation on time/frequency domains with sub-Nyquist linear sampling

4. Verification of the Principle in a Ku-band Airplane SAR Experiment

This section studies the effect of compressive sensing for improving the level of ambiguity of a SAR image for which the data size was reduced at regular intervals. Figure 5 shows a Ku-band airplane SAR system developed by Mitsubishi Electric. The airplane was Diamond Air Service Inc.'s Gulfstream-II. Table 1 lists the experimental parameters. The sampling ratio is defined as the value obtained by dividing the pulse repetition frequency (PRF) by the Doppler bandwidth; when the ratio is 1.0 or higher, the sampling theorem is satisfied. Figure 6 shows a SAR image when the data size was reduced at regular intervals and when the sampling ratio was 0.6. Figure 7 shows the result of applying compressive sensing to the data in Fig. 6. The figure shows that compressive sensing suppressed the ambiguity (in the white box) caused by the sampling theorem no longer being satisfied due to the reduction of data size at regular intervals. Figure 8 shows a SAR image that satisfies the sampling theorem. Comparing Fig. 7 and Fig. 8, the data has been equally reconstructed thanks to the compressive sensing. The ratio of the intensity between the point with the maximum intensity among the true points composing the image and the point with the maximum intensity in the ambiguity domain is defined as the ambiguity level. Table 2 shows the evaluation results. The table shows that the ambiguity level was reduced by 9.6 dB to −45.5 dB by compressive sensing compared with −35.9 dB before its application. On the other hand, the ambiguity level of the SAR image satisfying the sampling theorem is −58.7 dB. These results show that compressive sensing could further improve the ambiguity level by 13.2 dB, indicating room for improvement.

5. Conclusion

This basic study of compressive sensing for SAR confirmed in an airplane SAR experiment that even when the data size is halved at regular intervals unlike conventional random sampling, the data can be reconstructed by the compressive sensing technology. The ambiguity level was improved by 9.6 dB. Meanwhile,

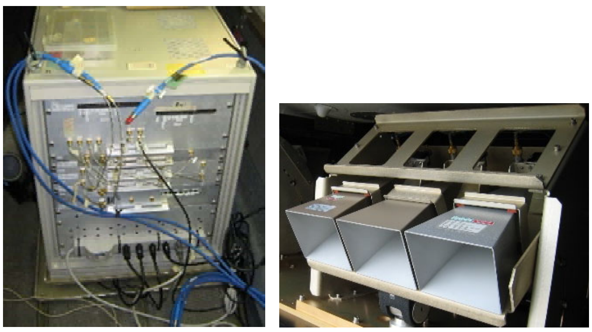

Fig. 5 Ku-band airplane SAR system

Table 1 Parameters of experimental study with airplane SAR

Center frequency	16.45 GHz
SAR image resolution	10 cm × 10 cm
Sampling ratio before reduction of data size	1.2
Sampling ratio after reduction of data size	0.6

Table 2 Evaluation of ambiguity level

SAR image with sampling ratio of 1.2	−58.7 dB
SAR image with sampling ratio of 0.6	−35.9 dB
SAR image with compressive sensing applied	−45.5 dB

Fig. 6 Half subsampled SAR imagery (sampling ratio is 0.6)

Fig. 7 Reconstructed result of Fig. 6 with proposed compressive sensing

Fig. 8 Original SAR imagery (sampling ratio is 1.2)

there is still room to improve the level by 13.2 dB. This technology is expected to be used to reduce the size and cost of SAR sensors and for other purposes, thus contributing to resource-saving space development.

6. References

(1) Eldar, Y.C., et al., Compressed Sensing, Cambridge University Press (2012)
(2) Liu, D., et al., Synthetic aperture imaging using a randomly steered spotlight, IEEE IGARSS, 919–922 (2013)
(3) Hoshino, T., et al., Experimental studies of compressive sensing for SAR with Ka-band chamber room and Ku-band airplane SAR data, IEEE IGARSS, 5366–5369 (2017)