Synthetic Aperture Radar Imaging using COTS Components

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Abstract

Radar imaging calls for high resolution in at least two dimensions, typically in range and azimuth. Synthetic aperture radar techniques allow high resolution in azimuth without the need of a large physical antenna. For decades, imaging radar systems have been expensive and available only for special purposes such as space applications and high-end military airborne systems. This paper discusses an inexpensive and accessible means for synthetic aperture radar imaging. We present a short-range experiment of high resolution using commercial off-the-shelf (COTS) hardware components.

1 Introduction

Radar is a classic remote sensing equipment that provides range and amplitude information about its surroundings. Radar determines the range of a target in the scene based on the time delay between the radio wave transmission and the received echo from the target. By using a directional antenna, the radar focuses the radiating intensity and determines the direction of arrival of the radio wave scattered back from the target of interest. Conventional radars have a resolution of tens or hundreds of meters in range and hundreds or thousands of meters in cross-range. Since the antenna provides the cross-range resolution via its angular resolution, the cross-range resolution in meters is dependent on the range between the radar and the target. Given that the angular resolution of the antenna is a constant, the larger the range, the lower the cross-range resolution in meters. If the objective is a picture of the radar scene to detect and recognize even the small targets, good resolution is required in both dimensions—range and cross-range. The process of producing such pictures of high resolution is called radar imaging. [1]

High resolution in range is achieved by the large bandwidth of the radar waveform: the range resolution $\Delta r = \mathrm{c}/(2B)$ where c is the speed of light and B is the bandwidth. The range resolution is independent of the range to the target, which enables the same high resolution at all ranges acquired by the radar. For instance, acquiring an image with a resolution of 10 centimeters at an imaging distance of 100 kilometers is difficult using an optical sensor but feasible using radar imaging.

High resolution in cross-range calls for a more complicated measurement setup compared with high range resolution. The cross-range resolution $\Delta y = \lambda_\mathrm{c}[r_0^2 + (L/2)^2]^{1/2}/(2L)$ where λ_c is the carrier wavelength, r_0 the range to the target, and L the diameter of the antenna [2]. Consequently, depending on the range to the scene, the cross-range resolution of 10 centimeters would require an antenna with a diameter between meters and thousands of meters. Such a requirement is obviously impractical in a typical application using a space or airborne platform. The solution is the synthetic aperture radar (SAR) techniques [1], [2]. With SAR, the large antenna aperture is generated using one small physical antenna moving during the aperture formation. The aperture is reconstructed using a time series of the responses from the scene illuminated by the side-looking antenna. We summarize the requirements for the geometry and sampling of the aperture to the following three main rules.

1) The length of the aperture and the cross-range resolution is determined by the change in the scene azimuth θ_tot. Thus, the cross-range resolution can be formulated as $\Delta y = \lambda_\mathrm{c}/(4\sin(\theta_\mathrm{tot}/2))$ and it is not directly affected by the range to the scene [2]. Nevertheless, the larger the range, the longer the aperture that provides the desired azimuth change θ_tot.

2) The sampling density of the aperture is dictated by the azimuth beam width of the physical antenna, typically represented by 3 dB beam width θ_3dB. The sample interval is derived based on the Doppler of the illuminated scene; i.e. the Doppler needs to be unambiguously

sampled over the whole illuminated scene. With an isotropic antenna, the spatial sample interval should be at least $\lambda_c/8$ to ensure that the change between the phase components of the response for any two points in the scene is less than $\pi/2$. Note that the phase components of the points may also be changing in opposite directions. Assuming the scene completely stationary, the highest phase derivatives are in the direction of the radar velocity vector and the direction opposite to it. A directive antenna restricts the illuminated area with the main lobe, so that the Doppler region narrows. The narrower the side-looking main lobe, the narrower the Doppler bandwidth, and the larger the allowed aperture sample interval: $\Delta L = \lambda_c/(8 \sin(\theta_{3dB}/2))$.

3) The beam width of side-looking main lobe must be larger than the required azimuth change: $\theta_{3dB} \geq \theta_{tot}$. This requirement ensures that the main lobe illuminates the scene on adequately long azimuth change within the aperture formation.

These three rules theoretically ensure that the SAR imaging can be achieved by a radar with an adequate bandwidth B corresponding to the intended image resolution. Perhaps the main reason, why such imaging radar systems have not been widely available, concerns the bandwidth requirement. E.g. the resolution in the order of 10 centimeters corresponds to a bandwidth of 1.5 GHz. The resolution is required in many applications, such as object detection and recognition, where cameras have been much cheaper and more efficient, yet prone to cloudiness, fogginess, and lack of light. Another reason is the availability of the computing power that increases all the time. Above, we considered only the theoretical restrictions, but after obtaining the aperture, one has to calculate the image that is a computationally demanding task [2]. In this paper, we discuss the recent development of frequency modulated continuous wave (FMCW) radars that allows new approaches to radar imaging.

2 SAR imaging based on a COTS FMCW radar

Within the last decade, the automotive industry has adopted the use of miniature radars that are based on integrated circuits. That has tremendously reduced the price of such systems. Recently, the operation principles of the FMCW radar have aroused some attention. The FMCW radar provides simultaneous measurement of range and Doppler by a way that is very efficient concerning wide bandwidth applications. Nowadays, the price of an FMCW radar having bandwidth of 2 GHz is reasonable for even consumer products.

We have applied a commercial off-the-shelf (COTS) software defined radar to SAR. In our report [3], we elaborate on several aspects related to this radar system—e.g. moving target indication and automatic target recognition. Next, we consider some concerns for the SAR imaging based on a COTS FMCW radar.

To enable the demonstration of radar imaging with a resolution of 10 centimeters, we purchased a K-band (24 GHz) FMCW radar that uses frequency modulation in the form of linear frequency sweeps. The maximum sweep bandwidth is 2 GHz, resulting in the theoretical maximum range resolution of 7.5 centimeters. Another main requirement for the radar concerned the sweep repetition frequency f_{sr}. In the three main rules we described in Section 1, the second rule defined the sampling interval ΔL. Using antennas with $\theta_{3dB} = 16°$ as in [3] and $f_{sr} = 1$ kHz, the maximum allowed velocity $v_{max} = \Delta L f_{sr} \approx 11$ m/s for the aperture formation. Thus, one important specification of the FMCW radar for SAR application is its f_{sr}. Another important FMCW parameter is the number of samples per sweep N_s. It determines the unambiguous range window $r_{win} = N_s \Delta r$, and through straightforward deduction, r_{win} is the same as the maximum range where to acquire SAR images. Our last note for the SAR system based on a COTS FMCW radar relates to the first rule described in Section 1: the ability to track the aperture depends on the choice of the navigation equipment. It is a sensible choice to pay for a good-quality inertial navigation system with support of a global navigation satellite system (INS/GNSS). In the SAR image reconstruction [2], the most challenging task is to reconstruct the antenna trajectory with high accuracy using the measured radar data. It is called motion compensation. The task is much easier when aided by INS/GNSS of good quality and properly synchronized with the radar. The measured trajectory provides an initial guess for the motion compensation process [2]. In addition, the trajectory measured with six degrees of freedom aids in the proper selection of the aperture so that the antennas are pointing toward the imaged area. Figs. 1 and 2 illustrate an example of a SAR experiment, a trajectory measured by a compact INS/GNSS, and a stripmap SAR image with a resolution of 15 centimeters. The result is calculated based on the measured trajectory using no motion compensation algorithms. An ideal trajectory would be produced by a platform that is moving along an inevitably rectilinear line. The unideal nature of the measured trajectory causes the systematic displacement between the actual location of the corner reflectors and their SAR response as seen in Fig. 2. This location bias could be corrected using a georeferencing procedure. The used SAR reconstruction method is presented in [4]. The method is computationally inefficient, but it is very accurate and easy to employ especially when the trajectory is not close to the ideal straight line.

3 Discussion and conclusions

This paper considered and demonstrated SAR imaging using COTS hardware components. Although the presented SAR image does not represent the result of the full imaging procedure (due to the lack of a focusing algorithm [2]), the result proves the feasibility of the COTS components to provide SAR images. The commercially available FMCW radars allow plenty of application prospects with reasonable costs. In the military domain, the typical applications are in surveillance and reconnaissance. In short-range applications, SAR provides the detection capability of interesting objects to be recognized using electro-optic sensors, as well as information to support the recognition. The radar observes the objects in a different manner concerning e.g. the information of the materials and shapes of the objects that are impossible to acquire by electro-optic sensing. In addition by using multi-channel acquisition [3],[5], a SAR system is able to indicate moving objects based on their Doppler. Nevertheless, the major benefits of SAR are revealed along with the medium-range or high-range applications when it is probably the only imaging method capable to provide high-resolution images through the unideal atmosphere. The FMCW technology is inexpensive for short-range applications but only medium-priced for medium-range applications.

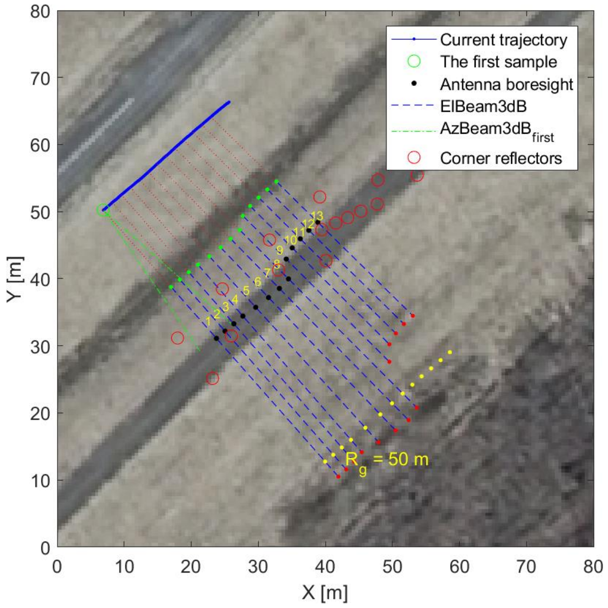

Fig. 1: An example of a SAR measurement visualized over an aerial photograph. The solid blue line is the trajectory, measured by an INS/GNSS chip. The dashed blue lines illustrate the swath width (illuminated by the antenna main lobe) at the starting point of each of the 13 SAR apertures. The yellow dots indicate the ground range of 50 meters for each aperture. The red circles indicate the locations of the corner reflectors that were placed in the scene.

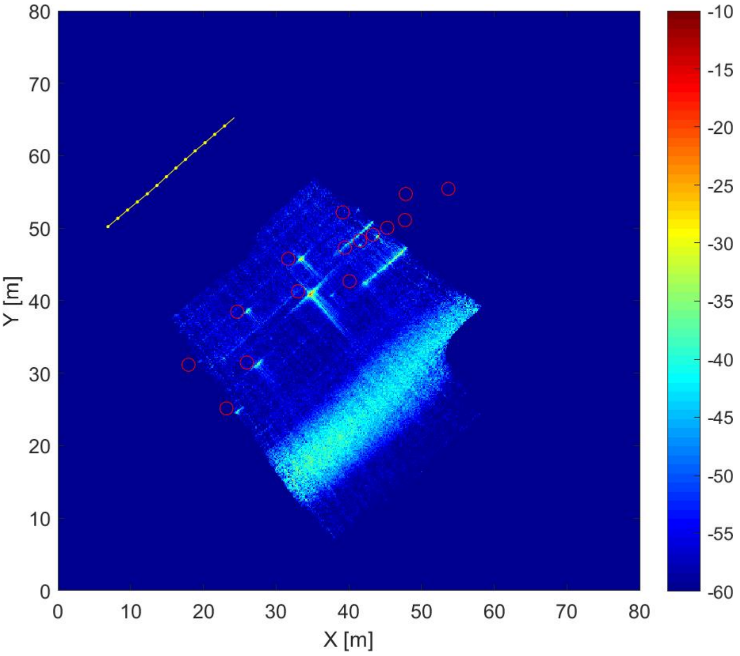

Fig. 2: A stripmap SAR image reconstructed from the 13 apertures visualized in Fig. 1. The resolution is 15 centimeters. The yellow line is the trajectory on which the yellow dots indicate the starting point of each aperture. The image color represents the logarithmic intensity after the signal acquisition and the image reconstruction. The bright dots in the image are the responses of the corner reflectors whose actual locations are indicated by the red circles. The offset between the responses and the actual locations results from the inaccuracies in the trajectory measured using a compact INS/GNSS. In addition, some artifacts caused by the unideal radar instrument are visible; they should be eliminated by filtering in a real application.

Acknowledgements

The authors would like to thank DA-Design (DA-Group) for the successful cooperation in the SAR research.

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