SAR AND SAS COMPARED – EQUALITIES, SIMILARITIES AND DIFFERENCES

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1 INTRODUCTION

Synthetic aperture radar (SAR) and sonar (SAS) are examples of synthetic aperture (SA) systems. All such systems use samples collected at different spatial locations to synthesize a larger antenna and are theoretically similar. Except some obvious physical differences between acoustic and electromagnetic waves and their propagation properties, SAR and SAS have the same geometry. Accordingly, one might expect that a working SAR processor system could easily be modified to be a SAS processor as well. This is not necessarily so as a result of the motion compensation requirements for the systems. The requirements turn out to be more difficult to fulfill for SAS. Motion compensation is the most difficult part of many SA processing systems, relying on careful engineering. Particulars of the platform motion must be taken into account, and what is valid for one system is not always applicable to a different one.

2 BASICS

2.1 Synthetic Aperture is Geometry

The general characteristic of a synthetic aperture system is that it relies on the coherent processing of signals received from reflectors as a result of wave scattering. The signal is received at a number of different positions, causing the range to the reflector to change and thereby also the received signal phase. The signal phase is the range to the reflector measured in wavelengths. Accordingly, range changes proportional to fractions of a carrier wavelength are significant in SA processing. Most practical systems try to follow a straight line, as this simplifies processing. The general geometry is shown in Figure 1.

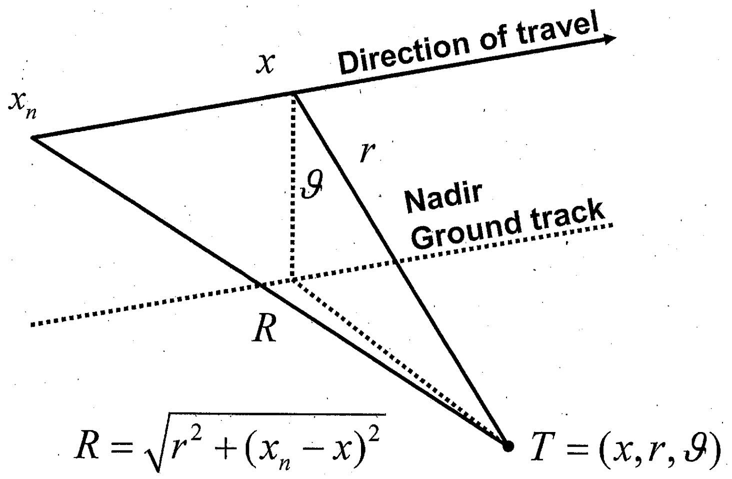

Figure 1 Overview of straight line trajectory synthetic aperture system.

At a position x_n, the receiver is at a distance R from a given reflector with cylindrical coordinates $T=(x,r,\theta)$. Although SA platforms are usually moving, the motion during signal reception, as well as the motion during signal transmission may often be ignored. This is sometimes called "the stop and shoot approximation". The phase changes of the signal from the stop and shoot approximation is sometimes seen as a Doppler shift in SAR work. This is called spatial Doppler by Soumekh[1] to discriminate it from the shift of the carrier frequency (and other effects) caused by actual platform or target motion. When the transmitting element is at the same place as the receiving element, the resulting range (and hence the phase) becomes a hyperbola in x_n. This is the starting point for many SA processors. When the trajectory is a straight line, the range is independent of the reflector angular position. Hence, a reflector may be focused properly regardless of vertical distance from some reference ground plane. This is not the case for other trajectories.

2.2 Motion compensation

A key step in any synthetic aperture processor is the motion compensation. Indeed, the SA focusing itself may be seen as motion compensation. However, it is usual to discriminate between intended and actual motion (see Figure 2). The term motion compensation is then used for the processing necessary to correct for the effects introduced by the difference of the actual and the intended motion. The intended motion is often, but not always, a straight line.

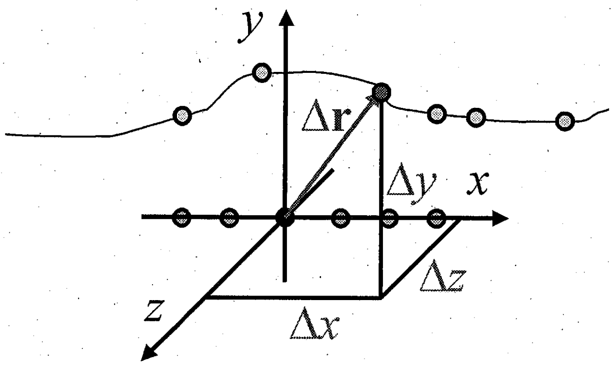

Figure 2 Intended (black) and actual (red) positions of a platform.

For completely general SA, the motion compensation cannot be seen separately from the SA focusing. General SA is characterized by arbitrary positions of transmitters and receivers and general sampling trajectories. In such cases, sufficiently accurate transmitter and receiver positions must be put directly into a back projection SA processor.

There are clear advantages for SA processing if the actual motion approximates a straight line, preferably with SA positions near equidistant. The two main advantages are: (1) The SA processing can be executed using a "fast" processor (how fast depending on system parameters), (2) Reflectors are properly focused (in slant range geometry) regardless of angular position (or vertical distance with respect to some ground plane). Sometimes, motion compensation can be performed "to a straight line" to enable fast focusing. The main problem, which is not easily overcome in a general setting, is that so called "out of plane motion" makes it necessary to know reflector vertical position in order to focus it properly[2]. The depth-of-focus scale factor (the factor that relates phase error to vertical distance from focus plane) is given by

$$S_D = \frac{4\pi}{\lambda}\frac{\Delta z_{\max}}{R_0}. \qquad (1)$$

Here, $\Delta z_{\max}$ is maximum out of plane motion and R_0 nominal slant range. Requiring the phase error to fulfill the criterion $\Delta\varphi < \pi$ the depth-of-focus is obtained as

$$\Delta h_D = \frac{\lambda}{8}\frac{R_0}{\Delta z_{\max}}. \tag{2}$$

The various possible effects of a position error (where position error is defined as difference between actual and intended position) are indicated in Figure 3. In general, a target reflector appears at a range different from the intended range, affecting both the received signal phase and perhaps the range cell that the reflector appears in. Furthermore, the beam will point in a direction different form what is intended. If this effect is severe, the reflector may even be outside the beam, and data is lost, resulting in decreased resolution or higher side lobes in the image of the reflector.

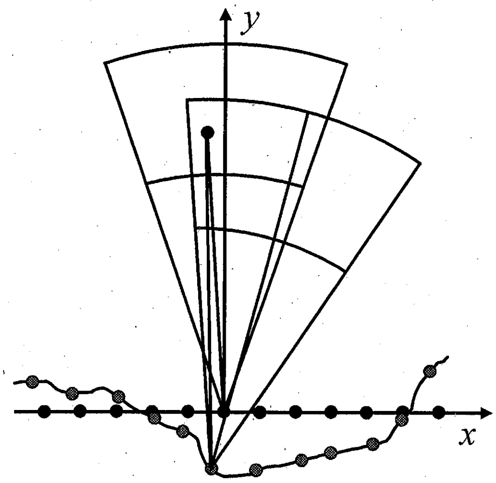

Figure 3 View of intended (black) and actual (red) motion of a platform with a transmitter or receiver observing a point reflector.

From the above comments, it is clear that how sensitive a system is to unintended motion is an important consideration. If the unintended motions that may be expected are small enough, motion compensation becomes easy or even unnecessary. If the unintended motion becomes large enough, it becomes all but impossible to obtain a focused image.

Another consideration is the estimation of the unintended motion. This must generally be very accurate in order to perform motion compensation. High quality sensors and careful signal processing are needed, often supplemented by data from the SA system itself.

As an example, consider so called bulk motion compensation. This is compensation for range deviation that is the same for an entire pulse, and accordingly it is not dependent on range, only on azimuth. For such compensation to be valid, the range deviation must be sufficiently small. Figure 4 shows how a range error affects the range to two different reflectors.

The reflectors at B and C are at the same range from the intended SA position, while the actual SA position is at A. Accordingly, the range is no longer equal to the two reflectors. If the phase difference caused by this effect is required to be below a certain limit, the following is obtained

$$\begin{aligned} &\Delta\varphi < \pi \\ &\Delta r < \frac{\lambda}{4(1-\cos\theta)} \end{aligned} \tag{3}$$

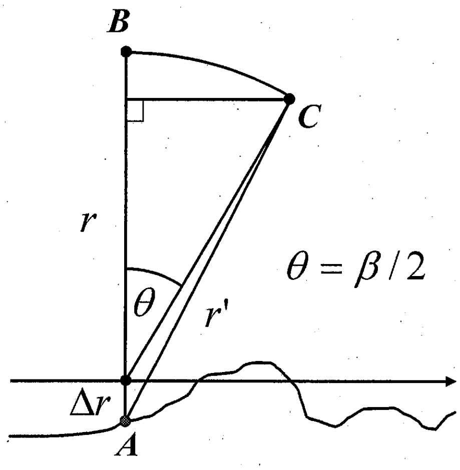

Figure 4 Geometry of a range error.

Here, θ is half the synthetic aperture element beamwidth β. This shows us that the allowed error is only a function of the beamwidth if the range error is measured in wavelengths.

3 SYNTHETIC APERTURE SYSTEMS

There exist many disparate radar systems that all make use of some form of synthetic aperture processing. For comparison purposes, it is accordingly useful to define some representative systems. The parameters used here are close to parameters for real systems, but they are not exactly valid for any particular systems. Five systems are defined: A satellite radar system, three aircraft radar systems and one synthetic aperture sonar system. Some relevant system parameters are given in
Table 1.

Parameter	Satellite	Aircraft 1	Aircraft 2	Aircraft 3	SAS
Slant range	1000 km	30 km	20 km	10 km	100 m
Signal bandwidth	16 MHz	100 MHz	1.8 GHz	70 MHz	50 kHz
Centre frequency	5.3 GHz	9.4 GHz	9.45 GHz	55 MHz	85 kHz
Wavelength	5.6 cm	3.2 cm	3.2 cm	5.5 m	1.8 cm
Swath	100 km	10 km	2 km	10 km	200 m
Platform speed	7100 m/s	250 m/s	150 m/s	100 m/s	2 m/s
Antenna	10 m	1 m	Phased array	Dipole	Phased array
Azimuth beamwidth	0.3°	1.9°	6°	60°	60°

Table 1 Representative system parameters.

The satellite system is similar to ENVISAT ASAR[3], the C-band SAR carried by the European Space Agency Earth observation satellite. This system is used for observing the Earth surface at geological and meteorological relevant scales, the finest resolution being about 10 m. Figure 5 shows a model of ENVISAT with the ASAR antenna underneath[4]. The satellite moves such that the longest dimension of the antenna is along the trajectory.

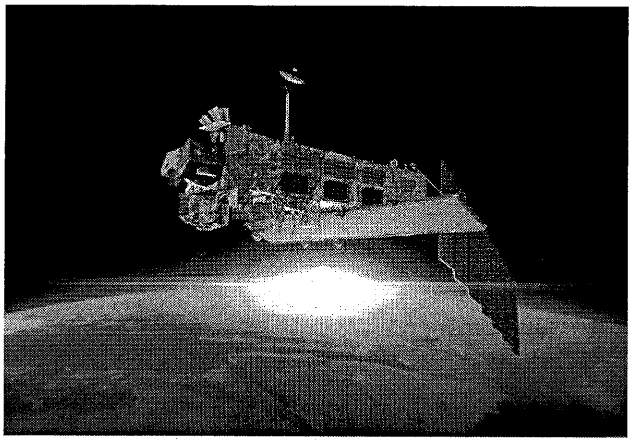

Figure 5 Model of ENVISAT showing the ASAR antenna.

The three aircraft systems are different, the first (Aircraft 1) being representative for many operational systems with moderate resolution. An example of such a system might be the DLR E-SAR at X-band. Operationally, such system can be used for wide area surveillance, mapping and target detection, particularly if coupled with ground moving target indication (GMTI) radar.

The second aircraft system (Aircraft 2) is similar to the PAMIR (Phased Array Multifunction Imaging Radar)[5] and represent state-of-the-art performance in term of SAR resolution. It has been demonstrated that resolution finer than 10x10 cm may be achieved with PAMIR. It is designed to achieve this resolution at ranges up to 30 km. Applications of such a system include target detection and recognition.

The third system (Aircraft 3) is similar to the CARABAS II system[6], and is a low-frequency (VHF) radar. Such systems are used, among other things, for detecting targets under foliage. Figure 6 shows photos of the three systems that have parameters similar to the aircraft parameter sets given in
Table **1**.

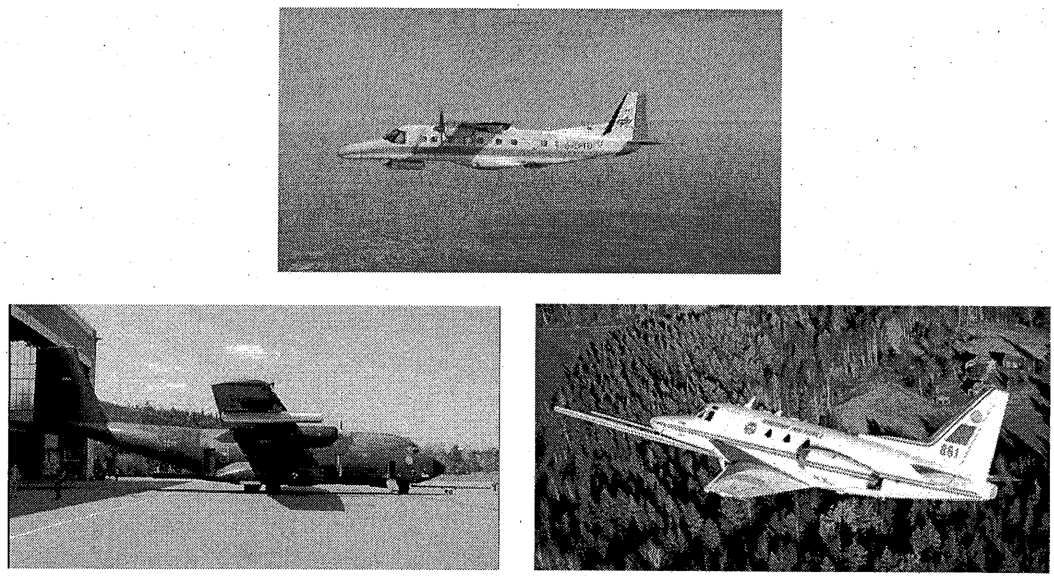

Figure 6 The DLR E-SAR[7], the PAMIR test system[5] and the CARABAS II system[6].

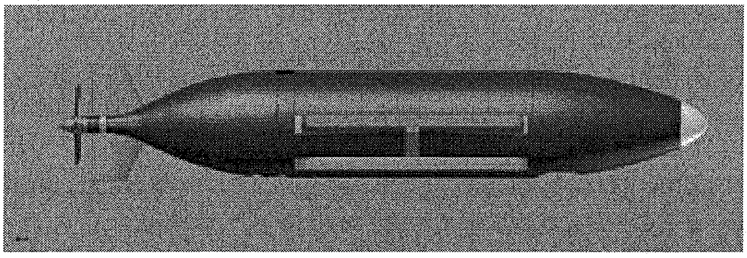

Figure 7 Sensotek SAS on the HUGIN MRS[9].

The SAS system is similar to the FFI SENSOTEK SAS[8]. This is a fine resolution interferometric system that operates from the HUGIN autonomous underwater vehicle. Applications include bathymetric mapping, target detection and target recognition. A model is shown in Figure 7.

Taking the system parameters, the motion compensation requirements may be compared. Using equation (3) the result is shown in Figure 8. The actual values in metres are given in Table 2. Also, in the same table, the maximum allowable out of plane motion for a vertical distance of 100 m from the focus plane is given. The result is calculated from equation (2). The results show that the SAS system has the strictest requirements, while the satellite system is at the other end of the scale. The out-of-plane limit for the SAS system is perhaps too tight as a vertical variation of the depth of 100 m over a swath of 200 m is too extreme. But a variation of 10 m is eminently possible, and this causes a limit of 5 cm instead of 5 mm, still a harsh requirement. Accordingly, some initial guess or prior knowledge about vertical variation is needed for general SAS operation. This is usually not necessary for airborne systems.

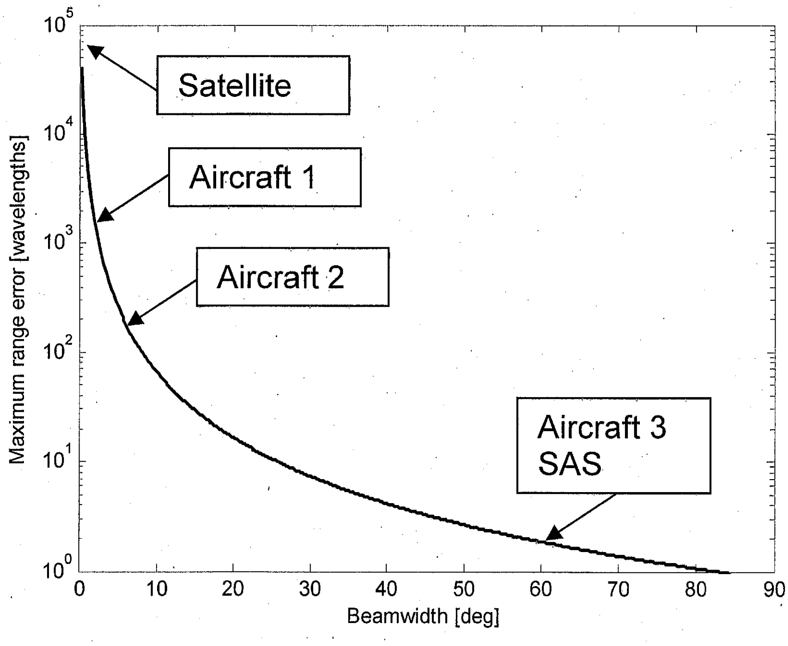

Figure 8 Maximum range motion that may be bulk compensated.

System	Satellite	Aircraft 1	Aircraft 2	Aircraft 3	SAS
Compensation limit	4 km	50 m	5 m	10 m	4 cm
Max out of plane motion	70 m	1.1 m	0.75 m	70 m	5 mm
v/c	2.4e-5	8.3e-7	5.0e-7	3.3e-7	1.3e-3

Table 2 Motion limits for the five systems.

4 DISCUSSION

From the previous two sections it is clear that SA systems are similar in many ways, but there are also significant differences. Not only are there significant differences between radars and sonars but there are just as large differences between various radar systems.

4.1 Equalities

The basics geometry is the same for sonar and radar, and SA is first and foremost a question of geometry. Accordingly, the phase histories of ideal reflectors are the same, and major processing steps in the focusing operations are the same as well. The fundamental concepts of range and azimuth resolution of reflectors are equal. There are accordingly opportunities for collaboration in this area.

4.2 Similarities

Sonar and radar SA systems are similar in that they require careful motion compensation. Indeed there are larger differences between SAR systems than between SAS systems and the finest resolution SAR systems. Satellite SAR of moderate resolution does not require the motion compensation that airborne systems and SAS does. This is a result of the smooth satellite trajectories. Relative bandwidths are similar between fine resolution systems. Most system are nominal straight line trajectory systems. This holds even for satellite systems where it can be shown that the phase history of a reflector is generally close to the straight line hyperbola, if an effective platform velocity is used[10].

4.3 Differences

The most obvious differences result from the propagation speed of electromagnetic and acoustic waves. Because the sound waves are much slower, the SAS platforms have to move slowly, even though an array along the direction of travel is used to increase spatial sampling rate. Also, the stop and shoot approximation is generally not valid, and the effect of bistatic geometry and Doppler pulse distortion has to be taken into account. Sensitivity to motion errors is high, and the compensation is more complicated than for most SAR systems.

SAS systems operate with wide beams and relatively short range. Many operational SAR systems are designed for stand-off ranges and have narrow beams. On the other hand, low-frequency SAR systems have more in common with SAS than many other SAR systems.

Some SAR systems are polarimetric, that is they make use of the vector field nature of electromagnetic waves. Acoustic waves do not have this property.

The out-of-plane motion problem is more severe for SAS than for SAR. Accordingly, if the trajectory cannot be sufficiently straight (a difficult requirement to fulfil), an initial bathymetry must be known to keep the focusing problem manageable. This is not required for most SAR systems.

5 CONCLUSIONS

SAR and SAS systems are conceptually similar. The basic geometry is the same, accordingly ideal point reflector responses are equal. Crucial focusing steps in the image formation of the SA images can accordingly be accomplished the same way. Obvious differences arise as a result of the physical difference between acoustic and electromagnetic waves. The propagation speed of the acoustic waves sets a rather strict limit on the top possible speed of a SAS platform, something that need not be taken into account for airborne systems. This problem is partly overcome using an along track array of transducer, but at the cost of more complex motion compensation.

The most difficult problem of implementing a fine resolution SA processor is arguably motion compensation. Indeed, motion compensation considerations are key to understanding the differences between systems. At one end of the scale, there are satellite systems that are effective ideal straight line systems that need no special motion compensation. At the other end of the scale are the SAS systems where every trick in the book have to be used, and this may still not be enough to obtain well focused images when there is significant vertical variations in the bottom topography. Airborne system need motion compensation to various degrees, but it is only the finest resolution systems and the very low frequency systems that begin to approach the same requirements.

6 REFERENCES

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