# SAR Systems and Related Signal Processing

P. Hoogeboom, R.J. Dekker and M.P.G. Otten
TNO Physics and Electronics Laboratory
P.O. Box 96864
2509 JG The Hague
The Netherlands

## 1. SUMMARY

Synthetic Aperture Radar (SAR) is today a valuable source of remote sensing information. SAR is a side-looking imaging radar and operates from airborne and spaceborne platforms. Coverage, resolution and image quality are strongly influenced by the platform. SAR processing can be performed on standard computers or dedicated hardware architectures, depending on required throughput and image quality. Besides imaging, SAR can perform other modes of operation and applications such as multi-frequency and polarimetric imaging, elevation mapping and moving target indication (MTI). Current developments in SAR systems are concentrated on higher resolution, and flexibility in performing advanced modes in the future.

## 2. INTRODUCTION

Synthetic Aperture Radar (SAR) is nowadays a well known source of remote sensing data. Space- and airborne SAR systems, with a range of characteristics, are available to provide information. Since SAR radiates and detects microwave radiation, it is able to make images under most weather circumstances, day or night. For these reasons SAR is a valuable remote sensing instrument in both militairy and civil information gathering.

SAR is a side-looking imaging radar instrument; it scans the surface of the Earth and focuses by coherently detecting the radar return and integrating over a distance flown, called the synthetic aperture. Another advantage of SAR compared to real-aperture systems is that the antenna can be smaller, which makes space-applications possible. Owing to the coherent detection process, SAR images also contain clearly visible speckle-noise, compared with images obtained from optical sensors. This noise is inherent to the system and can only be suppressed by averaging incoherently.

SAR has various and sometimes exclusive applications. Some are mapping, land classification, and change detection. All of these tasks can be done with both radar and optical instruments which can provide complementary information. Other, radar restricted applications are mapping of the sea-bed, interferometry and Moving Target Indication (MTI).

This article will give an overview of the state-of-the-art in present SAR systems, the related signal processing, their capabilities and future. The next section treats air- and space-borne SAR systems and the technology used today. Section 3 gives a general description of SAR signal processing and specific parts for air- and spaceborne systems, including real-time processing. Section 4 discusses several special SAR modes and applications. Section 5 closes with future developments.

## 3. AIRBORNE AND SPACEBORNE SAR

The platform is an important part of the SAR system. It strongly impacts its general characteristics. Two types of platforms can be distinguished, aircraft and spacecraft (satellite or space-shuttle). The major differences between the two types of systems are range, swath, resolution, platform motion and availability. For illustration, table 1 shows the characteristics of the European satellite SAR system ERS-1 [Vass 1992] and the Netherlands aircraft SAR system PHARUS [Hoogeboom 1992, 1994].

The table shows the extreme difference in range and the width of the scanned area (swath). Recording in along-track (azimuth) direction is unlimited, in principle. A long range SAR needs more power and a longer antenna because of free-space loss and smaller antenna beamwidth. Note that the need for smaller beamwidth is prescribed by the antenna-gain and not by resolution. The azimuth resolution of SAR is mainly determined by the length of the synthetic aperture, instead of the footprint of the antenna (real aperture). The synthetic aperture is formed by flying the antenna over a certain distance. Platform motion behaviour is very important: spacecraft are extremely stable platforms; they can repeatedly scan areas from almost identical tracks (repeat-pass imaging). Aircraft are much less stable. However, because of motion compensation techniques, focus and geometry of SAR images can be accurately reconstructed. It is also clear that satellite systems are less maneuverable than aeroplanes, and that they are less versatile. The suitability of a SAR system is very dependent on the task or application. For any task the best trade-off has to be found between the size of the area to cover and the resolution. For repeated monitoring of the same areas, for instance, satellites are extremely suitable. For more flexible gathering of SAR data, aircraft are often more suitable.

Many technologies are used in building synthetic aperture radar systems. Classical components that are still being used are traveling-wave-tubes (TWT) for the transmitters and waveguide antennas. The ERS-1 satellite, for instance, has been built with TWT's for reasons of robustness. New technologies such as monolithic microwave integrated cicuits (MMIC) and phased array antennas are emerging for the purpose of smaller and more flexible systems. Phased array antennas have the advantage of non-mechanical beam steering, which increases the flexibility of the system. The PHARUS system is equipped with MMIC's and an active phased array antenna. Obviously, there are many more systems, both satellite and aircraft, available. To name a few, the successor of the ERS-1, the ERS-2, and the Japanese JERS-1, the recent Canadian RADARSAT-1 SAR satellite,

*Paper presented at the AGARD SPP Symposium on "Remote Sensing: A Valuable Source of Information", held in Toulouse, France from 22-25 April 1996, and published in CP-582.*

| | | ERS-1 | PHARUS |
|---|---|---|---|
| Peak Power | | 4.8kW | 475W |
| Antenna | length | 10m | 1m |
| | beamwidth | 0.288° | 2.3° |
| Altitude | | 785km | 6km |
| Range | | 875km | 16km |
| Swath-width | | 102.5km | 11.2km |
| Resolution | range | 30m | 4m |
| | azimuth | 6m | 1m |

Table 1. Technical characteristics of the SAR systems ERS-1 and PHARUS in single polarization mode.

**Figure 1.** SAR image recorded with the PHARS system, the testbed of PHARUS, of the Hague, the residence of TNO Physics and Electronics Laboratory, the Netherlands.

the well known airborne SAR sytems AirSAR of JPL, and the Danish KRAS, see [Raney 92] for an extensive overview.

## 4. SAR PROCESSING

The signal processing related to SAR systems is usually called SAR processing and roughly consists of two resolution processing stages. The first is a common radar compression technique, in which the received modulated pulse (chirp) is compressed by convolution with a replica. This technique combines the advantages of high power and an effectively short pulse. This stage is also called the range compression stage, because it achieves high resolution in across-track direction. The next stage compresses in azimuth, or along-track direction. Here, the radar returns of the synthetic aperture are correlated with the doppler history of a point target. Between the two stages the data matrix is transposed to match the change in compression direction. Because of the side-looking geometry, the image is converted from the slant view into a plan-view image (i.e., as viewed from above). Full registration to a map coordinate system is then also possible. To reduce the amount of speckle-noise multi-looking can be applied during azimuth compression. With this technique the synthetic aperture is divided in a set of smaller apertures, called looks, that are separately compressed and averaged incoherently.

In SAR processing special attention has to be paid to antenna motion in case of airborne SAR, and to the motion and curvature of the Earth in case of spaceborne SAR. Due to cross-track motions of the aeroplane, the doppler history along the synthetic aperture is distorted. By measuring the motion of the aeroplane, this history can be reconstructed, as well as the image geometry. Motion information can mostly be obtained from a high performance navigation system in the aircraft, or otherwise a radar embedded navigation system. In airborne SAR imaging, the surface of the Earth is often assumed to be flat because of the small swaths relative to the circumference of the Earth. In spaceborne SAR this assumption is no longer valid. Also, an airborne radar operates in the atmosphere, and so has the same rotation as the Earth, contrary to satellites, which orbit around it. Due to Earth curvature and -rotation, every part of the imaged scene has a different speed towards the sensor, yielding a different doppler offset-frequency, in case of spaceborne SAR.

An important feature of a SAR processor is the accuracy of reconstructing the recorded scene spatially as well radiometrically. The required accuracy depends on the application. Moreover, in some applications it is very important that the SAR processor preserves the phase. On the other hand, there are applications where the throughput of the processor is the main concern. Different kinds of SAR processors have been built throughout the years, ranging from the early optical processors, to software architectures on standard computers, to dedicated hardware parallel architectures. Some examples of processors are the ERS-1 SAR processors of several ERS-1 Processing and Archiving Facilities (PAF). For instance, the United Kingdom PAF uses a Micro VAX II based system with three array processors. The German PAF uses a set of general purpose workstations and micro computers linked by a local area network [Guignard 90]. Another example of a processor on a standard platform is the Netherlands Generic SAR Processor (GSP). This processor, which is able to process data from airborne and spaceborne systems as PHARUS and ERS-1, runs on a SUN SparcStation with an optional external vector processor [Otten 94]. An example of a dedicated hardware processor is the Norwegian CESAR processor [Toverud 88]. This processor is based on a systolic array parallel architecture. A special kind of SAR processors are the real-time processors [Bierens 95] which process the SAR data on-board during recording. Technologies used for dedicated hardware and real-time processors are transputers, DSP pocessors and VLSI techniques.

## 5. SPECIAL SAR MODES AND APPLICATIONS

Beside the basic imaging modes a SAR system can be made to operate in other modes to perform special applications. The next section gives an overview of current special modes and applications of SAR.

### 5.1 Multi-frequency imaging

Like multi-spectral images in optical remote sensing, multi-frequency SAR images yield more information. Objects give different backscatter intensities for different radar wavelengths. To show the multi-frequency information, the different wavelength images can be viewed in composite colours. The differences can be amplified by applying techniques such as principal-components analysis. Sometimes, images from different sensors can be used like the ERS-1 operating in C band and JERS-1 operating in L band. Some sensors operate at different frequencies at the same time, like the AirSAR of JPL operating in C, L and P band. The advantage of one sensor operating at different frequencies is that spatial registration is almost automatic. A successful application of multi-frequency imaging is land-use classification.

### 5.2 Polarimetry

Polarimetry is a technique that exploits the polarization of microwaves. Generally two polarization directions are used, horizontal and vertical. As in multi-frequency imagery, most objects also have different backscatter properties for different polarizations. Normal SAR systems transmit and receive in equal polarization directions, like the ERS-1 system which is vertical-vertical (VV) polarized. Polarimetric SAR systems transmit alternating polarizations, and simultaneously receive both. This way all polarizations are recorded. An example of a polarimetric SAR is the Netherlands PHARUS system, which can operate in single and full polarization mode. Applications are land-use and crop classification, contrast enhancement etc.

### 5.3 Interferometry

In this technique [Rocca 96], the phase difference between two images recorded from different tracks with different points of view, is used to make a three-dimensional reconstruction of the sensed area. The different points of view have to be separated across-track and can be obtained by two sensors or by one sensor in repeat-pass mode. In the last mode, the difference in consecutive satellite passes provides the required across-track displacement. Single pass interferometric SAR systems use mostly one transmitter and two receive antennas to obtain the different points of view. Because the receive antennas must be displaced across-track, this technique is also called across-track interferometry. Since interferometry is based on the phase difference, the phase-preserving characteristics of the used SAR processor

Figure 2. The Phased Array Universal SAR (PHARUS) mounted under a Cessna Citation II aircraft.

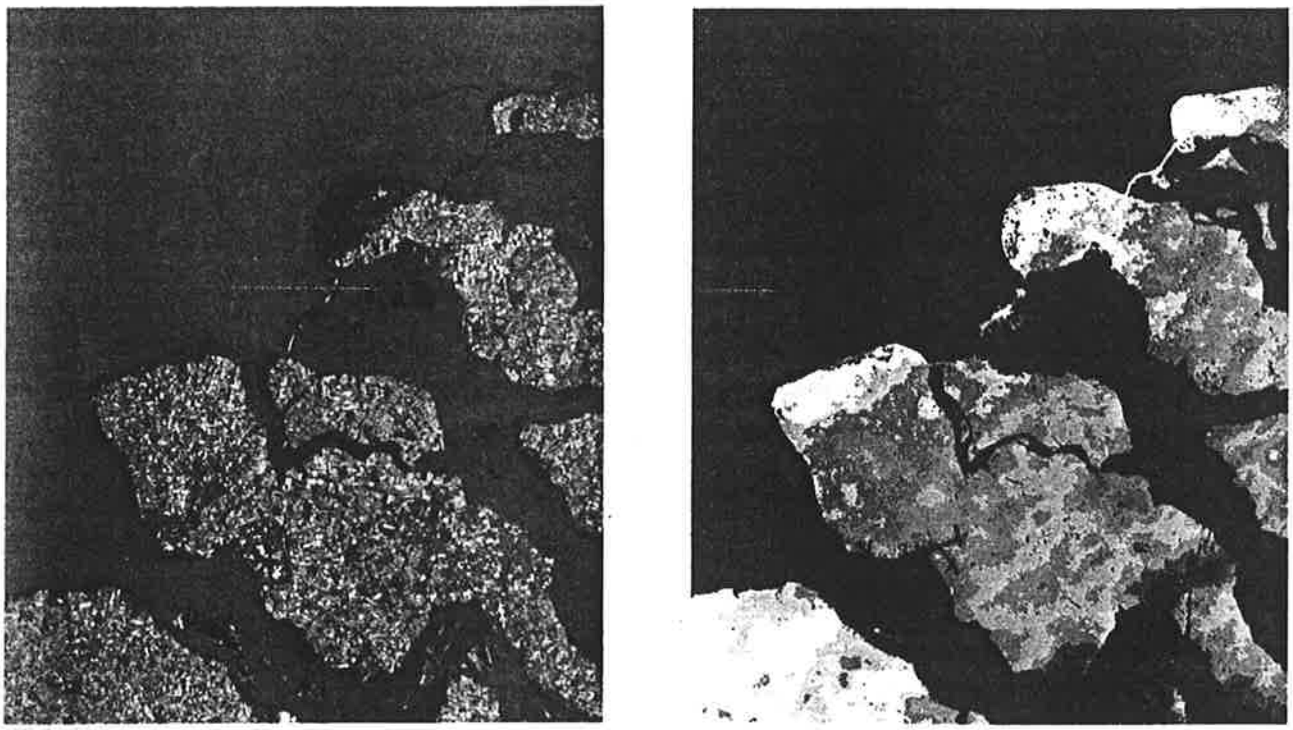

Figure 3. SAR intensity image (left) and phase-difference image (right) of Zeeland, the Netherlands, generated with the interferometric SAR processor of TNO Physics and Electronics Laboratory, the Netherlands, using repeat-pass ERS-1 imagery.

are very important, and pose additional quality requirements on SAR algorithms. Some applications of interferometry are elevation mapping and land subsidence monitoring [van der Kooij 95].

### 5.4 MTI

Moving Target Indication (MTI) is the proces of instantaneously discriminating moving targets from the stationary background. The target's speed in the direction of the radar can be accurately determined. In an airborne radar, radially moving targets can often be discriminated because of their different Doppler frequency. This does work well on very fast platforms, such as satellites, because the ground targets are relatively slow. In this case clutter suppression techniques involving multiple receive apertures are required. Multiple receive apertures can also be used to perform along-track interferometry, to accuractely determine target speed or direction. While MTI techniques exist in airborne systems, future satellite SAR systems are also expected to have MTI capabilities.

### 5.5 ScanSAR mode

ScanSAR is a technique which enables SAR to image wider swaths. A system that operates in this mode uses a steerable beam that scans the swath in range-direction. Because of the decreased observation time per unit area, the resolution in ScanSAR imagery is lower. The Canadian RADARSAT-1 satellite includes a ScanSAR mode [Raney 92].

### 5.6 Spotlight mode

The SAR spotlight mode makes it possible to increase azimuth resolution by keeping objects longer in its beam, thus extending the synthetic aperture [Munson 83]. This can be done by keeping the beam on the imaged scene during some time in-flight. Spotlight SAR processing has to deal with very long integration lengths, and large range migration. Therefore, spotlight algorithms are typically different from strip-mapping algoritms. The advantage of phased array antenna SAR systems such as PHARUS is that the beam can be pointed electronically, without any delay, from pulse to pulse.

## 6. FUTURE

The use of SAR systems in remote sensing is increasing. Moreover, there are many further developments in the understanding of the interaction between microwaves and what takes place on the ground, and there are many new system developments. SAR system development concentrates on several subjects. One is the increase of resolution, which is necessary for military applications, such as identification and verification. Another is the possibility of imaging areas on demand. Especially for spaceborne systems, this is an important item. The Canadian RADARSAT-1 satellite already proved this to be possible. Smaller airborne platforms like unmanned aircraft also expand the use of SAR. Intergration of several SAR modes and applications in one system also qualify the use of a SAR system in the future. Important developments are active phased array antennas, and interferometric and polarimetric capabilities. Microwave integrated circuits allow miniaturization of radar hardware. Advanced hardware will also lead to more advanced algorithms for processing. Such algorithms are being developed at many places throughout the world.

## 7. REFERENCES


Bierens, L., "Architectures for Real-Time On-Board Synthetic Aperture Radar Processing", Technical University Delft, The Neteherlands, 1995 (ISBN 90-6743-402-7).

Guignard, J.P., "ERS-1 SAR Processors", ESA er tn esa gs 0051, 1990.

Hoogeboom, P., P. Snoeij, P.J. Koomen and H. Pouwels, "The PHARUS project, results of the definition study including the SAR testbed PHARS", IEEE Trans. On Geosci. And Remote Sensing, 30(4):723-735, 1992.

Hoogeboom, P., H. Greidanus, P.J. Koomen, P. Snoeij and H. Pouwels, "PHARUS: An Autonomous Airborne SAR Capability", Symposium on Satellite and Airborne Synthetic Aperture Radar, Jakarta, Indonesia, 1994.

Kooij, M.W. van der, D. van Halsema, W. Groenewoud, B.A.C. Ambrosius, G.J. Mets, B. Overgaauw and P.N.A.M. Visser, "Satellite radar measurements for land subsidence detection", *in* Proceedings of the 5th International Symposium on Land Subsidence, The Hague, The Netherlands, 1995.

Munson, D.C., J.D. O'Brien and W.K. Jenkins, "A Tomographic Formulation of Spotlight-Mode Synthetic Aperture Radar", *in* Proceedings of the IEEE, 71(8):917-925, 1983.

Otten, M.P.G., J.S. Groot and H.C. Wouters, "Development of a Generic SAR Processor in the Netherlands", *in* Proceedings of IGARSS'94, Pasadena, pp. 903-905, 1994.

Raney, R.K., "Review of Spaceborne and Airborne SAR Systems", *in* 'Fundamentals and Special Problems of Synthetic Aperture Radar (SAR)', AGARD Lecture Series 182, Ref. 11, 1992.

Rocca, F., "Possibilities and Limits of SAR Interferometry", *in* Proceedings of AGARD Symposium 'Remote Sensing: A Valuable Source Of Information', Toulouse, France, 1996.

Toverud, M., "CESAR - A Programmable High Performance Systolic Array Processor", *in* Proceedings of IEEE Int. Conf. On Computer Design: VLSI in Computers and Processors, New York, 1988.

Vass, P. and B. Battrick, "ERS-1 System", SP-1146, ESA, 1992.

Paper 3

G.S. Brown (US)

You said there would be no speckle in the phase of a pixel element, but there would be in the amplitude. Could you please explain this?

Author's reply:

When the baseline is small, the combination of the scatterer's complex amplitudes is the same in the two views and therefore a random variate; their phase **difference**, however, is dependent on the geometry only and it is not random (not speckled).

AGARD-CP-582

# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE



**AGARD CONFERENCE PROCEEDINGS 582**

# Remote Sensing: A Valuable Source of Information

(la Télédétection — source précieuse de renseignements)

Papers presented at the Sensor and Propagation Panel Symposium, held in Toulouse, France 22-25 April, 1996.

North Atlantic Treaty Organization

*Organisation du Traité de l'Atlantique Nord*