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Synthetic Aperture Radar and Interferometry Development at Sandia National Laboratories

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Introduction

Environmental monitoring, earth-resource mapping, and military systems require broad-area imaging at high resolutions. Many times the imagery must be acquired in inclement weather or during night as well as day. Synthetic aperture radar (SAR) provides such a capability. SAR systems take advantage of the long-range propagation characteristics of radar signals and the complex information processing capability of modern digital electronics to provide high resolution imagery. SAR complements photographic and other optical imaging capabilities because of the minimum constraints on time-of-day and atmospheric conditions and because of the unique responses of terrain and cultural targets to radar frequencies.

SAR technology has provided terrain structural information to geologists for mineral exploration, oil spill boundaries on water to environmentalists, sea state and ice hazard maps to navigators, and reconnaissance and targeting information to military operations. There are many other applications or potential applications. Some of these, particularly civilian, have not yet been adequately explored because lower cost electronics are just beginning to make SAR technology economical for smaller scale uses.

Interferometry is a method for generating a three-dimensional image of terrain. The height projection is obtained by acquiring two SAR images from two slightly differing locations. It is different from the common method of stereoscopic imaging for topography. The latter relies on differing geometric projections for triangulation to define the surface geometry whereas interferometry relies on differences in radar propagation times between the two SAR locations. Interferometry can be used to rapidly survey large areas, monitor surface change due to erosion or other processes, and, potentially, to more precisely locate radar reflector locations.

Sandia has a long history in the development of the components and technologies applicable to synthetic aperture radar – 40 years in radar, antenna, and miniature electronics development; 30 years in microelectronics; and 25 years in precision navigation, guidance, and digital-signal processing. Over the last decade, we have applied these technologies to imaging radars to meet the needs of advanced weapon systems; verification and nonproliferation programs; and most recently environmental applications. Sandia's expertise in electromagnetics, microwave electronics, high-speed signal processing, high performance computing, and navigation, guidance, and control have established the Labs as world leaders in real-time imaging, miniaturization, processing algorithms, and innovative applications for SAR.

This paper presents the capabilities of SAR, explains how SAR works, describes a few SAR applications, provides an overview of SAR development at Sandia, and briefly describes the motion compensation subsystem.

Capabilities of SAR

An airborne SAR produces an image that in many ways appears similar to a photograph taken with a camera. However, SAR has several advantages and some disadvantages over optical photography because of differences between the two imaging processes. Unlike photography, which depends on receiving scattered sunlight to produce an image, SAR provides its own source of illumination and thus provides coverage day or night. In addition, many frequencies over which SAR can operate (hundreds of MHz to tens of GHz) penetrate heavy cloud cover, precipitation, fog, dust, smoke, etc. – media normally opaque to optical sensors. At selected frequencies SAR can penetrate optically opaque media, such as camouflage, foliage, and, under some conditions, even soil.

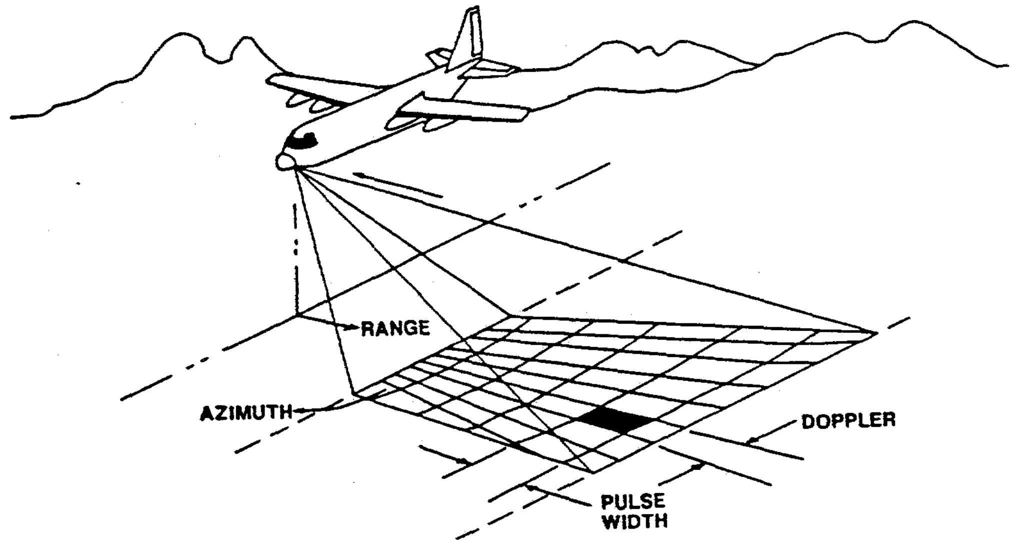


Figure 1. A side-looking SAR receives target echoes of its transmitted radio-frequency energy. Range resolution is achieved by precise measurement of echo time delays. Azimuth resolution is achieved by doppler filtering.

A primary disadvantage of SAR over optical sensors is its complexity, which is often reflected in cost, size, weight, and power. Optical imaging systems achieve their high resolution by virtue of their short wavelengths relative to radar. Compared to SAR, they are simple systems. Continuing advances in technology have reduced SAR's disadvantages to where SAR is presently being used for many military and selected commercial applications. The key technology advance has been digital signal processing, including algorithms, hardware, and software. With today's technology, real-time or near real-time processing of SAR imagery is being done in a relatively small volume (cubic foot), small weight (tens of pounds), and low power consumption (few hundred watts). Each year technology advances permit these numbers to decrease and SAR is becoming a "more practical" solution for additional applications.

How Does SAR Work?

A detailed description of the theory of operation of SAR is complex and beyond the scope of this paper. Instead, this section is intended to give the reader an intuitive feel for how SAR works.

Consider an airborne SAR that is imaging perpendicular to the aircraft velocity as shown in Figure 1. Typically, SARs produce a two-dimensional (2-D) image. One dimension in the image is called range (or cross track) and is a measure of the "line-of-sight" distance from the radar to the target. Range measurement and resolution are achieved in SAR in the same manner as most other radars: Range is determined by precisely measuring the time from transmission of a pulse to receiving the echo from a target and, in the simplest SAR, range resolution is determined by the transmitted pulse width, i.e. narrow pulses yield fine range resolution.

The other dimension is called azimuth (or along track) and is perpendicular to range. It is the ability of SAR to produce relatively fine azimuth resolution that differentiates it from other radars. To obtain fine azimuth resolution, a physically large antenna is needed to focus the transmitted and received energy into a sharp beam. The sharpness of the beam defines the azimuth resolution. Similarly, optical systems, such as telescopes, require large apertures (mirrors or lenses which are analogous to the radar antenna) to obtain fine imaging resolution. Since SARs are much lower in frequency than optical systems, even moderate SAR resolutions require an antenna physically larger than can be practically carried by an airborne platform; antenna lengths several hundred meters long are often required. However, an airborne radar could collect data while flying this distance and then process the data as if it came from a physically long antenna. The distance the aircraft flies in synthesizing the antenna is known as the synthetic aperture. A narrow synthetic beamwidth results from the relatively long synthetic aperture, which yields finer resolution than is possible from a smaller physical antenna.

Achieving fine azimuth resolution may also be described from a doppler processing viewpoint. A target's position along the flight path determines the doppler frequency of its echoes. Targets ahead of the aircraft produce a positive doppler offset, while targets behind the aircraft produce a negative offset. As the aircraft flies a distance (the synthetic aperture), echoes are resolved into a number of doppler frequencies. The target's doppler frequency determines its azimuth position.

While this section attempts to provide an intuitive understanding, SARs are not as simple as described above. Transmitting short pulses to provide range resolution is generally not practical. Typically, longer pulses with wide-bandwidth modulation are transmitted which complicates the range processing but decreases the peak power requirements on the transmitter. For even moderate azimuth resolutions, a target's range to each location on the synthetic aperture changes along the synthetic aperture. The energy reflected from the target must be "mathematically focused" to compensate for the range dependence across the aperture prior to image formation. Additionally, for fine-resolution systems, the range and azimuth processing is coupled (dependent on each other) which also greatly increases the computational processing.

Interferometric SAR, as illustrated in Figure 2, is an extension of conventional SAR. As aircraft carries two receivers (shown as A and B) that are offset some distance. The two receiver positions allow precise estimates of the angle of radar reception, Θ. Consider two adjacent imaged cells along the flight direction as shown in Figure 2. If these two cells have different heights above the ground, the received radar signal will have different angles of reception (Θ_1 and Θ_2). These small angle differences can be used to compute the heights of the cells above a reference plane, usually referred to as the ground plane.

Applications

This section discusses a few of the applications for SAR. These applications increase as new technologies and innovative ideas are developed. While SAR is often used because of its all-weather, day-or-night capability, it also finds application because it renders a different view of a "target," with SAR being at a much lower electromagnetic frequency than optical sensors.

Reconnaissance, Surveillance, and Targeting. Many of the early applications for SAR were for reconnaissance, surveillance, and targeting. These applications were driven by the military's need for all-weather, day-and -night imaging sensors. SAR can provide sufficiently high resolution to distinguish terrain features and to potentially recognize and identify selected manmade targets.

Figures 3 and 4 are SAR images which illustrate the capability for reconnaissance, surveillance, and targeting. These images could have been taken at long stand-off ranges with little degradation. The airborne SAR is illuminating each image from the top, with the vertical axis representing range and the horizontal axis azimuth.

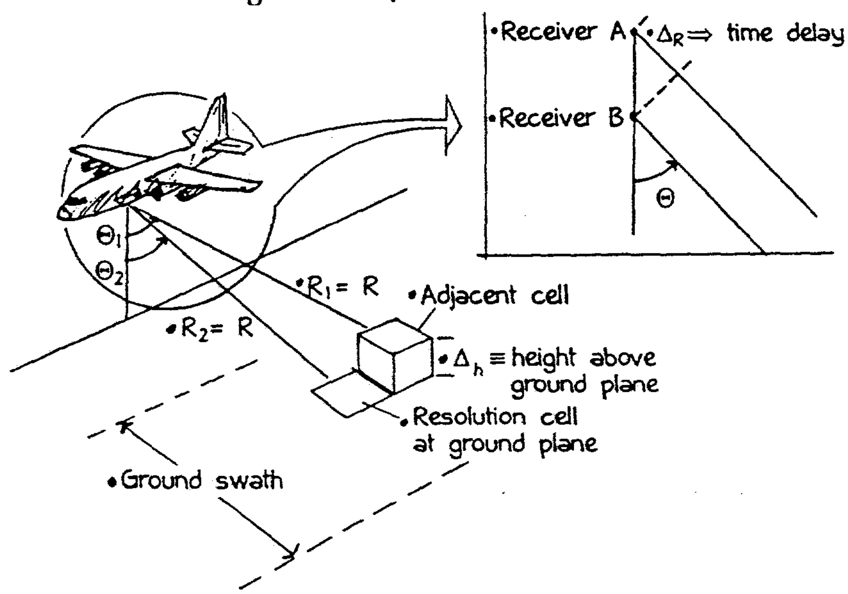


Figure 2. Interferometric SAR Concept

Figure 3. A SAR image of the China Lake Airport. Smooth surfaces such as runways appear dark while cultural targets, such as buildings, have a large radar backscatter and appear bright.

Figure 4. A SAR image of a horsetrack and surrounding fields south of Albuquerque.

Environmental Monitoring. SAR is used for a wide variety of environmental applications, such as monitoring crop characteristics, deforestation, ice flows, and oil spills. As an example, Figure 5 is a SAR image of a naturally occurring oil seepage. Oil spills can often be detected in SAR imagery because the oil changes the backscatter characteristics of the ocean. Radar backscatter from the ocean results primarily from capillary waves through what is known as Bragg scattering (constructive interference from the capillary waves being close to the same wavelength as the SAR). The presence of oil dampens the capillary waves, thereby decreasing the radar backscatter. Thus, oil slicks appear dark in SAR images relative to oil-free areas.

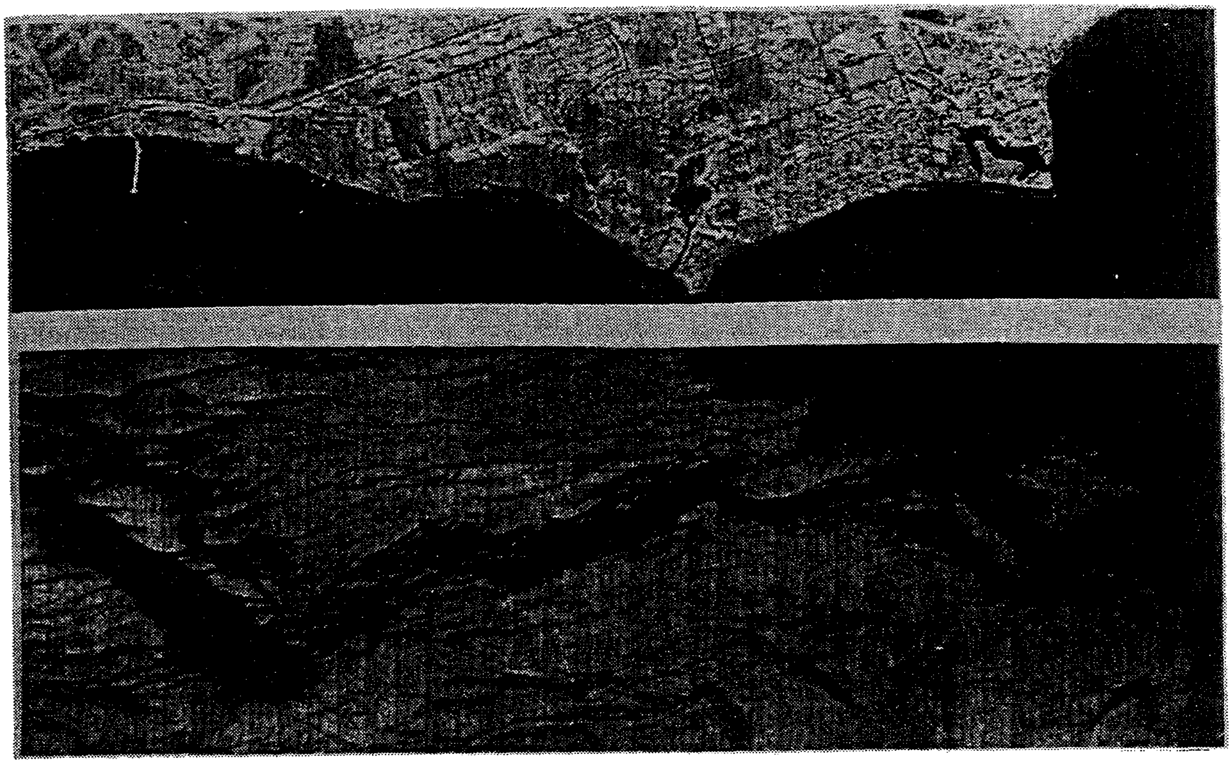


Figure 5. The top SAR image shows a coastline, while the bottom SAR image shows oil (dark areas) on the open ocean.

Treaty Verification and Nonproliferation. The ability to monitor other nations for treaty compliance and for the nonproliferation of nuclear, chemical, and biological weapons is increasingly critical. Often, monitoring is possible only at specific times, when overflights are allowed, or it is necessary to maintain a monitoring capability in inclement weather or at night, to ensure an adversary is not using these conditions to hide an activity. SAR provides the all-weather capability and complements information available from other airborne sensors, such as optical or thermal-infrared sensors.

Interferometry. Interferometric SAR (IFSAR) data can be acquired using two antennas on one aircraft or by flying two slightly offset passes of an aircraft with a single antenna. Sandia has developed new mathematical techniques for relating the radar reflection from the terrain surface to the time delay between radar signals received at the two antenna locations. The techniques are directed at removing ambiguities in estimates of surface heights and are referred to as "2-D least squares phase unwrapping." Figure 6 illustrates an interferometric SAR image created by two imaging passes (two synthetic apertures). Interferometric SAR can be used to generate very accurate surface profile maps of the terrain.

Navigation and Guidance. SAR provides the capability for all-weather, autonomous navigation and guidance. By forming SAR reflectivity images of the terrain and then "correlating" the SAR image with a stored reference (obtained from optical photography or a previous SAR image), a navigation update can be obtained. Position accuracies of less than a SAR resolution cell can be obtained. SAR may also be used in guidance applications by pointing or "squinting" the antenna beam in the direction of motion of the airborne platform. In this manner, the SAR may image a target and guide a munition with high precision.

Foliage and Ground Penetration. SARs offer the capability for penetrating materials which are optically opaque, and thus not visible by optical or IR techniques. Low-frequency SARs may be used under certain conditions to penetrate foliage and even soil. This provides the capability for imaging targets normally hidden by trees, brush, and other ground cover. To obtain adequate foliage and soil penetration, SARs

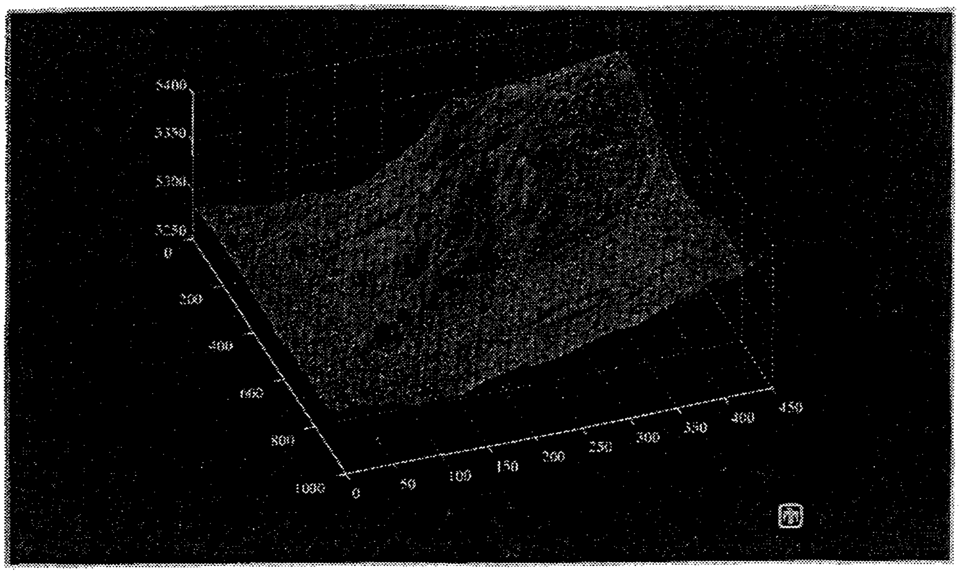


Figure 6. This interferometric SAR image of terrain relief at a site located south of Albuquerque illustrates SAR's topographic mapping capability.

must operate at relatively low frequencies (tens of MHz to 1 GHz).

Recent studies have shown that SAR may provide a limited capability for imaging selected underground targets, such as utility lines, arms caches, bunkers, mines, etc. Depth of penetration varies with soil conditions (moisture content, conductivity, etc.), radar frequencies, and target size, but individual measurements have shown the capability for detecting 55-gallon drums and power lines at depths of several meters. In dry sand, penetration depths of tens of meters are possible.

Change Detection. A technique known as coherent change detection offers the capability for detecting changes between imaging passes. To detect whether or not a change has occurred, two images are taken of the same scene, but at different times. These images are then geometrically registered so that the same target pixels in each image align. After the images are registered, they are cross correlated pixel by pixel. Where a change has not occurred between the imaging passes, the pixels remain correlated, whereas if a change has occurred, the pixels are uncorrelated. Of course, targets that are not fixed or rigid, such as trees blowing in the wind, will naturally decorrelate and show as having "changed." While this technique is useful for detecting change, it does not measure direction or the magnitude of change.

Sandia Capabilities

Sandia National Laboratories offers state-of-the-art capability in the design and development of synthetic aperture radars, from system design through system integration to data collection and analysis. As a multidisiplinary laboratory, Sandia can apply world-class expertise, such as high performance computer processing, semiconductor device physics, mechanical stress analysis, flight dynamics, motion measurement, etc., to the difficult problems SAR systems may present. This section describes the Twin-Otter SAR Testbed and outlines some of the technologies used in that SAR system.

Testbed Aircraft. Sandia designed, developed, and now operates a state-of-the-art SAR installed in a DOE-owned Twin-Otter aircraft (Figure 7). The Twin Otter provides a low-cost testbed which is easily adaptable to varied applications. The SAR is a flexible, calibrated sensor which has been applied to a number of imaging problems of national importance. An identical copy of this SAR has been integrated for the DOE Office of Arms Control and Nonproliferation and is being installed in a pod on a Lockheed P-3 aircraft.

Figure 8 shows the antenna, microwave front end, gimbal, and inertial measurement unit (IMU) with the radome removed. Figure 9 illustrates the Synthetic Aperture Radar Assembly, with and without the cover. This assembly contains the microwave receiver and frequency generator; high-speed timing & control; waveform synthesis; A/D converters; and the signal processor. In addition, Sandia designed and developed the image-formation processor, signal processing algorithms, and motion compensation subsystems.

Figure 7. Twin-Otter SAR Testbed. The radome, containing the antenna and gimbal, is located on the underside of the aircraft just behind the rear landing gear.

Twin-Otter SAR Parameters

Parameter	Value
Center frequency	15 GHz
Operating modes	strip map or spotlight
Operating range	4 to 20 km
Depression angle	20 to 90 deg
Squint angle	45 to 135 deg
Aircraft velocity	35 to 100 m/s
Range swath width	1800 pixels
Resolution	coarse to fine
Peak transmitted power:	
Solid state	30 W
TWTA	600 W
Pulse repetition frequency	11 kHz
Transmitted pulse width	25 us
Pulses presummed	1 to 64 pulses
Noise equivalent reflection coefficient	< -30 dB
Antenna:	
Type	offset fed dish
Azimuth beamwidth	5 deg
Elevation beamwidth	15 deg
Data storage:	
Type	Ampex DCRSi
Data capacity	45 gbytes
Record time	about 2 hr

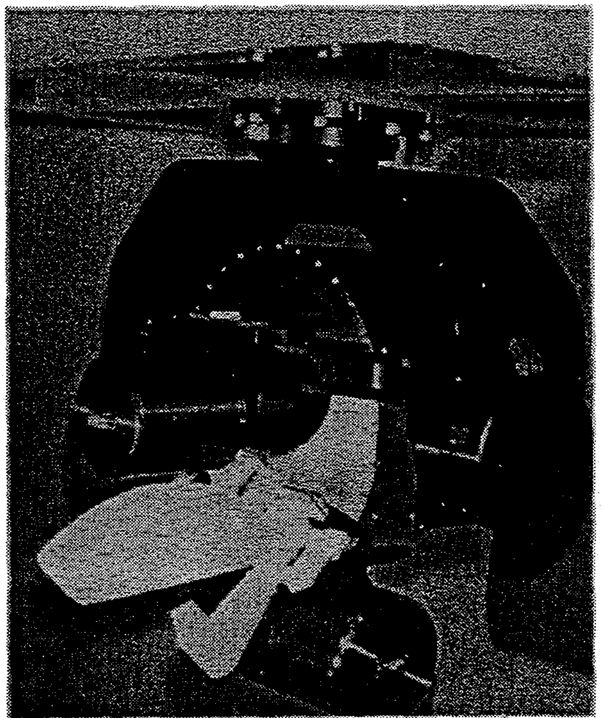
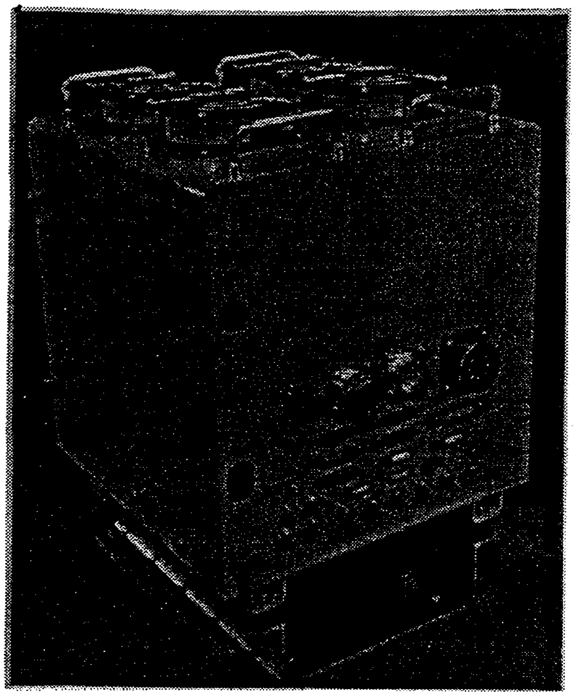


Figure 8. Antenna (white), Microwave Front End, Gimbal (black), and Inertial Measurement Units (cylinders). Two IMUs are shown mounted for trade-off studies, although only one IMU is used at a time.

The table lists the significant parameters of the Twin-Otter SAR. These parameters are programmable and allow the testbed to meet the needs of varied programs. As the imagery is processed, it is displayed on a high-resolution (2048 line) MegaScan monitor. An Ampex DCRSi high-density tape recorder stores the radar raw data (phase-history), processed imagery, and auxiliary data (motion compensation, state-of-health, etc.) on-board the aircraft.



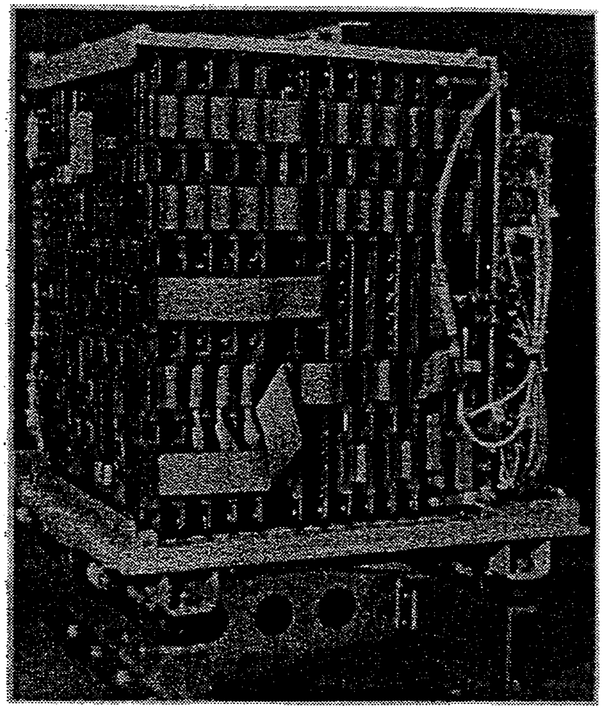


Figure 9. Synthetic Aperture Radar Assembly, with and without cover, showing the SAR microwave receiver and frequency generator; high-speed timing & control; waveform synthesis; A/D converters; and the signal processor, which forms the image.

Microwave Components. The microwave components represent the state-of-the-art in wide bandwidth and miniaturization. Figure 10 shows the 15-GHz receiver and frequency generation electronics for the SAR. This assembly contains all of the microwave components in the SAR, except for the transmitter and rf front end. The assembly uses a hybrid technology known as soft-substrate networks, which allows a high level of miniaturization. Sandia has been a leader in developing soft-substrate technologies and this technology may now be applied to the next generation of radar fuze, providing lower cost and greater miniaturization. To reduce the design and development cost, and further reduce the size, the receiver and frequency generator make extensive use of monolithic microwave integrated circuits (MMICs), a technology enabled by the DoD's MMIC program.

High-Speed Digital. In addition to the microwave components, a SAR contains several digital components that operate at high speeds. Examples are the A/D converters, which sample the microwave signal and provide a digital representation to the signal processor; the timing and control circuits, which provide the critical timing and functional control for the SAR; and the waveform synthesizer, which generates the transmitted waveform. To obtain the highest performance, these circuits often use gallium-arsenide (GaAs) digital integrated circuits (ICs) which are capable of operating at clock rates over 1 GHz.

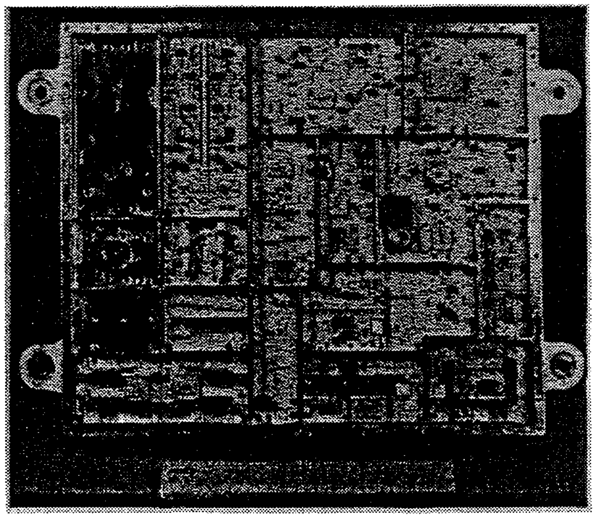


Figure 10. The Microwave 15 GHz Receiver and Frequency Generator uses soft-substrate networks and monolithic microwave integrated circuits to achieve a high level of miniaturization.

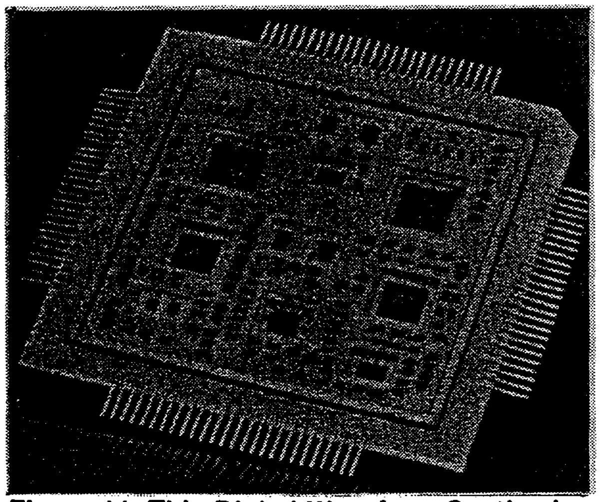


Figure 11. This Digital Waveform Synthesizer Multi-Chip Module consists of digital GaAs ICs operating at clock frequencies up to 800 MHz and can generate a linear-frequency-modulated signal from DC to 350 MHz.

Figure 11 shows a multi-chip module (MCM) implementation of the SAR digital waveform synthesizer. This module contains custom digital GaAs ICs designed by Sandia which have set the state-of-the-art in digital-waveform synthesis. The module operates at a clock rate of 800 MHz, dissipates 22 W of power, contains about 200 components, and can generate a linear-frequency-modulated waveform from DC to 350 MHz.

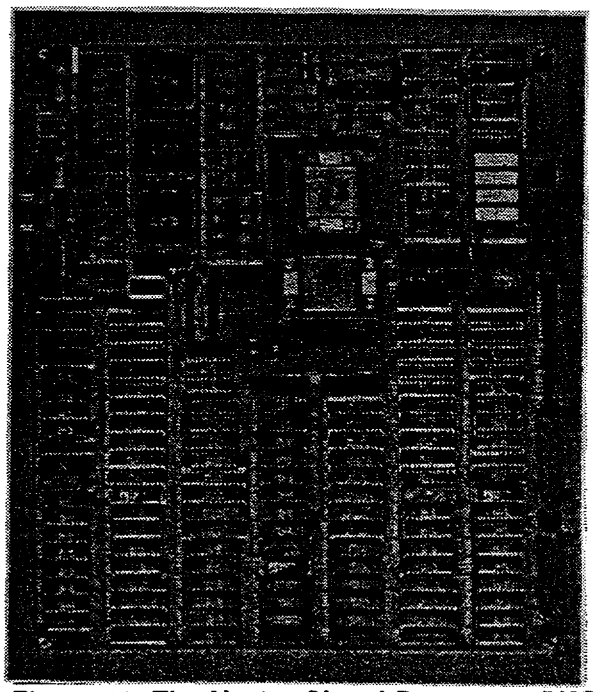


Figure 12. The Vector Signal Processor (VSP) provides the computational engine for the SAR. Each VSP board can perform computations at a sustained rate of 300 million operations per second (MOPS).

Image-Formation Processing. The SAR image-formation processor, contained within the SAR Assembly shown in Figure 8, uses a number of custom boards designed and developed at Sandia for SAR. Figure 12 is the Vector Signal Processor (VSP), which is the main computational engine for the SAR. A SAR may contain several VSPs, each one of which is capable of a sustained rate of 300 million operations per second (MOPS). Advanced semiconductor and packaging technologies will enable these rates to be far exceeded in the near future.

Signal Processing Algorithm Development. In addition to the hardware described above, forming a SAR image in real- or near-real-time requires computationally efficient algorithms. Sandia is an established leader in algorithm development with the invention of an image-formation algorithm known as the overlappedsubaperture algorithm (OSA) and an autofocus algorithm known as phase-gradient autofocus (PGA). OSA provides an efficient mapping of the required mathematical operations to available hardware, such as the VSP shown above, and yields excellent image quality over large image sizes.

High-Performance Computer Implementations of SAR Image Formation. Some SAR platforms gather the SAR data and temporarily store it until it can be conveniently down-linked for processing. In such scenarios, high computational throughput is required to form all of the images as rapidly as possible before the next data down-link cycle. Ground-based high-performance computers offer the computational power to form images in real or near-real time. Sandia National Laboratories is a recognized leader in applying commercially available massively parallel computers to rapidly form SAR images. A 1024-processor nCUBE 2 supercomputer is currently dedicated to this task. Sandia has also adapted its image formation software to the Cray YMP for its customers.

Motion Compensation and Navigation. Fine resolution image focusing requires compensation for aircraft motion which deviates from a nominal straight line flight path. Thus precise knowledge of the position and velocity of the SAR platform is necessitated. In addition to this precision motion measurement requirement, an autofocus algorithm is required to complete fine resolution image focusing. Sandia's PGA algorithm offers several advantages over previous autofocus algorithms: it is computationally efficient, robust, and corrects for higher order phase errors. Figure 13

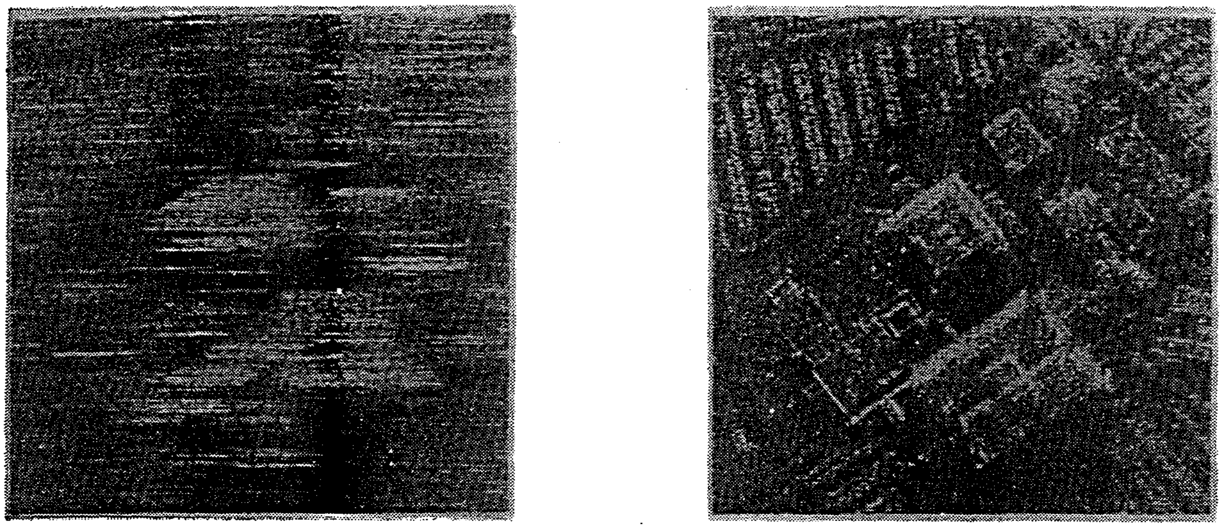


Figure 13. Before and after motion compensation.

illustrates an unfocused SAR image, and the same image after motion compensation and autofocus have been applied.

Additionally, precise knowledge of the SAR platform position allows the location targets of interest in the SAR image to be accurately computed. Finally, precise position knowledge allows very accurate repeat imaging passes, facilitating two-pass IFSAR terrain mapping and 3-D target imaging. Sandia is uniquely postured to provide the required SAR platform motion measurement because of our experience in the development and testing of precision navigation systems. This development has focused on small, rugged strapdown inertial navigation systems ~~and use~~ of the Global Position System (GPS).

Summary

This paper has presented the capabilities of Sandia's SAR and IFSAR development technologies and activities. The integration of these technologies has provided Sandia with national recognition for well focused, high resolution, calibrated SAR imagery. Inquiries regarding additional information or potential application of this expertise to probelms of national importance are encouraged.

For additional information, please contact:

Dr. Larry Hostetler, Assistant Director
Exploratory Systems Concepts
Department 9102
P. O. Box 5800
Albuquerque, NM 87185
(505) 844-4885

Dr. Dan Cress
Remote Sensing Systems
Application Department 9134
P. O. Box 5800
Albuquerque, NM 87185
(505) 844-7182

or

Mr. Bruce Walker
Synthetic Aperture Radar Department 2345
P. O. Box 5800
Albuquerque, NM 87185
(505) 844-1261

or

Dr. Charles Jakowatz
Analysis Department (II) 5912
P. O. Box 5800
Albuquerque, NM 87185
(505) 844-1704