Synthetic Aperture Radar

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Optics and synthetic aperture radar (SAR). At first glance
one might question what the two technologies have in common;
in reality they share an intertwined history that dates from the
earliest coherent radar imaging effort.[1]

In the early 1950s, researchers dis-
covered that an airborne side-look-
ing radar's antenna beam could
be artificially narrowed to improve its
angular resolution by use of the Doppler
characteristics of the radar echoes. To
achieve this effect, the corresponding
antenna aperture was synthesized by
summing multiple returns to create a
much narrower beam than that of the
real antenna carried by the aircraft.
Significant technical challenges were
rapidly overcome, allowing practical
operational systems to be flown as early
as 1958. Since then, the pace of develop-
ment in the field has not slowed; subse-
quent work has generated ever more
sophisticated synthetic aperture radar
(SAR) systems that today offer incredi-
bly detailed images with all the atten-
dant advantages of a microwave radar
system, including the ability to image
at night and through clouds, fog, dust,
adverse weather and, in special circum-
stances, foliage and the ground itself.

Image of Washington, D.C., created by Sandia National Laboratories radar system.

SAR systems have been successfully operated from raised platforms, manned and unmanned aircraft of all types, spacecraft orbiting Earth and other planets, and even from Earth to image the moon and other planets. The nature of SAR images also facilitates a number of other useful products, such as high-fidelity topographic maps and sensitive change detection maps. SAR processing embodies, in a single technology, the principles of holography, tomography, optics and linear filtering. Engineers have successfully fielded systems that operate at meter to millimeter wavelengths. Systems that operate at optical wavelengths are now under development. Each type of system has its own advantages and disadvantages.

Although the concept of SAR is more than 50 years old, relatively recent technological advances in components and algorithms have allowed a leap in its utility and desirability as a remote sensing instrument, so that today SAR often rivals electro-optical/infrared (EO/IR) systems.

The fundamentals of SAR

A SAR image such as that illustrated in Fig. 1 is usually a two-dimensional (2D) map of the radar reflectivity of a target scene which includes dimensions of range and azimuth. Most airborne and orbital SAR systems are monostatic, in that they employ a single antenna for transmission and reception of the radar signal. The transmitted signal is typically a sequence of modulated pulses generated at various positions along the radar's flight path. Ranging is accomplished in the usual manner for radar, via pulse echo timing. SAR is unique in that echo data from the different positions, also sequential in time, are processed as a collection to artificially lengthen the antenna array to the spatial extent of the collection, or in other words, to the synthetic aperture length. The technique narrows the array beam pattern and makes it possible to achieve finer azimuth resolution. This type of coherent processing across multiple pulses is often called Doppler processing.

In SAR the essential measurement is a record of the pulse echoes at various positions along the flight path, where specific echo time delays correspond to round-trip ranges via the propagation velocity. Recognition of the fact that the same delay is achieved for a one-way range at half the propagation velocity (something the seismic imaging

Figure 1. SAR image of a location at Kirtland Air Force Base, Albuquerque, N.M., exhibiting 4-inch (10 centimeter) resolution. Note that the aircraft are better defined by their shadows than by their direct echo return.

community terms "the exploding reflector" model) allows a meaningful illustration of aperture synthesis such as that shown in Fig. 2.

In optics, an imaging lens applies a phase function to a scattered field so that coherent summation occurs at the correct location in the image plane. If, however, the field itself can be sampled with both magnitude and phase, then the focusing operation of the lens can be applied with signal processing rather than by the dielectric properties of the lens. As can be seen in Fig. 2, any arc of samples across the aperture would suffice, with no restrictions on the linearity or curvature of the arc. If the target scene is static, then clearly the field measurements need not be simultaneous, or even collected in any particular order. Sampling, in which the pulse echo data is collected during the course of the aircraft's flight, is inherent to a pulsed radar system. The Doppler signatures of objects in the target scene are manifested in their

pulse-to-pulse phase variations. In an analogy with the field of lens design, it is however essential that the spatial locations of the samples—or at least their precise positions relative to each other—be known to a fraction of a wavelength.

Modern inertial measurement systems, especially when aided by Global Positioning Satellite (GPS) information, can often measure relative radar location to within centimeters per second of synthetic aperture collection time, with submillimeter random position error. Excessive motion measurement errors, which result in smeared or blurred images, can often be remediated by means of autofocus signal processing techniques. A popular SAR autofocus algorithm with roots in astronomy is known as the phase-gradient autofocus algorithm.[2] In any case, whether autofocus is used or not, if the residual phase errors in the compensated data set are less than a fraction of a wavelength, then the image will exhibit resolution

approaching the desired diffraction limit of the synthetic aperture. Good radar designs often achieve what is, in effect, diffraction-limited imaging.

Strictly speaking, SAR entails synthesizing a longer antenna aperture to the end of achieving finer azimuth angular resolution. The azimuth resolution is limited only by the length of the synthetic aperture, not by the size of the antenna carried by the aircraft. However, a constraint on the real (physical) antenna remains: to be capable of keeping the scene of interest within the antenna beam footprint. Appropriate synthetic aperture lengths, which are commonly from several meters to tens of kilometers, are calculated from range, resolution and wavelength.

SAR images are more appealing in aesthetic terms when the range resolution is commensurate with that of the finer azimuth resolution. Finer range resolution is achieved by sending a pulse of adequate bandwidth; this can be done either by sending a suitably short pulse or by modulating a pulse so as to yield a narrow autocorrelation function similar to that which characterizes spread-spectrum communications. Popular modulation schemes include random phase codes and the linear-frequency-modulated (LFM) chirp signal. Modern SAR systems typically employ pulses that range from several microseconds to several hundred microseconds in length, with time-bandwidth products that are sometimes in the tens of thousands. The LFM chirp signal is particularly advantageous for fine resolution SAR systems in that it can be easily generated; another advantage is that it can be partially processed before the data is digitized. Prior to sampling, the chirp can effectively be removed from the echo signals via heterodyning. The resulting video signal has reduced bandwidth, in which a constant frequency maps to a constant relative delay (range).

The collected data set represents a section of a surface in the Fourier space of the target scene being imaged, as illustrated in Fig. 3. Since the raw SAR data consist of samples of the Fourier space of the target scene, it is only natural to employ Fourier transform techniques to process them into an image. Because the

data are collected on a polar raster, they often have to be reformatted or resampled before digital signal processing can take place efficiently. A popular technique for processing raw SAR data is the polar format algorithm.

"Spotlighting" and "strip-mapping" are the two principal operating modes for SAR systems. In spotlight SAR, the radar dwells on a single scene for one or more synthetic apertures, with the image width confined to the antenna azimuth beam footprint. Originally, the term strip-map SAR was used to describe cases in which the radar was used to scan during a synthetic aperture, forming an arbitrarily long image from multiple overlapping synthetic apertures along a flight path that was generally much longer than the azimuth footprint of the antenna beam. Modern SAR systems often form strip maps by mosaicking a sequence of spotlight images.

A number of subtleties in the characteristics of the data have been ignored in this discussion; some of them become problematic as resolutions become finer or scene sizes increase. Various processing algorithms have been developed to accommodate these characteristics and mitigate their effects; each has its proponents for different applications. All share the objective of creating an image from field measurements along a synthetic aperture over a finite bandwidth.

SAR optical processing

From the very early days, synthetic aperture radar imaging and optics have been closely linked.[3-5] Fourier optics provided the necessary signal processing technology for what might be considered the first successful SAR systems. The very successful application of optical signal processing to synthetic aperture radar development was also a big stimulus for interest in, and development of, Fourier optics and optical signal processing. The equivalence between SAR image formation and holography also played an important role in the development of the technology. Harger[3] states in his book, "The elegant ideas of [Dennis] Gabor and [Emmett] Leith are not essential but [are] very instructive in understanding and generalizing the synthetic aperture radar principle." It would be very difficult
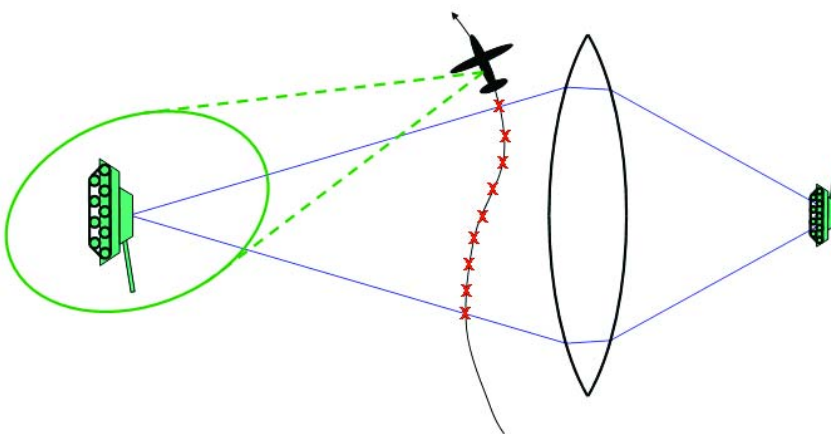
Figure 2. SAR processing samples the scattered field and applies the imaging functions depicted to the right of the aircraft flight path.
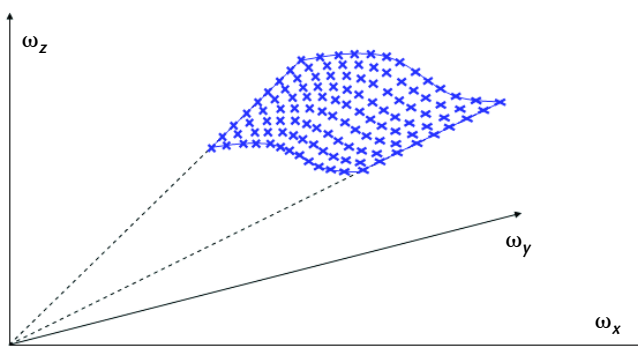

Figure 3. SAR data represent a surface in the 3D Fourier space of the target scene.

to treat in significant detail the fruitful interaction between the radar and optics community in these few pages, but by the same token it would be difficult to overstate the role that optics played in the development of SAR technology.

Early research culminated in 1953 in a much larger effort known as Project WOLVERINE,[6] coordinated by the University of Michigan. SAR technology developed rapidly from this point. Early in development, it was recognized that there was a data storage problem: the electronics of the day did not offer a practicable storage method for the data rates generated by SAR systems. A clever solution was to use photographic film as a storage medium. High-resolution photographic film offered data storage densities on the order of 1,000 line pairs per millimeter. Film recording was used

successfully in airborne SAR systems as early as 1957.[6]

The electronics of the day also did not measure up to the data processing problem; computers at that time were not up to the task. Although there were attempts at electronic analog data processing, Fourier optical processing of the film-recorded data was recognized almost immediately as a very viable solution to the 2D signal processing problem. Figure 4 illustrates the components of a successful optical processing system. A key component, the conical lens, is another of the many contributions of Leith.[3] In this system, each range line of data is written across the film as a data line and high-resolution SAR images are obtained as the output recording film tracks the motion of the input film through the system. This system was
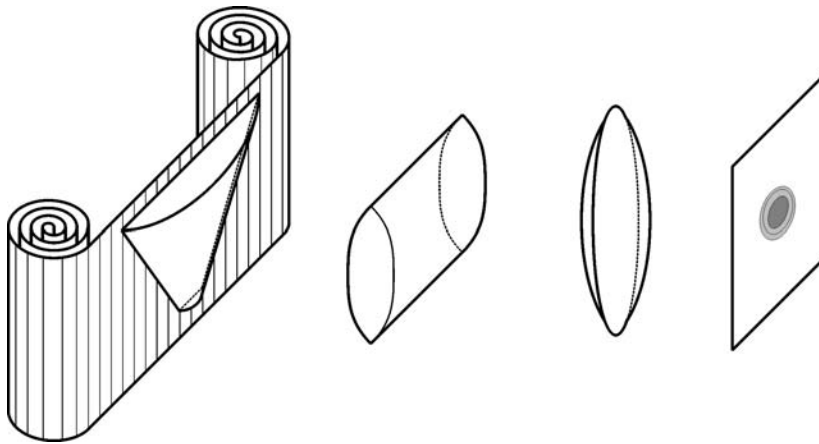
Figure 4. Components of an optical SAR processing system: a collimated beam illuminates the film recorded data from the left; the conical and cylindrical lenses compensate for the tilt and separation of the range and azimuth image planes. The focused image is recorded at the plane on the right.

eventually replaced by the more flexible, tilted-plane optical processor, which consisted of a cylindrical telescope, a spherical telescope and tilted input and output planes. The tilt of the planes could be changed to accommodate changes in SAR system parameters.

Eventually, advances in electronics and computing technology made optical processing of SAR data obsolete. But the epoch of optical processing was not as short as people relatively new to the fields of optics or radar might think. Optical processing was the major method of producing high-resolution images from the late 1950s (before the advent of the laser[7]) until the 1980s. In his 1980 paper, Dale Ausherman[5] states, "While current operational SAR systems almost unanimously employ coherent optical methods, proponents of new systems stress the need for digital technologies in order to overcome the apparent limitations of optical approaches." It can be argued that it was the success of coherent optical processing that fueled the relatively large research efforts that followed in areas of optical data processing and optical pattern recognition.

There are other ties between the optics and SAR communities. One example is the aforementioned autofocus algorithm, which evolved from techniques used in optical astronomy. Currently there is interest in developing SAR type systems at optical wavelengths.

Modern systems and applications

As digital computers became more powerful, optical processing techniques were supplanted by digital signal processing techniques which offered greater flexibility and more processing options. Later, when computer hardware shrank in size and weight, image formation processing left the laboratories and became an integral part of the radar, a move which offered the user real-time images as well as multiple and flexible operating modes.

Today, a variety of systems fill important roles in surveillance, reconnaissance, mapping, monitoring and resource management. SAR systems are used by the military, government agencies and commercial entities.

One operational high-performance airborne system is the Lynx (AN/APY-8) SAR, designed by Sandia National Laboratories and produced by General Atomics. It offers a variety of imaging modes and is capable of forming high-quality real-time 4-inch resolution images at 25 kilometer range (representing better than arc-second resolution) in clouds, smoke and rain. This system, which weighs 120 pounds, has flown on a variety of unmanned and manned aircraft, including helicopters. Sandia National Laboratories is now engaged in developing a MiniSAR system which offers the same flexibility and high-quality images and resolutions at a

somewhat reduced range, but weighs less than 20 pounds.

In 1978, SeaSat became the first Earth-orbiting SAR launched by NASA. Since then, a plethora of orbital SARs have been (and continue to be) flown by several nations. One of them is the Shuttle Imaging Radar flown by NASA. In 1990, the Magellan SAR began orbiting and mapping the cloud-enveloped planet of Venus, offering observers unprecedented views of its shrouded surface.

Normally in imaging only the magnitude of image pixels is displayed as the image. However, SAR images formed by digital computers retain their phase information. This factor can be exploited to display a number of interesting scene characteristics.

Interferometric SAR (IFSAR or InSAR) is a technique in which images are formed from two synthetic apertures taken at slightly different radar antenna elevation angles. The images exhibit a very subtle parallax which is observable as a phase difference that depends on target height. The phase difference is measured on a pixel by pixel basis to ascertain the surface topography of the scene; this procedure allows 3D surface maps with unprecedented detail and accuracy to be composed. Sandia's Rapid Terrain Visualization project demonstrated an IFSAR with on-board processing capable of forming topographic maps with 3-meter post spacing and 0.8-meter height accuracy. Figure 5 shows a typical product of this system, in which color maps height.

If flight geometries are sufficiently different, then the parallax results in a measurable displacement of image features. Stereoscopic measurements can then be made to also measure topography with great accuracy.

Since SAR is essentially a narrowband imaging system, SAR images exhibit speckle in regions of diffuse scattering, such as vegetation fields, gravel beds and dirt roads. For a static target scene, if a synthetic aperture is repeated (same flight path and viewing angle), then the speckle patterns will be identical in both magnitude and phase: the speckle, in other words, is coherent. If a region of the scene is disturbed between the times in which the two images are captured,
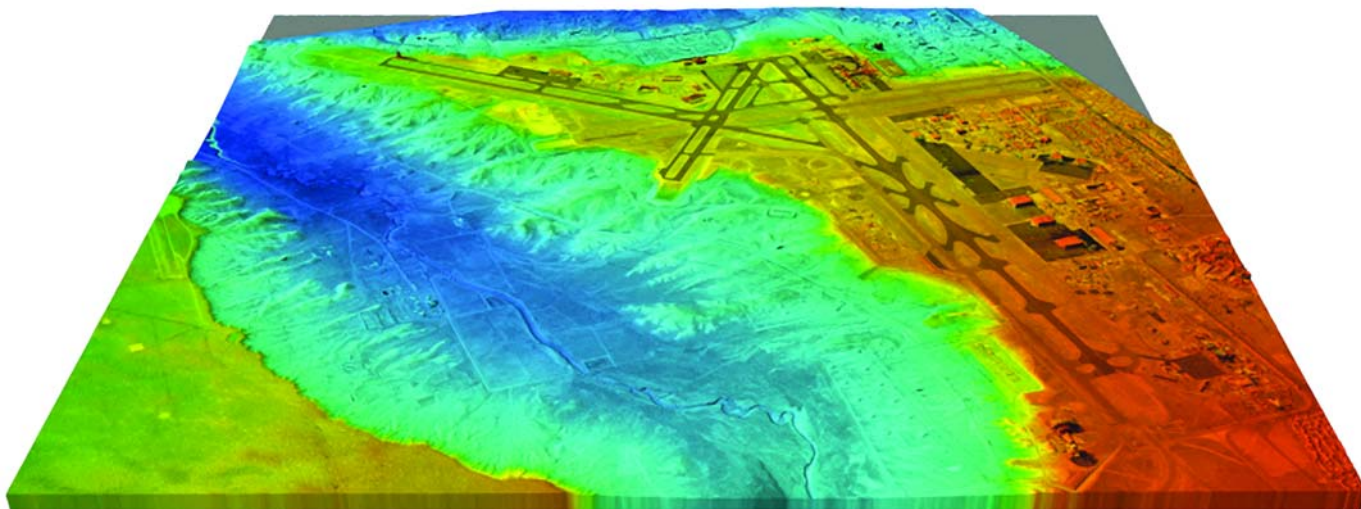
Figure 5. Three-dimensional rendering of IFSAR data of Albuquerque International Airport. Color maps height.

then the speckle coherence for that region is destroyed. Pixel-by-pixel coherence measurement and mapping for the two images will display the destroyed coherence and distinguish it from its surroundings. This technique is called coherent change detection. It can be used to map vehicle tracks on a dirt road, footprints in a grassy field and other subtle changes otherwise indistinguishable in the individual SAR images or by means of any other sensor. An example in which footprints and mower tracks in grass are revealed is shown in Fig. 6.

Areas of current research and development include foliage penetration, ground penetration, imaging moving vehicles, bistatic imaging (transmitting and receiving antenna on separate vehicles) and techniques for improved image quality, particularly at long ranges, fine resolution and for large scenes.

SAR was once termed "the sensor of last resort." Today's modern high-performance SAR systems, with their multiple modes and unique capabilities, are increasingly being turned to as indispensable imaging tools.
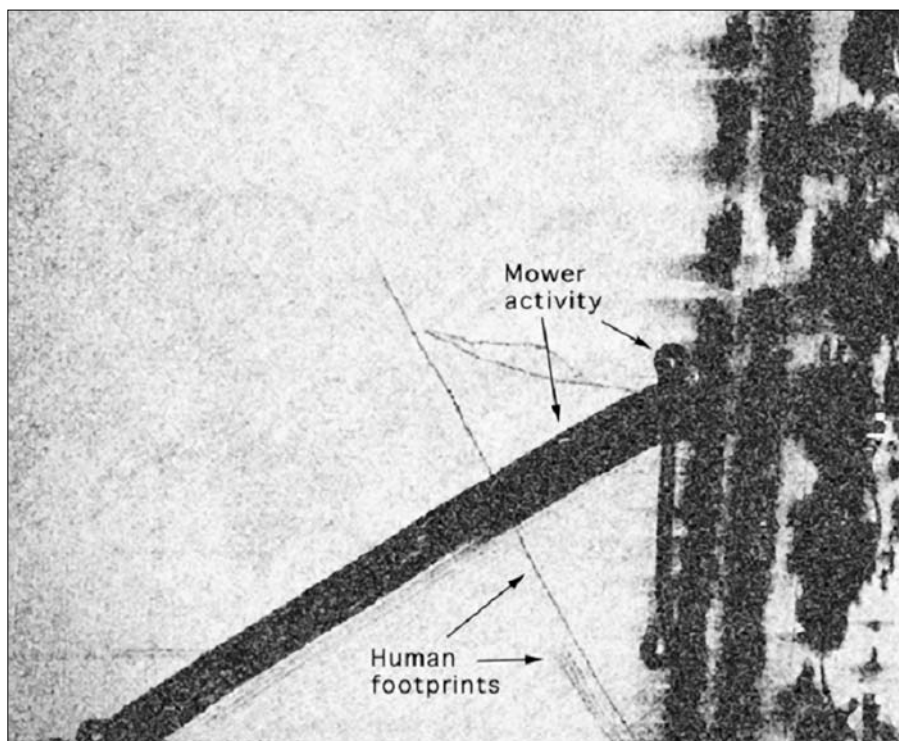
Figure 6. Coherent change detection map showing mower activity and footprints on Hardin Field Parade Ground at Kirtland Air Force Base. Dark areas denote regions of decorrelation caused by a disturbance to the clutter field; light areas denote no disturbance. The foliage along the right side of the image decorrelates because of wind disturbance.

Armin W. Doerry and **Fred M. Dickey** are both Distinguished Members of Technical Staff at Sandia National Laboratories, Albuquerque, N.M. They invite the reader to visit many more examples of SAR images, image products, programs and applications at www.sandia.gov/radar. Radar questions can also be directed to Armin Doerry at awdoerr@sandia.gov.

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