by Diane L. Evans

Geologic process studies using Synthetic Aperture Radar (SAR) data

Numerical models of climatic processes offer the promise of simulating future global trends; however, it is crucial for us to understand how changes in climate are manifested locally before we can evaluate the true impact of climate change. Thus, increased awareness and concern about global climate change have led to an equal interest in remote sensing as a tool for mapping and monitoring changes in the land surface and cover.

Geologic processes, such as soil erosion, transportation, deposition, and degradation, affect not only the amount of arable land available for cultivation but also have an impact on sedimentation in estuaries, deltas, and other coastal environments. Additional geologic processes, such as tectonism and volcanism, have a profound impact on human life as well. These additional processes become modulators of global climate not only through destructive seismic activity but also through the influence of volcanoes on the chemistry of the oceans and atmosphere and through eruptions of gases and particulates into the stratosphere.

Synthetic Aperture Radar plays an important role in landform mapping and structural interpretation because viewing geometries can be optimized for different terrain types in a way similar to that used for low sun-angle aerial photography. In addition, radar data are important for geologic process studies because unique quantitative information about surface roughness, vegetation extent, soil moisture, topography, and topographic change can be extracted from calibrated data sets.

Introduction

The image brightness of Synthetic Aperture Radar (SAR) is related to radar backscatter at the pixel level, and it is a function of slope, surface roughness, dielectric constant, and subsurface discontinuities. Therefore, it provides intrinsic physical information about surfaces and volumes that complement measurements made by sensors operating in the visible, shortwave infrared, and thermal infrared parts of the electromagnetic spectrum.

Radar sensors provide their own illumination and, as a result, can provide reliable multitemporal data that are independent of weather or sun illumination through all seasons and at all latitudes. Radar waves penetrate through clouds and, under certain conditions, through vegetation canopies and thin veneers of alluvial overburden, which makes it possible to explore regions of the Earth's surface that are not accessible by the use of other remote sensing techniques.

Geologic processes that are particularly amenable to studies employing SAR data include volcanism; soil erosion, degradation, and redistribution; coastal erosion and inundation; glacier fluctuations; permafrost; and crustal motions. Such process studies are critical not only to our understanding of recent tectonic activity and climate change but also to the mitigation of geologic hazards and to exploration for nonrenewable resources.

Sensors flying now, as well as those planned for flight in the 1990s, provide an opportunity to develop models and test methods for large-scale mapping, geophysical processing, and the generation of high-resolution digital elevation models that will make it possible to use SAR data routinely for global process studies. Data acquired from airborne sensors such as the Airborne Imaging Radar (AIR-SAR), which was developed by the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL), are being used for investigations that focus on fairly small test sites (figs. 1-3). Data from the Shuttle Imaging Radars (SIR-C and X-SAR), scheduled for flights in 1993, 1994, and 1996, will expand these studies to regional scales; and the Earth Observing System (EOS) SAR, planned later in the decade, will provide both global coverage and a monitoring capability.

When data from these systems are combined with data from other planned spaceborne sensors, such as the European Space Agency's (ESA) European Remote Sensing satellites (ERS-1 and ERS-2), the Japanese Earth Resources Satellite (JERS-1), and the Canadian Radarsat, it will be possible to build a time-series view of temporal changes over many regions of the Earth. Operating parameters for these SAR systems are given in table 1. Key geophysical products that will be derived in support of geologic process studies from the resulting data are given in table 2. The status of our current capability to generate these geophysical products is described below.

Landform mapping

Exploitation of radar data for geological studies has advanced most in the area of landform mapping. Several studies have shown the value of SAR images for mapping structures in volcanic and sedimentary terranes (Greeley and Martel, 1988; Campbell and others, 1989; Gaddis and others, 1989; Sabins, 1983; Wadge and Dixon, 1984; Lynne and Taylor, 1986) and for studying the processes of erosion, weathering, and deposition (see Blom and Daily, 1982; Evans, 1988; Arvidson and others, in press).

Images from the Shuttle Imaging Radars (SIR-A and SIR-B) of the eastern Sahara in northern Africa revealed the capability of spaceborne radars' providing insight into the geologic record that is

Figure 1.—Multifrequency AIRSAR images of Kilauea Crater, Hawaii, USA, showing lava flows of varying ages and surface roughness. Images such as these will be used to support the Earth Observing System's (EOS) volcanology investigation (for example, see Mouginis-Mark and others, 1991). See table 1 for explanation of abbreviations.

buried beneath thin deposits of windblown sand and is masked from sensors that operate in the visible part of the spectrum (McCauley and others, 1982; McCauley and others, 1986; Schaber and others, 1986). Subsequent reexamination of data acquired in 1978 from the Seasat satellite and in 1988 from AIRSAR showed that significant penetration also occurred in the Mojave Desert of southern California, USA, which indicates that subsurface features of potential tectonic significance may be revealed in radar images of semiarid terranes (Blom and others, 1984) (fig. 4).

Several techniques have been developed that may result in automated landform mapping. For example, a technique that can be used to map textural variations was described by Blom and Daily

(1982) and was used by Stromberg and Farr (1986). The technique involves the production of images that represent only certain scales of texture. This is accomplished first by filtering the Fourier transform of an area into several spatial frequency bands and then by producing an image for each of these bands. These bandpass images are used next in a standard, unsupervised classification algorithm in order to produce a map, the units of which represent unique textural signatures. One also could use images in which pixels represent local variance, or other statistical quantities, in different sized boxes in the classification algorithm. These techniques not only discriminate units that are based on texture, but they produce a spatial frequency signature for the units as well. These signatures allow the comparison

Figure 2.—Multifrequency AIRSAR images of Death Valley, California, USA, showing alluvial fan units of varying ages and surface roughness. Such images will be used to determine the relative ages of geomorphic surfaces, information that is required for studies of modern erosion rates, past climate fluctuations, and dating of young faults.

of units between maps and may allow the identification of rock types if adequate knowledge exists about the climate, tectonic history, and response of different rock types to these factors.

Surface roughness

Weathering and depositional processes generally cause surfaces to smooth as they age, whereas erosional processes can cause a rough-

ening of surfaces. The scales of these processes are different, and their rates vary as a result of climate, rock type, and geologic structure. However, their effects can be used to date surfaces relatively for studies of climatic change and tectonic history. In cases where numerical ages exist, average process rates over time also may be derived.

Microtopography or surface roughness is the link between weathering and depositional processes and radar remote sensing data.

Figure 3.—Multifrequency AIRSAR images of glaciers near the southwest coast of Greenland showing variations in both surface and subsurface structure. Images such as these will be used in order to study changes in glacier mass balance (see Rott, 1990; Jezek and others, 1991).

Work by van Zyl and others (1991) showed that surface microtopography could be inferred from multifrequency SAR data by the inversion of a radar backscatter model. In that study, physical properties were measured at three different 10 m by 10 m sites representing surfaces that had root mean square (rms) heights varying from less than 1 cm to tens of centimeters. Ground measurements included soil

moisture content, dielectric constant, and microtopographic profiles. The profiles were generated from helicopter photography using twin metric framing cameras that was reduced later to profiles covering 10–30 m at 1-cm spacing, which allowed the estimation of the power spectrum, rms height, and correlation length of the surfaces (Wall and others, 1991). AIRSAR data acquired at three different incidence

Table 1.—Operating parameters of examples of current and future SAR systems

[Abbreviation: N/A, not applicable]

	AIRSAR	ERS-1	SIR-C/X-SAR	JERS-1	RADARSAT	EOS SAR
Spectral coverage ¹	P,L,C	C	L,C,X	L	C	L,C,X
Polarization ²	Quad	VV	Quad (C,L) VV (X)	HH	HH	Quad (L) Dual (C,X)
Look angle (degrees)	15–60	23	15–60	35	20–50	15–40
Resolution (m)	10	30	25	30	10–100	20–250
Swath coverage (km)	12	100	10–150	80	50, 500	30–500
Orbit altitude (km)	10	800	215	568	792	620
Orbit inclination (degrees)	N/A	98	57	98	98.6	98
Launch date	N/A	1991	1993 1994 1996	1992	1994	1999

¹ X-band wavelength is ~3 cm

C-band wavelength is ~5.6 cm

L-band wavelength is ~24 cm

P-band wavelength is ~68 cm

² HH, horizontally transmitted, horizontally received wave

VV, vertically transmitted, vertically received wave

Quad=amplitude and phase of returned wave are both recorded so that any combination of transmit and receive polarization can be synthesized through ground processing

Table 2.—Examples of solid Earth products that are required from EOS SAR data

[Abbreviation: res, resolution; —, not applicable]

Products	Units	Accuracy	Horizontal res	Temporal res
Geologic feature distribution	m	30	30 m	3 months, once
Surface roughness, high res	cm	5–10%	30 m	1 year, once
Surface roughness, low res	cm	10	25 km	1–2 weeks
Vegetation extent, high res	—	10%	30 m	1 season, 1 year
Land topography, high res	m	5–10, vertical	30 m	Once
Topographic change	cm	10, vertical	30 m	After event
Soil moisture	—	10–25	60–100 m	1 week

angles and three wavelengths over the test site were calibrated by using trihedral corner reflectors that were deployed in the area prior to obtaining the images in order to provide radar backscatter values (σ^0) for each resolution element in the scenes (van Zyl, 1990). The radar backscatter model was used next in order to infer the power spectra of surface microtopography for the three surfaces, and the power spectra were compared to the field measurements. The result was that van Zyl and others (1991) found a close match between the estimated and measured surface microtopography.

Evans and others (in press) extended this work to the Cima volcanic field in California and the Lunar volcanic field in Nevada, USA. They not only found a close match between the estimated and measured surface microtopography, but they also confirmed work by Farr (in press) that showed that surface roughness changes can be correlated with age.

In order to determine the areas of an image for which the radar backscatter model is valid, van Zyl (1989) described an unsupervised classification technique that provides a means to segment images into classes displaying different types of scattering. The algorithm classi-

fies scatterers into one of three types on the basis of the polarization characteristics of the transmitted and received waves. The three scattering classes are single reflection, double bounce, and diffuse scattering. For single reflection from a slightly rough dielectric surface, the incident wave will experience little multiple scatter. A dihedral reflection exhibits a double-bounce geometry and results in a 180-degree phase shift between horizontally transmitted-horizontally received (HH) waves and vertically transmitted-vertically received (VV) waves. For diffuse scattering, highly varying phase differences of HH to VV exhibit a noiselike character. The orientation angle of the average scattered wave tracks that of the transmitted wave, a behavior that is similar to the behavior observed for the single-reflection case. However, the sense of rotation of the scattered wave is the same as that of the transmitted wave polarization, which is more consistent with a double-bounce mechanism. Papers by van Zyl (1989) and Evans and others (1988) noted that this behavior is generated by a class of "three-layer" vegetation models, such as the one discussed in van Zyl (1985), Richards and others (1987), and Durden and others (1989). The classification technique was used by Evans and others (1988) in order to map clearcut areas in a Maine, USA, forest that were not discernable in L-band HH and VV images. Evans and van Zyl (1990) also used this technique for differentiating areas that had been burned recently near Mt. Shasta in California, USA, as did Evans and others (1988) and Evans and Smith (1991) for differentiating areas having less than 10 percent vegetation cover in a semiarid region in Wyoming, USA. Figure 5 shows these two examples and a classification map for the area around Kilauea Crater, Hawaii, USA. In each of these examples, the radar backscatter model is valid for roughness scales on the order of one-half the radar wavelength for areas that are classified as single reflections for all three frequencies.

Soil moisture

Soil moisture is a hydrologic storage variable, as well as an indicator of moisture fluxes, and is, therefore, a critical parameter for many earth science investigations. SAR images have been applied successfully to map saturated soils in temperate regions (Waite and others, 1981; Krohn and others, 1983; Ormsby and others, 1985; Evans and others, 1986; Imhoff and others, 1986, 1987). This success largely

Figure 4.—Comparison of multifrequency AIRSAR images over Means valley in the Mojave Desert of California, USA. Features at arrows in P-band image, which are seen to some extent in the L-band, are shallow subcrops and a dike.

Figure 5.—Classification results based on C-, L-, and P-band polarimetric AIRSAR data of (a) Wind River basin of Wyoming; (b) Mt. Shasta, California; and (c) Kilauea Crater, Hawaii, USA. Pixels classified in red are consistent with a double bounce; in blue, with a single reflection; and in green, with diffuse scattering. According to Evans and others (1988) and Evans and Smith (1991), areas having less than 10 percent vegetation cover in the Wind

River example are classified as single reflection. In the Mt. Shasta example, Evans and van Zyl (1990) found that areas that had been burned recently allowed additional penetration into the canopy, which results in the increased double bounce at the P-band in the lower left of the image. In the Kilauea example, the forest canopy is so dense on the right edge of the image that very little return resulted from the ground under the vegetation.

results from the cloud penetration capabilities of radar and the enhanced backscatter that results from standing water beneath vegetation canopies. This backscatter enhancement, modeled by Engheta and Elachi (1982), is caused by forward scattering of waves from stems (or trunks) and the flooded surface (double bounce). L-band backscatter enhancement from flooded vegetation also has been noted in the Tropics from 12.5-m-high mangroves in Bangladesh (Imhoff and others, 1986, 1987), from 10–12-m-high swamp forests in Guatemala (K.O. Pope, written communication, 1987), and from 7–10-m-high swamp forests in Borneo (Ford and Casey, 1988).

Change detection techniques are being investigated in order to assess their applicability to monitoring changes in soil moisture in

less humid environments by the use of the ratios of images. An example of the detection of soil moisture change from multitemporal coverage (fig. 6) was described in Evans (in press).

Multitemporal SAR data were acquired in support of soil moisture studies at Mahantango Creek, Pennsylvania (Engman and others, 1991), and Walnut Gulch, Arizona (Dubois and others, 1991), in the USA in the summer of 1990. Results of these experiments were incorporated into the planning for additional SAR soil moisture experiments flown in Europe in 1991. Multitemporal aircraft data and correlative field measurements were acquired at Slapton Wood, UK; Orgeval, France; Montespertoli, Italy; and Castilla La Mancha, Spain, as part of the deployment.

Topography and topographic change

Topography is required in order to complete the three-dimensional view of surface properties and to correct the distortions that are inherent in SAR images. Active microwave techniques that use interferometry may provide a feasible method for acquiring these data. Zebker and Goldstein (1986) showed the feasibility of generating topographic data bases through the use of radar interferometry. Mission studies and the development of aircraft prototypes are underway for the purpose of investigating a variety of methods for the acquisition of a global topographic data base from space (Cumming and others, 1990; Goldstein and others, 1988).

NASA's JPL has implemented an aircraft interferometer that is similar to the one described by Zebker and Goldstein (1986). For the JPL system, the phase difference image that results from combining the two complex data sets has been used to generate topographic data having an rms error of typically 2–5 m for a 10 m by 10 m pixel (Zebker and others, in press). These data are acquired in a single polarization state at C-band simultaneously along with standard L- and P-band polarimeter data so that the data are registered automatically.

In order to address problems at the global scale, discussions are taking place about the generation of a high-resolution digital elevation model of the entire globe, which could serve as a topographic data base for all remote sensors. Among possible options for spaceborne interferometry is the use of subsequent passes of the EOS SAR or two antennas separated on a single structure or by a tether on a dedicated spacecraft. Once the baseline topography is determined, a third interferometric pass can be used to determine what, if any, topographic change has occurred in the intervening time between SAR overpasses (Gabriel and others, 1989). The near cancellation of systematic errors is possible, and sensitivity to topographic change on the order of tens of centimeters is attainable (fig. 7). The extreme sensitivity of this technique to elevation changes, its high spatial resolution (typically 10–30 m), and its broad swath coverage mean that it could be used to monitor erosion, sand encroachment, and soil shrinking and swelling (Gabriel and others, 1989). It also may be used to make extensive, accurate measurements of geophysical phenomena, including warping and buckling in fault zones, plate motions, and residual displacements from seismic events.

The use of SAR interferometry will be tested extensively for geological studies as part of the ERS-1 mission. Current plans are to monitor changes in surface topography due to eruptions (either

SEPTEMBER 14, 1989

SEPTEMBER 8, 1989

RATIO $\frac{\text{SEPTEMBER 14, 1989}}{\text{SEPTEMBER 8, 1989}}$

Figure 6.—Example of the ratio of multitemporal images for a soil moisture study area near Fresno, California, USA. Gray field (left arrow) showed no apparent difference in moisture between the 2 days in this CVV image. Dark field (right arrow) was drier on the second day. Courtesy of E. Engman and J.J. van Zyl, modified from Evans (in press).

Figure 7.—Image showing topographic changes derived from Seasat SAR data over an area in the Imperial Valley of California, USA. Yellow represents no change, black represents loss of phase coherence between the data sets, and red and blue represent

changes in topography on the order of 2–3 cm. These changes were interpreted to be related to soil swelling as a result of irrigation. Taken from Gabriel and others (1989).

explosive activity or events that produce lava flows) and to swelling of the flanks of volcanos because of the intrusion of magma at a shallow depth; frost-heave displacement in regions of both continuous and discontinuous permafrost; and the topography, motion, and disturbances of glaciers.

A look to the future

Major challenges in the future include the development of strategies that will allow us to extrapolate from regional to global scales (for example, the validation of geophysical products and the reconciliation between scales of radar backscatter models and atmospheric general circulation models) and the development of new technology that will result in additional sensor capabilities (for example, 35- and 90-GHz systems and lightweight electronics). Along with these advances will come many new applications of active microwave remote sensing (for example, precipitation mapping and subsurface mapping) that, in turn, will require new techniques for data processing and analysis.

In addition, several strategies are being pursued for the synthesis of other data sets and the geophysical information derived from SAR data. For example, multisensor classifications, which have included radar images as adjunct bandpasses to optical or infrared sensor systems (Blom and Daily, 1982; Rebillard and Evans, 1983; Evans, 1988), have reported improved classification accuracies over visible and infrared data alone. These studies, however, did not exploit the full diversity of the SAR sensors available at this time (for example, Evans and others, 1990). A different approach being investigated is to derive geophysical parameters from sensor systems independently and then do a combined interpretation on the derived geophysical products (Srinivasan and Richards, 1990; Evans, in press).

Finally, new data handling and analysis tools will be required in order to handle the enormous increase in SAR data that are expected over the next decade. The Magellan mission to Venus provided the first planetary-scale data base using SAR. Although complex in itself, future Earth-orbiting missions will acquire this same amount of data routinely so that changes can be monitored and possibly can be predicted.

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