RADAR REMOTE SENSING

S. Quegan
Sheffield Centre for Earth Observation Science, University of Sheffield, U.K.

Keywords: Scatterometry, altimetry, synthetic aperture radar, SAR, microwaves, scattering models, geocoding, radargrammetry, interferometry, differential interferometry, topographic mapping, digital elevation model, agriculture, forestry, hydrology, soil moisture, earthquakes, floods, oceanography, sea ice, land ice, snow

Contents

Summary

Radar sensors transmit radiation at radio wavelengths (i.e. from around 1 cm to several meters) and use the measured return to infer properties of the earth's surface. The surface properties affecting the return (of which the most important are the dielectric constant and geometrical structure) are very different from those determining observations at optical and infrared frequencies. Hence radar offers distinctive perspectives on the earth. In addition, the transparency of the atmosphere at radar wavelengths means that cloud does not prevent observation of the earth, so radar is well suited to monitoring purposes. Three types of spaceborne radar instrument are particularly important. Scatterometers make very accurate measurements of the backscatter from the earth, their most important use being to derive wind speeds and directions over the ocean. Altimeters measure the distance between the satellite platform and the surface to centimetric accuracy, from which several important geophysical quantities can be recovered, such as the topography of the ocean surface and its variation, ocean currents, significant wave height, and the mass balance and dynamics of the major ice sheets. The third and most versatile radar instrument is synthetic aperture radar (SAR). A unique aspect of SAR is its ability to provide precise measurements of surface displacement, using techniques known as interferometry and differential interferometry. This capability, together with the fine spatial resolution of the images and the provision of long temporal sequences undisturbed by cloud, has led to SAR being applied in numerous fields, from topographic mapping to oceanography.

1. Introduction

The word “radar” is derived from “radio detection and ranging,” which makes clear the military context in which it was first developed. It involves the transmission of signals at radio frequencies. These signals scatter from objects in the radar beam, and information about these objects is gained by measuring the scattered radiation (bats employ the same principle, but using sound rather than electromagnetic waves). For military purposes (and also for many civilian tasks, such as air-traffic control or ship monitoring), the objects of interest are usually human-made and relatively small, and the problem is to detect them against a background of scatter from their surroundings (commonly called “clutter”) and random system noise. However, from an environmental point of view, the clutter is often the most interesting part of the return, because the scatter from natural surfaces can yield information about a wide range of geophysical phenomena.

Systematic experiments, beginning in the 1960s with ground-based systems, demonstrated the sensitivity of radar to phenomena such as sea state, soil moisture, vegetation development, etc. This motivated the development of remote sensing radars designed to look down at the earth. The early systems were carried on aircraft, but the event that really demonstrated the value of this technology was the Seasat satellite mission, in 1978. As its name implies, the purpose of Seasat was to gather information about the oceans. To this end it carried three radar instruments: an altimeter, a scatterometer, and a synthetic aperture radar (SAR) (these are still the most important types of radar sensors for remote sensing; their principles are described in Section 5). The Seasat mission lasted only 100 days, but it produced truly remarkable images, including maps of the topography of the ocean surface, measurements of surface wind speeds over the ocean, and unexpected signatures of internal waves within the ocean. There were also interesting images of land surfaces, indicating the possibility of measuring land processes.

The success of Seasat stimulated worldwide interest in satellite radar, and the last decade of the twentieth century saw the launch of the European Space Agency (ESA) ERS-1 and ERS-2 satellites (launched in 1991 and 1995 respectively), the Russian Almaz, the Japanese JERS-1, and the Canadian Radarsat. The United States has not launched any further satellite SARs for Earth observation, but carried out the spectacularly successful Magellan SAR mission to Venus, which allowed the surface of the planet to be mapped at unprecedented detail. American efforts in space-based radar remote sensing have instead been through satellite altimeters (for example, TOPEX-Poseidon, in collaboration with France), scatterometers (NSCAT, jointly with Japan, and QuikSCAT), and systems carried on the space shuttle. The shuttle has helped to carry the field forward by demonstrating the space deployment of techniques, like polarimetric radar, and to carry out specific tasks, such as global topographic mapping by using interferometry (the SRTM mission). In addition, the JPL/NASA AirSAR airborne SAR system has played a major role in exploring the value of multiple frequencies and polarisations for remote sensing.

Since the early 1990s we have had continuous observations by radar satellites, and there have been major advances in understanding what they bring to our knowledge of the earth and its processes. Radar data have provided information on phenomena as diverse as earthquakes, ocean currents, forest biomass, and the dynamics of glaciers. Many of these applications exploit properties that are unique to radar systems, and that ensure the place of radar in the range of sensors needed to understand properly the earth as a system. To appreciate what makes radar special in the panoply of remote sensing instruments, we first set out some of these properties. The basic terminology of radar and types of radar are then explained, together with a non-exhaustive survey of the many environmental applications where radar has contributed. The last decade of the twentieth century taught us a lot about the role of radar in environmental remote sensing, and what we have realised is that current sensors are often not ideal for many purposes: understanding and the development of new ways to recover information from radar have leapt ahead of the design cycle of satellite sensors. The last section of this article therefore attempts to look to the future of radar, and the systems likely to be of most importance over the coming years.

2. Basic Properties of Radar Systems

As the name suggests, radar remote sensing systems operate in the radio (microwave) range of frequencies, from about 0.03 to 30 GHz. This is five to six orders of magnitude less than those of the optical bands, and corresponds to wavelengths from about 1 cm to about 10 m. Many consequences flow from this, both for the measurements possible by these systems and their response to the environment. Among these are:

- At these wavelengths, the atmosphere is essentially transparent, so the radar is unaffected by cloud. Except at the shortest wavelengths, it is also unaffected by rain. Hence radar can acquire images of Earth under all weather conditions. In a wider context, the outstanding images of Venus provided by the Pioneer, Venera, and particularly the Magellan radar satellites strikingly illustrate this cloud-penetrating property. The planet Venus is completely cloud covered, and everything we know about its surface comes from these radar images. A dramatic example is given in Figure 1, derived from Magellan data, which shows a remarkable "half crater" caused by the formation of a fault valley across the crater some time after an asteroid impact.

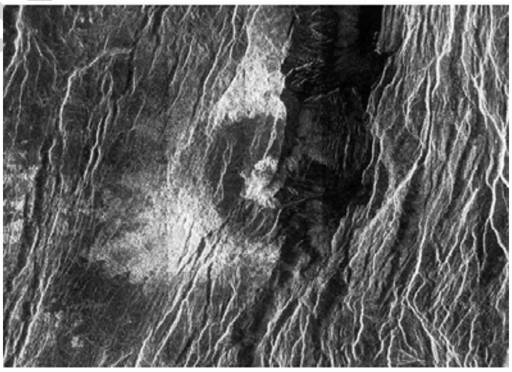

Figure 1. Image of an unnamed crater located in the rift between Rhea and Theia Montes in Beta Regio on the surface of Venus, derived from Magellan data (*Source*: NASA/JPL/Caltech)

- As wavelength increases, the ability of the radar to penetrate vegetation canopies and into the soil also increases, giving the possibility of measuring soil properties through overlying vegetation and observing sub-surface structures.
- Whereas optical sensors respond essentially to rotational and vibrational energy bands of surface materials, radar is sensitive to geometrical structure and dielectric. For many types of land cover, such as vegetation, the water content is a major determinant of the dielectric, and changes in water content have large effects on the properties of the returned signal. For example, the depth to which a radar signal can penetrate into soil is very dependent on the soil moisture. In arid areas, long wavelengths can penetrate many metres; this has been used, for example, to delineate former drainage patterns under what are now sand deserts.
- The technology at these wavelengths allows the phase **(see Section 3. Characteristics of Radar Systems)** of the returned signal to be measured. This has important consequences, because phase carries information about the nature of the interaction with the earth's surface. It is exploited to explore the polarisation properties of the earth in radar polarimetry. In addition, differential phase (between the returns to two antennae or to the same antenna at different times), measured at a given sensor position, allows height measurements to be made. This is the basis of radar interferometry, from which digital elevation models and extremely precise measurements of surface motion can be made.
- Related to the ability to measure phase is the radar's sensitivity to motion, through the Doppler effect. This has both good and bad consequences: it allows inferences to be made about the speeds of moving objects like ships or cars, but it also greatly complicates the imaging of targets like the ocean surface, which are in constant motion.

As well as their huge difference in frequency, radar systems differ from optical sensors by being active—they transmit the energy used to illuminate the earth's surface, typically as short pulses of radiation, then measure the returned signal. This has two major consequences:

- They are not dependent on solar illumination, so can operate just as well by day or by night. Combined with their insensitivity to atmospheric conditions, this makes radars well suited to multi-temporal observations.
- The emitted signal is precisely known, so calibration is relatively straightforward. In addition, because there is normally no need to worry about the intervening atmosphere, the measurements correspond directly to geophysical properties of the surface. This is quite different from the situation at optical wavelengths, where changes in both solar illumination and the atmosphere have big effects on what is measured at the sensor, making conversion to geophysical units difficult.

3. Characteristics of Radar Systems

Before discussing what radar actually measures, it is important to have an idea of the system properties affecting the radar signal. Designers of remote sensing radars must make a variety of choices, depending on the intended application of the sensor (and, of course, the funds available). The most important decisions concern the frequency, polarisation, and incidence angle characteristics of the system, although also very important issues for applications are spatial resolution and time between successive data acquisitions (the revisit time of the sensor). Two important descriptors of an electromagnetic wave are its amplitude and phase. In its simplest terms, the electric field measured at a fixed position for a pure sinusoidal wave has the form $a \cos(2\pi ft + \varphi_o)$, where f is frequency (in Hz) and t is time. The positive quantity a is known as the amplitude of the wave and gives the maximum value of the electric field. The expression $(2\pi ft + \varphi_o)$ is called the phase of the wave, with φ_0 representing a phase reference when $t = 0$.

3.1. Frequency

The choice of frequencies is determined not just by the desired properties of the sensor, but also by the need to accommodate the needs of other users of the radio bands. This restricts the available frequency bands, which, as a hangover from World War II, are often referred to by letters. The frequencies most commonly used by remote sensing radars are given in Table 1, along with the corresponding wavelengths and examples of systems using them. (Note that conversion between frequency and wavelength is easy: frequency in GHz x wavelength in cm = 30.) Some of these systems used several frequencies: for example, the space shuttle SIR-C/X-SAR mission carried instruments operating at X, C, and L bands, while the airborne NASA/JPL system operates at C, L, and P bands. At present, no P band instrument has been flown in space, although this possibility is being actively pursued, because of its importance for measuring vegetation biomass and thus contributing to carbon-cycle studies. Longer wavelengths would be of even greater value for this purpose, as demonstrated by the CARABAS airborne radar operating at VHF frequencies (3–15 m wavelength), but the technical problems of deploying such an instrument in space are too great for this to be considered at present.

Band	**Frequency (GHz)**	**Wavelength (cm)**	**Sensor**
K	15.0	2	ERS altimeter
X	10.0	3	SIR-C/X-SAR
C	5.0	6	ERS, Radarsat SARs
S	3.0	10	Almaz SAR
L	1.2	24	Seasat, JERS SAR
P	0.5	68	AirSAR

Table 1. Radar frequency bands commonly used for remote sensing, and examples of systems employing them

3.2. Polarisation

Most remote sensing radars transmit linearly polarised signals. These are described as vertically (V) polarised if the electric field of the wave lies in the plane defined by the propagation direction and the direction of a line pointing outwards from the earth's centre (a radius vector), and as horizontally (H) polarised if the electric field is perpendicular to this plane. The return signal typically contains both vertically and horizontally polarised components, which can be measured separately by an appropriately designed system. The measured signals are then described as the VV, VH, HV, or HH channels, where VH, for example, denotes V transmit, H receive. Some systems use interleaved transmissions at H and V polarisations, allowing them to measure all four channels. An important system characteristic is whether the phase differences between the channels are preserved. If all four channels are measured with their correct phase differences, the system is described as fully polarimetric (or partially polarimetric if a single polarisation is transmitted but two are measured; for example, only V may be transmitted but VV and VH may be measured). If the phase differences are lost, the sensor is multi-polarised. Fully polarimetric sensors give a complete description of the scattering properties of the surface at the probing frequency. An important property of such data is that it allows reconstruction of the signal that would be measured for any choice of transmitted and received polarisation configurations, through a process known as polarisation synthesis.

Examples of the polarisations and frequencies used by a variety of systems are given in Table 2. Note that the Envisat ASAR (launched in early 2002) will not preserve phase differences, so will not be polarimetric, whereas the Canadian Radarsat-2 (to be launched in late 2005) and Japanese PALSAR (to be launched in late 2004) will both have polarimetric modes.

Sensor	Frequency band	Polarisation	Incidence angle
ERS SAR	C	VV	23^o
ERS scatterometer	C	VV	18^o to 59^o
Radarsat	C	HH	Selectable: 20^o to 50^o
JERS	L	HH	35^o
SIR-C	C, L	Fully polarimetric	15^o to 55^o
AirSAR	C, L, P	Fully polarimetric	Approx. 20^o to 60^o
Envisat ASAR	C	HH & HV, VV & VH, or HH & VV	Selectable: 14^o to 45^o

Table 2. Frequencies, polarisations, and approximate incidence angles for selected sensors

3.3. Incidence Angle

Incidence angle is the angle between the propagation vector of the radar wave and the radius vector at the earth's surface. For satellite SAR, the range of incidence angles within a swath is normally only a few degrees, although Radarsat and Envisat have selectable swaths, allowing a large range of angles to be covered. For airborne sensors, the incidence angle normally varies considerably across the swath. This is important because it can significantly affect the nature of the dominant scattering processes, and hence the properties of the response. Table 2 gives the approximate incidence angles associated with a variety of sensors.

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Bibliography

Elachi C. (1987). *Spaceborne Radar Remote Sensing: Applications and Techniques*, 254 pp. New York: IEEE Press. [A readable account of the principles behind the main spaceborne radar instruments and their use in geophysical applications.]

Henderson F.M. and Lewis A.J., eds. (1998). *Principles & Applications of Imaging Radar* (Vol. 2 of *The Manual of Remote Sensing*), 3rd ed., 866 pp. New York: John Wiley. [This source book covers most of the main areas to which SAR has been applied. Several of the chapters are valuable both as overviews of basic concepts and reviews of the literature, although other chapters are less useful, and several are not up to date.]

Kingsley S.P. and Quegan S. (1992). *Understanding Radar Systems*, 375 pp. London: McGraw-Hill. [A beginner's guide to radar, including elementary descriptions of radar remote sensing systems.]

Oliver C.J and Quegan S. (1998). *Understanding Synthetic Aperture Radar Images*, 479 pp. Boston: Artech House. [A comprehensive description of the properties of SAR images and methods of data handling to recover information from them.]

Schreier G., ed. (1993). *SAR Geocoding: Data and Systems*, 435 pp. Karlsruhe, Germany: Wichmann Verlag. [This collection of 18 papers covers many aspects of SAR images, in addition to their geometric properties and the operations necessary to correct them geometrically.]

Ulaby F.T., Moore R.K., and Fung A.K. (1981, 1986). *Microwave Remote Sensing: Active and Passive*, 3 vols., 2160 pp. Norwood, Mass.: Artech House. [This is an outstanding text. Despite its age, it is the basic reference on scatterometry and SAR, dealing with systems, physics, and applications, as well as giving a good account of the historical development of the field.]

Ulaby F.T. and Elachi C., eds. (1990). *Radar Polarimetry for Geoscience Applications*, 364 pp. Norwood, Mass.: Artech House. [A wide-ranging survey of polarimetric systems, polarimetric scattering theories, and applications of polarimetry.]

Biographical Sketch

Shaun Quegan received the B.A. (Hons. First Class, 1970) in mathematics and M.Sc. (1972) in theoretical statistics from the University of Warwick. He taught for a number of years, before undertaking a Ph.D. concerned with atmospheric modelling, which was awarded by the University of Sheffield in 1982. Between 1982 and 1986 he worked as a research scientist at Marconi Research Centre, for the last two years of which he led the Remote Sensing Applications Group. He established the SAR Research Group at the University of Sheffield in 1986, whose success led to his professorship, awarded in 1993. In the same year, he helped to inaugurate the Sheffield Centre for Earth Observation Science, of which he remains the director. In 2001, he became director of a new National Environmental Research Council Earth Observation Centre of Excellence in Terrestrial Carbon Dynamics, whose purpose is to give better understanding and greater quantitative estimation of the role of terrestrial ecosytems in the earth's carbon cycle. He has great expertise in the physics, systems, and data analysis aspects of radar remote sensing, but his current interests lie more in the exploitation of radar and other remote sensing technologies in environmental science and land applications.