CURRENT APPLICATIONS OF IMAGING RADAR

M.R. Inggs and R.T. Lord

Dept. Electrical Engineering, University of Cape Town, Rondebosch, 7701, South Africa
mikings@ebe.uct.ac.za

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ABSTRACT:

This paper discusses the current status of imaging radar systems deployed on spacecraft and airborne platforms, such as aircraft and unmanned airborne vehicles (UAVs). Imaging radar technology has advanced considerably over the last twenty years, and the user can now be fairly certain of finding a sensor ideal for a specific application. The objective of the paper is to demonstrate some of the available systems and current applications, and to indicate what will be available in the near future. A short overview of subsurface radar is also given, since this is another type of imaging radar. The paper is aimed at the remote sensing specialist with or without extensive radar expertise.

1 INTRODUCTION

In this review paper we show that imaging radar is used in a wide range of applications in an almost routine way. We start by defining radar, based on the waveform utilised. The treatment is limited in detail, but references to more complete texts are given. The paper then reviews well established radar applications, followed by a description of the important platforms used for deploying imaging radar. Since the paper intends to be introductory, we have covered radar technology and the platforms used to deploy imaging radar first.

Due to the space limitations, it is not possible to show a large number of images, which would, in many cases, make the applications much clearer. We have included a brief look at subsurface radar, since it provides two- and three-dimensional information about the subsurface. We will examine applications such as underground utility detection, landmine detection and borehole radar used in mining.

Since the paper is aimed at current technology, the systems mentioned are restricted to those currently operational, with some indications of imminent systems. The list of sensors is not exhaustive, since the objective is to show the range of applications.

2 RADAR TECHNOLOGY

In this section we will look at the basic operation of radar sensors and the necessary signal processing. The principle is that an active unit illuminates the scene of interest and the backscattered energy is processed to extract information about the scene. A good overview of radar technology in general is given by Kingsley and Quegan (1999), and a more specific text concerning imaging radar is due to Curlander and McDonough (1991).

2.1 Pulsed Radar

These are well-known to most scientists, i.e. a burst of energy (pulse) at a carrier frequency is coupled to an antenna for radiation. The antenna is usually directive, and ensures that the radiated (and received) energy is distributed optimally for the application. The backscatter depends on the properties of the objects scattering energy, and the propagation medium. The location of the scatterers has to be inferred from the time delay of the echo and the narrowness of the radar antenna beamwidth. The resolution in range depends on the bandwidth of the transmitted pulse (Kingsley and Quegan, 1999).

2.2 Pulsed Coherent Radar

The same principles are applied as for conventional pulsed radar, but the radar is able to determine the distance to the scatterers modulo the carrier wavelength, since the transmitter and receiver maintain carrier coherence. However, the spatial resolution is determined by the time of flight, the bandwidth of the radiated energy and the directive properties of the antenna. For coherent radar, the echoes from repeated transmissions can be overlaid, thereby improving the signal to thermal noise ratio.

Some radars (especially those used in ground penetrating applications) transmit a short pulse to a band-limited antenna structure. Since only a band of frequencies is thus transmitted, the waveform is similar to a pulsed coherent radar. However, to maintain coherency, the sampling and display of the received signal must be carefully controlled, since it depends on sampling each point in time at exactly the same, relative time, for each pulse.

2.3 CW and SFCW Radar

Continuous Wave (CW) radar is only able to measure range modulo the wavelength (metres to cm), but by stepping (SFCW) the waveform over a range of frequencies (bandwidth), range can be determined (see (Wehner, 1995)). However, the receiver is potentially desensitised by the close proximity of the transmitter to the receiver. With the extra signal processing, the resolution capability is similar to that of a pulsed coherent radar.

2.4 Image Formation

Early imaging radars were essentially side-looking, narrow beam systems, that relied on the time domain to provide resolution in range away from the platform, and the beamwidth to discriminate in the along track direction. However, it is clear that since the beam diverges, the along track resolution degrades with range. These are known as real aperture radars.

In the next section, we see that matched filter processing is able to provide improved resolution, independent of range. This is usually ascribed to Synthetic Aperture Radar (SAR).

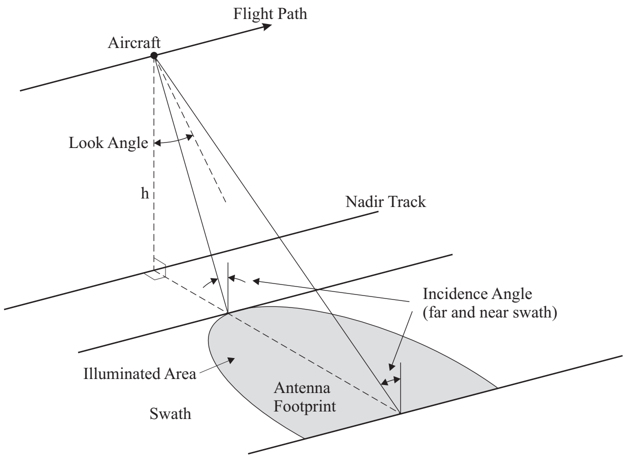

Figure 1: Synthetic Aperture Radar imaging geometry.

2.4.1 Geometry The geometry of an airborne SAR system is shown in Figure 1. The innovation is that the sensor is allowed to view the image space from a number of aspect angles. This is actually tomography (Munson et al., 1983). Modern radars use high-speed recording equipment to store the received energy, and feed it to a recording or real-time processing system. The signal processing system, based on extremely accurate knowledge of the radar trajectory, is able to apply a phase rotation unique to each pixel in image space to the ensemble of data. The returns from the target pixels add constructively, thereby producing an image. The resolution of the image is dependent on the bandwidth of the sensor and the range of angles over which the scene is viewed.

2.4.2 Signal Processing The ability to image is entirely dependent on the imaging geometry and the radar bandwith. A number of processing algorithms have evolved over time that take advantage of simplifications in the geometry that may be applicable to a particular system. The most common is the Range-Doppler algorithm. This is applicable to short wavelengths with respect to the range extent and close to straight line flight paths. The geometry is shown in Figure 1. and is appealing in that the radar can be thought of as forming a synthetic aperture in the sky. The range resolution is due to the radar bandwidth, and the azimuth resolution is ascribed to the artificial array antenna formed by the platform motion. The further away the image pixel is, the longer the synthetic aperture required to achieve the required along-track resolution.

2.5 Interferometry

Interferometry exploits the fact that the radar signal phase (distance to target modulo the wavelength) is available in the recorded pixels, often known as a complex image. If images are made from two antennas passing over the scene at different vertical and and/or horizontal displacement, then, after careful co-registration, the phase difference image can be formed. Depending on the radar line of sight to the image, it is possible to resolve the movement of the scatterers into lateral and vertical changes, measured in wavelengths. The most common application of this is to produce height maps, since the phase change can be ascribed to the vertical height change. Due to the ambiguity in phase (modulo the wavelength), phase unwrapping must be carried out to produce the digital elevation model.

The processing of interferometric data, however, relies on all the scatterers within each resolution cell being displaced as if frozen together. This is measured by calculating the coherence, i.e. the complex pixels in a window are summed and normalised, and if the resulting number is high, the coherence is sufficient. Coherence is destroyed by changes made during the imaging process, or if the images are separated by a significant amount of time, for example due to different orbits or different passes of an aircraft. Vegetation changes are often responsible for this loss of coherence. If the platform is equipped with two antennas gathering data simultaneously, the decorrelation is largely avoided.

2.5.1 Moving Target Indication If the interferometric images are produced from antennas along the track of the flight, then ground and target motion can be observed. This has applications in traffic monitoring, and observations of the magnitude and spatial distribution of ocean currents.

2.5.2 Differential Interferometry If the terrain height is known (say, from another interferometric pair), then a third co-registered image will show changes in the terrain height, to sub-wavelength resolution. This has been exploited successfully to image crustal changes pre and post earthquake activity (Zebker et al., 1971) the inflation and deflation of volcano cones, ground subsidence due to mining (oil, gas) and water extraction.

A recent method (Colesanti et al., 2000) exploits the fact that even in vegetated areas, certain reflectors remain consistent amongst the changing vegetation returns. These “permanent” reflectors are identified by careful, statistical examination of a number of pixels in a large number of images (20 to more than 100) of the same scene. Once identified, the phase of these pixels then indicates the surface motion. However, these point readings must be interpolated to indicate surface behaviour, and there is no guarantee that the surface will be sufficiently sampled to reveal small-scale motion.

It was also noted during the production of these permanent scatterer images that area deformations were present, and these were found to be due to water vapour changes over the image. This distribution thus was a good measure of the water vapour distribution. This effect is also noticeable in normal interferograms.

It is thus very clear that interferometry is routinely applied to geophysical surface movement applications, as well as the extraction of water vapour distribution. The lack of coherence between images is also a very sensitive indicator that surface change has occurred due to land use changes and vegetation changes.

2.6 Polarimetry

The signal radiated by the imaging radar sensor can be arranged so that the electrical field has a known orientation with respect to the local surface. Usually this is arranged to be horizontal or vertical to the local surface, i.e. horizontal or vertical polarisation. The scatterers on the surface, if they have curvature of the same order as the radar wavelength, will couple energy to varying extents from one polarisation to the other, and will also shift the phase of the returned signals differently for the co-polar and cross polar signals. The relative magnitudes of these shifts are very good indicators of the surface structure.

The sensor is then thought to be able to return three images, i.e. co-polarised (HH or VV) or cross-polarised (VH or HV). The H and V refer to the order transmit and receive, and the plane of polarisation used (vertical or horizontal). It turns out that the HV and VH components are symmetrical, and only one has to be measured.

The calibration of these sensors is complicated, and beyond the scope of this paper (Ulaby and Elachi, 1991). More correctly, the Stokes parameters of the image pixels are returned from a properly calibrated sensor. These polarisation matrix images are extremely powerful indicators of surface properties, right down to dielectric properties. At a simple level, heavily vegetated surfaces produce equal HH and VV returns, whereas urban areas, with numerous dihedral and trihedral reflectors formed by buildings, have a distinctive signature.

In summary, a properly calibrated, polarimetric image is a very powerful means for surface classification, such as heavily vegetated, flooded, crop type, and so on. An example of how polarisation can enhance different features in an agricultural scene is shown in Figure 2.

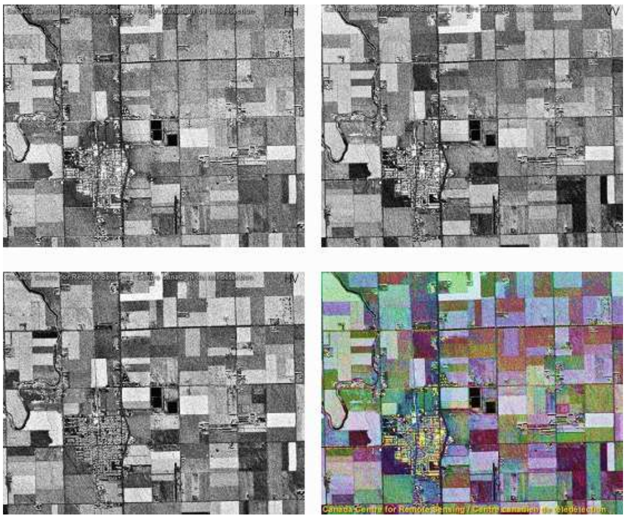

Figure 2: Illustration of how different polarisations (HH, VV, HV and colour composite) bring out different features in an agricultural scene (from http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter3/chapter3_8_e.html)

3 PLATFORMS

The most important difference between an imaging radar sensor deployed on an aircraft versus a spacecraft is summarised in Figure 3. The airborne sensor cannot achieve the wide swath coverage of the satellite, and its far range imagery is at a low grazing angle, with consequent problems with shadowing by terrain. In the following sections we discuss further differences.

3.1 Airborne Systems

In this section we examine the general considerations around an airborne imaging sensor, followed by a brief review of current systems. This list is not complete, since there are a large number of systems currently available, and we have only selected some as examples.

3.1.1 Airborne Platform Considerations An aircraft can be deployed at will, given favourable weather conditions for take-off and landing. This is ideal for local operation, i.e. in-country or close by. Depending on the size of aircraft, the endurance can vary enormously, i.e. from just a few hours for an Unmanned Airborne Vehicle (UAV) through to many hours for a large jet aircraft. Modern UAVs are beginning to achieve the performance of larger aircraft in terms of survey speed and endurance, however.

The viewing geometry is somewhat constrained, i.e. the operational altitude of air breathing engines limits operations to below

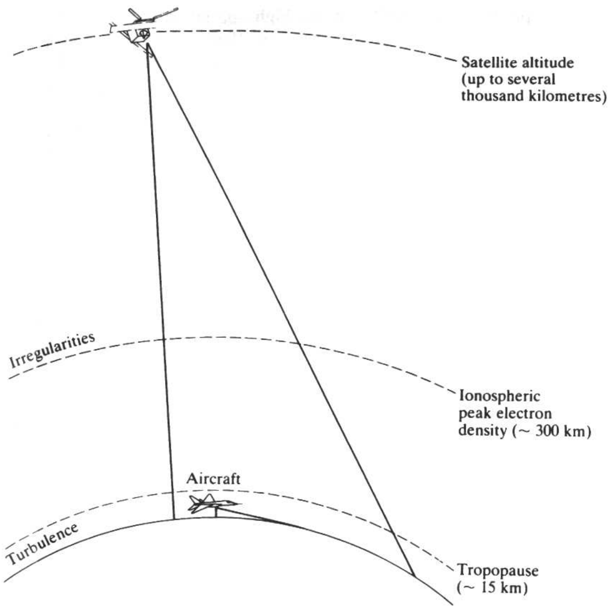

Figure 3: Typical airborne versus satellite imaging radar viewing geometry (figure taken from (Kingsley and Quegan, 1999)).

20km. As shown in Figure 3, the swath width is limited, and the far-range incidence angle is large, leading to problems due to shadowing by high relief.

Coverage rate is limited to aircraft speed, but this is usually not a constraint for real-time viewing of small areas. Wide area survey can, however, be time consuming.

3.1.2 Examples of Current Airborne Systems There are a large number of these systems available, varying between private and government ownership. Due to space constraints, we have not attempted to list all of these and their characteristics, but have lifted out two, at opposite ends of the ownership spectrum i.e. the JPL AirSAR and the system operated by Orbisat of Brazil. We have also indicated a typical, compact system that could probably be deployed on a large UAV, i.e. the Lynx system.

3.1.3 AirSAR AirSAR is operated by the Jet Propulsion Laboratory (JPL), and a great deal of information about this system can be gleaned from the web site `http://airsar.jpl.nasa.gov/`. The sensor suite is flown on the NASA DC 8 aircraft, capable of long endurance flights at high speed and at high altitudes. Imaging sensors at 23cm, 6cm and 3cm are carried. The antennas are configured to allow for both across track and along-track interferometry. The operational costs of this system are high, and many missions have been carried out as multi-government sponsored endeavours.

3.1.4 OrbiSAR-1 OrbiSAR-1 is the SAR system of OrbiSat Remote Sensing, Brazil. It operates simultaneously at X-Band (HH polarisation) and P-Band (fully polarimetric). It obtains high geometric resolutions: 0.5m for X-band and 2.5m for P-band. The height accuracy of the DEMs is up to 10cm (1-σ).

OrbiSat offers a complete SAR package consisting of the InSAR system, the flight management and planning system, the navigation system, the GPS ground station, the real-time DGPS link, the transcription system and the offline data processor which includes SAR processing, interferometry and geocoding and mosaicking.

Figure 4 shows an example of an orthorectified SAR image map of Monteiro, Brazil, produced by OrbiSat Remote Sensing.

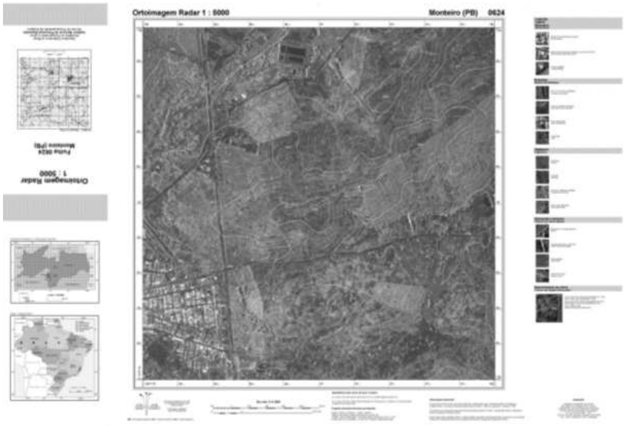

Figure 4: SAR orthorectified image map of Monteiro, Brazil, 1:5 000.

3.1.5 Lynx Lynx is a high-resolution SAR that may be operated on a wide variety of manned and unmanned platforms, but is primarily intended to be fitted on UAVs [tsunoda:1999]. It has been designed and built by Sandia National Laboratories in collaboration with General Atomics (GA). It operates at Ku-Band and is capable of 0.1m resolution in spotlight mode and 0.3m resolution in stripmap mode.

The Lynx SAR has four primary operating modes:

1. SAR geo-referenced stripmap mode;
2. SAR transit stripmap mode;
3. SAR spotlight mode;
4. Ground moving target indication (GMTI).

It also has a coherent change detection mode, where it makes registered, complex image comparisons, which can indicate minute changes in two SAR images taken at different times.

3.2 Satellite Systems

In this section we investigate the general considerations around satellite imaging radar operation, followed by a look at current systems, and some systems close to launch.

3.2.1 Satellite Platform Considerations Figure 3 shows that satellite systems are able to cover a large swath width, and this is at very high speed (about 7km/s) for typical orbits. The low incidence angle does not change much across the swath, and the shadowing problem is not so severe. However, foreshortening gives a distorted image in high relief terrain. This is where the top and bottom of a mountain lie at the same time delay from the radar, and the overlap makes the mountain appear to lean towards the radar sensor.

Orbital mechanics dominate the revisit time of a satellite. Often a close to polar orbit is utilised, at an altitude of 400km to 800km. This gives an orbital period of about 100 minutes. If global coverage is required, then the orbit is set up to allow each ground track to precess. The precession rate can be adjusted to allow the same point to be revisited at fixed intervals. Typically this is about 35 days, but can be adjusted to be just a few days. The coverage pattern becomes a difficult trade-off with the revisit time. A further complication shows that due to orbital tracks converging at the poles, the coverage at mid latitudes can have large gaps. There is no reason, of course, to use only polar orbits. For example, for mid to equatorial latitudes, an equitorial orbit might make more sense (similar to the Space Shuttle). The launch costs are, of course, higher for this configuration.

Figure 5: Image of Envisat ASAR deployed.

Some radars deploy electronically steered antennas in the direction orthogonal to the satellite motion. This allows the beam to be widened, at the expense of spreading the transmitter energy over the wider resulting swath.

A satellite platform and space qualified sensor are orders of magnitude more expensive than the equivalent airborne system. In addition, a sophisticated ground infrastructure has to be maintained to monitor the satellite station keeping. Inevitably, the satellite will have to be de-orbited before the station-keeping fuel is exhausted, and the expense of another satellite and sensor are incurred.

3.3 Examples of Current Satellite Systems

3.3.1 Envisat ASAR The Advanced SAR (ASAR) deployed on the Envisat satellite is an advanced version of the radar deployed on the previous missions, ERS1 and ERS2. It is also a 6cm system, but is able to produce VV, HH and HV, and VV and VH images, although not simultaneously from each pulse. More information on this sensor and its data distribution network is given in the ESA web page, `http://earth.esa.int/services/esa_doc/doc_env.html`.

Figure 5 shows an image of the Envisat ASAR system deployed.

3.3.2 RadarSat 1 The satellite was launched in November 1995. It carries an advanced C-band (5.6 cm), HH-polarized SAR with a steerable radar beam allowing various imaging options over a 500 km range. Swaths can be varied from 35 to 500 km in width, with resolutions from 10 to 100 metres. Incidence angles range from less than 20° to more than 50°. Even at Equatorial latitudes, complete coverage can be obtained within six days using the widest swath of 500 km, and low resolution.

3.4 Satellite Systems due for Launch

3.4.1 Alos The satellite is due for launch in 2006. Further information is available from `http://www.eorc.jaxa.jp/ALOS/cd_alos/eng/alos2.htm`

The radar sensor is PALSAR, which is an active microwave sensor for cloud-free and day-and-night land observation and provides higher performance than the JERS-1's SAR. This sensor

Table 1: ALOS PALSAR specification

Observation mode	High Resolution	Scan SAR
Frequency	L-BAND (23cm)	
Polarization	HH,VV,HH&HV,VV&VH	HH,VV
Spatial Resolution	10m	100m
Number of Looks	2	8
Swath Width	70km	50-350km
Off-nadir Angle	10-51deg.	
NE σ^0	Approx.-23dB	

has a beam steerable in elevation and a scan SAR mode, which allows the radar to obtain a wider swath than conventional SARs (see Table 1).

3.4.2 TerraSAR-X TerraSAR-X is a new German radar satellite that shall be launched in April 2006, with a scheduled lifetime of 5 years. Further information is available from `http://www.eid.dlr.de/tsx/start_en.htm` The mission's objectives are the provision of high-quality, multi-mode X-band SAR-data for scientific research and applications as well as the establishment of a commercial EO-market and to develop a sustainable EO-service business, based on TerraSAR-X derived information products. Along with Radarsat, we now see an emerging commercialisation of spaceborne imaging radar. The mission is realized in a Public Private Partnership (PPP) between the German Ministry of Education and Science (BMBF), the German Aerospace Center (DLR) and the Astrium GmbH.

The satellite design is based on technology and knowledge achieved from the successful Synthetic Aperture Radar missions X-SAR/SIR-C and SRTM. The X-Band sensor operates in different modes:

- the "Spotlight" mode with 10 x 10 km scenes at a resolution of 1–2 meters,
- the "Stripmap"mode with 30 km wide strips at a resolution between 3–6 meters,
- the "ScanSAR" mode with 100 km wide strips at a resolution of 16 meters.

Additionally TerraSAR-X supports the reception of interferometric radar data for the generation of digital elevation models.

The orbit parameters include an eccentricity of 0.001, inclination about 97°, and semi major axis is about 6883 km.

Figure 6 shows an image of the TerraSAR-X satellite.

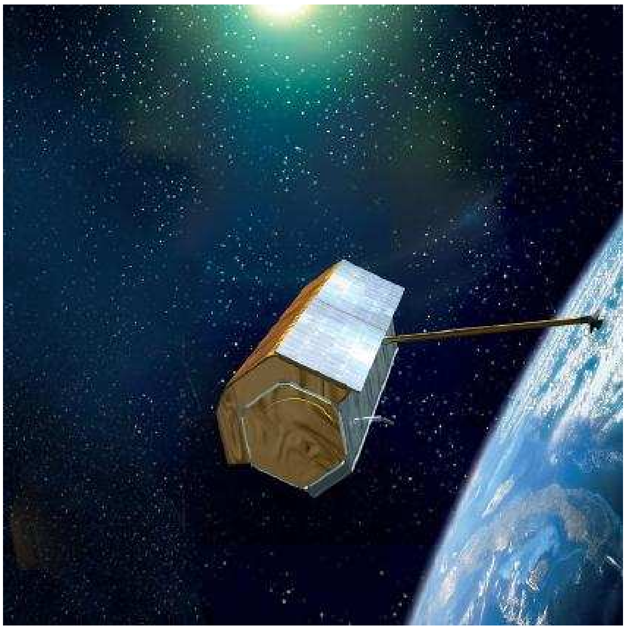

Figure 6: TerraSAR-X satellite.

3.4.3 RadarSat 2 Co-funded by Canadian Space Agency (CSA) and MacDonald Dettwiler (MDA), it is intended to be an example of a sophisticated, commercial operation. The company provides a complete range of data and value added products, at a price.

The system is to provide data continuity from RADARSAT-1. All RADARSAT-1 imaging modes supported, plus many additional capabilities. It is due for launch in early 2006, with a mission duration of 7 years.

The RADARSAT-2 orbit characteristics are the same as RADARSAT-1 i.e. 798 km altitude, sun-synchronous orbit, 6 PM ascending node and 6 AM descending node. The same repeat cycle and ground track as RADARSAT-1. RADARSAT-1 and -2 scenes will be precisely aligned. The image location knowledge is ¡ 300 metres at downlink (c.f. RS1 1.4 km) and $<$ 100 metres post-processed.

RADARSAT-2 innovations and improvements are a 3-metre Ultra-Fine resolution with routine left-looking and right-looking mode. Fully-polarimetric imaging modes are possible (HH,HV,VH,VV)

The downlink is designed to operate with a 3-metre minimum size antenna, which implies a lower "cost of entry" for new ground stations.

3.5 Archived Data

A number of imaging radars have been deployed over the years, and although this paper reflects current applications, it must be stressed that the archive of data available from these systems is a very important resource for current applications, e.g. change detection. We mention some of the important systems below.

Seasat was the satellite system that provided a large impetus for further developments. It was launched in 1978 and operated for just over 3 months before failing. American spaceborne systems have, since then, focussed on the Space Shuttle, i.e. the Shuttle Imaging Radar (SIR) missions A, B and C. The SIR-C mission data is an extremely valuable resource, since the sensor was fully polarimetric in L- and C-Band (23cm and 6cm). It also carried the German/Italian X-Band radar. The SIR series culminated in the Shuttle Radar Topographic Mission (SRTM), where the SIR-C hardware was modified to form an interferometer at C- and X-Band. The land mass between 60 degrees latitude was imaged, and an important new, high resolution digital elevation model (DEM) was produced. Data is available from the DLR (X-Band) and from the US Government. The former contains large gaps in coverage due to the narrow swath, and the latter is somewhat tied up in US Government regulations of the high resolution data. The GTOPO30 data set is now available as SRTM30, with the orginal data corrected with the SRTM30 data. In addition, the 90m$\times$90m DEMs are available on DVD sets `http://edcsns17.cr.usgs.gov/srtm/index.html`.

Table 3.5 shows a summary of the systems where archives exist. This table is a mixture of mostly satellite and some airborne systems. The airborne datasets are more difficult, since many of these systems had a limited lifetime.

Table 2: Archives of Imaging Radar Data

System	Wavelength	Organisation
SIRC	23cm, 6cm, 3cm	NASA/DLR/ISA
SIRA/B	23cm	NASA
SRTM	6cm, 3cm	NASA, DLR, ISA
ERS1/2	6cm	ESA
JERS1	23cm	NASDA
SeaSat	23cm	NASA
Almaz	10cm	Russia

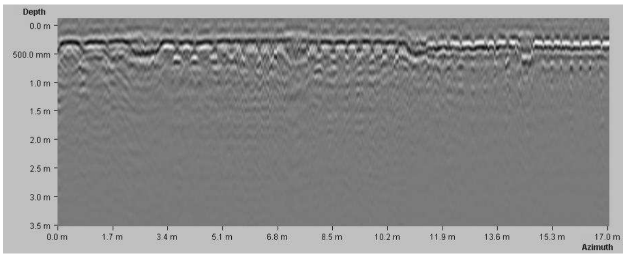

Figure 7: Re-inforcing rods in floor of building.

4 SUBSURFACE RADAR

In this section, we look at a number of routine applications of subsurface radar. Ground penetrating radar (GPR) (also known as surface penetrating radar (Daniels, 1990)) services are available commercially, and equipment is in routine production. Most systems utilise pulsed transmitters, but a number of SFCW systems are available (Farquharson et al., 1998). These modulations have been described in Section 2.

4.1 Surface Search Systems

There are essentially two types of radar, namely surface search systems and borehole systems. The surface search system (for example see `http://www.sensorsandsoftware.com/`) usually has an antenna that is dragged in contact with the ground surface. The antenna is screened from behind to prevent spurious responses from targets above the radar. As the antenna moves, the echoes are recorded as a depth-traverse plot, providing a two-dimensional view of the subsurface.

Some thought shows that due to the broad beam of the antenna, point targets show up as hyperbolic trajectories. This clearly overlaps with the image processing methods described above (Section 2.4), and synthetic aperture and tomographic signal processing is routinely applied to focus the image in the along-trajectory direction. An example of an unprocessed image of the re-inforcing rods in the floor of a building is shown in Figure 7. The radar utilised was a SFCW system, operating over the 200–800MHz band.

4.2 Borehole Radar

Mining operations have relied on borehole core information for inferring subterranean geological structure. Geophysicists soon realised that the borehole, which only provided limited sampling, could also be used to deploy a radar that could sample a volume around the hole. Practically, the antenna used has to lie along the length of the borehole, meaning that no azimuthal direction information was possible, since the radiation pattern is omnidirectional in the plane at right angles to the borehole direction. It is possible, however, to apply along-track image processing to focus the image, as described above.

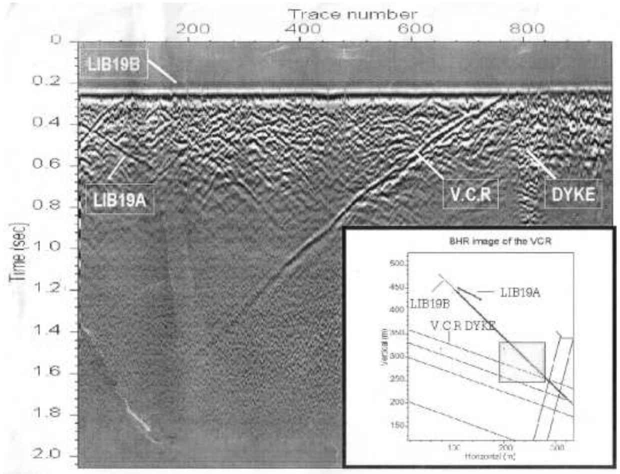

Figure 8: Pulsed borehole radar in hard rock.

Borehole radar is currently being deployed in exploration geophysical applications, but the ultimate goal is to investigate the use for operational applications, such as stope monitoring, and probing ahead of mining operations, using the cover holes drilled as protection against water. An example (Trickett et al., 2000) of the success of borehole radar in hard rock exploration is shown in Figure 8. The radar has detected a lava layer some 80m from the inclined borehole.

5 APPLICATIONS

In some sense, many of the applications of imaging radar have probably become clear during the description of the sensors and the platforms that carry them. This section will detail some of the more important applications. We have restricted ourselves to earth remote sensing. The split in applications is somewhat arbitrary, but we have chosen to classify them into classical land and sea applications, and then to lift out real-time monitoring applications. Geophysical applications using subsurface radar are discussed separately.

5.1 Aspects of Propagation

It is important to have at least a heuristic knowledge of the interaction of electromagnetic waves with dielectric objects to be able to exploit the power of imaging radar, and its differences to optical imagery. A full exposition is beyond the scope of this paper, but some important features can be mentioned.

Firstly, the radar wavelengths utilised are often similar is scale size to the objects being imaged. This means that the reflections are thus fairly diffuse. Usually, a large number of objects are contained within the resolution area of the sensor, and this means that the return is the vector sum of a large number of normally distributed reflectors. When the magnitude is taken, this results in something like a Rayleigh distribution (more generally, an asymmetric distribution), which characteristic speckle of of cohernet illumination.

The stronger coupling to scale size means that there is often a good descrimination between objects of different size, for example, fields of different shaped crop plants.

Polarisation also comes into the backscatter mechanism. Vertical polarisation will couple more strongly with vertically oriented, stalk-like objects. This means crops such as rice just emerging from water will reflect differently to a field of cabbages when illuminated with vertical polarisation.

Radar provides its own illumination, meaning that imaging is possible by day and night. In addition, the wavelengths between 68cm and 3cm are not affected strongly by cloud or rain. This has advantages in cloudy areas, such as the tropics and higher lattitudes.

5.2 Land Remote Sensing Applications

As a rule of thumb, a radar penetrates successfully into the subsurface by about a wavelength. This means that most microwave radar systems are only suitable to detect the dielectric change in reflection due to surface water. This has been successfully demonstrated by a number of workers (Rao et al., 1993).

Care must be exercised with soil moisture measurements at shorter wavelengths, since the returns from vegetation changes will mask the ground return. This is especially true for 6cm and shorter wavelengths. However, it is still possible to classify geological parameters (Zyl et al., 1988). The effects of vegetation are problematic, meaning that longer wavelengths are more suitable.

Crop monitoring has become almost routine. Optical images are very successful at monitoring mature crops, due to the abundance of chlorophyl and characteristic absorption and reflection signatures. When the crop is in its early growth phases, there is not enough plant material to raise an optical signature. It has been found that microwave images are very successful in picking up the plant shoots. Applications involving rice crops have been followed by similar work with maize.

As mentioned above, interferometric SAR is able to detect millimetric changes due to crustal movement, especially if the Permanent Scatterer method is used on a large time sequence of images. This has lead to a number of applications, e.g. the inflation of a volcano indicating imminent eruption, land subsidence due to mining and dewatering, indications of the fracture lines and residual stress in rocks around the time of earthquakes, and many others.

Tsunami potential assessment seems to be a topical application, i.e. the production of detailed, high resolution DEMs of coastal zones, to see which areas are likely to be susceptible to being overwhelmed during a tsunami. Allied to this, of course, is the use of similar measurements along river valleys to demark areas likely to be flooded. These height resolution DEMs will have to be produced by airborne sensors.

5.3 Maritime Remote Sensing Applications

The pioneering SeaSat mission in 1978 confirmed that imaging radar is very successful at monitoring the surface sea state, which is influenced by surface wind speed and direction. Wave sets are set up by the ocean winds. The ERS1/2 sensors produce a wave product that indicates the height and direction of waves. This can be useful for navigation and storm warnings for neighbouring coastlines. This analysis is most successful away from the influence of land and shallow water, i.e. the deep ocean.

Surface films alter the viscosity of the sea surface, almost preventing the generation of capillary waves. These areas are thus abnormally flat, and little energy is reflected to the radar. Oil and other surface films are thus shown very clearly in images of the sea. However, calm water due to shadowing of the sea by coastal mountains can give a false signature.

Bathymetry can often be detected due to internal waves set up within the ocean by currents streaming over the ocean bottom, leading to a modulation of reflective properties. This has been exploited to obtain bathymetric information.

5.4 Geophysics

Geophysical applications will be discussed in the next section (volcano monitoring, earthquake prediction and analysis). In addition, in the sections above discussing interferometry, it is seen that minute surface subsidence due to mining and pumping of oil and water can be observed.

5.5 Real-Time Applications

These applications are mostly related to disaster management, where the timeliness of the data is important. The first successes were the observation of flooding extent. The inundated areas around rivers appear very smooth to the radar, and little backscatter results. An image taken before a flood and overlaid with one after the flood gives a very clear indication of the extent of the flooding. The real-time images can be taken through cloud and during day or night, thus being more useful than optical images. After the flood, the destruction of infrastructure and river bank vegetation (such as crops) can also be clearly seen.

Earthquake prediction is currently under investigation. As the magma chamber of a volcano fills before eruption, the flanks of the volcano are observed to swell.

Pollution monitoring has been mentioned above, and is also being turned into an operational capability, i.e. trying to police ships and oilrigs discharging illegally into the ocean and estuaries.

6 CONCLUSIONS

The paper has provided an overview of current imaging radar technology and its applications. These applications cover a wide range from long term studies, through to real-time applications associated with disaster management. The platform used to deploy the sensor is seen as important, as there are large differences between the geometry of the coverage achieved and its repetition rate. Airborne sensors provide the most time-flexible coverage and are suited to many real-time applications. Satellite systems provide more rapid coverage of large areas, but are restricted in terms of real-time coverage.

Subsurface radar has emerged as a viable technology for geophysical survey, as well as for real-time survey of existing urban, underground infrastructure. Due to the unfavourable propagation conditions on the surface, very short ranges (metres) are achieved. Operation in boreholes in unaltered rock allows for an order of magnitude improvement in range.

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