Remote Topographic Mapping with Airborne Interferometric SAR

A.Currie*, T.Bungey**

* R102 DERA (Malvern)
St. Andrews Rod
Great Malvern
Worcs.
WR14 3PS
Tel. (01684) 896162
FAX. (01684) 894481
Email tony@sar.dra.hmg.gb

** N.A.S.
Roscoe house
62 Roscoe St.
Liverpool
LI 9DW

ABSTRACT

There is increasing interest in the utilisation of height-finding interferometric synthetic aperture radar (HFISAR) for civil mapping and large area change detection applications. The technique has been demonstrated from spaceborne platforms using combinations of data collected from multiple imaging passes, and from airborne platforms which generically operate in a 'single pass' mode by deploying two physically distinct antennas. In the case of airborne operation there is a particular need to perform highly accurate motion compensation to the data in order to reduce height reconstruction errors to acceptable levels. The criticality of this is particularly evident in the case of multiple-pass airborne HFISAR. The present paper will summarise work which has been carried out at DERA (Malvern) U.K. on airborne HFISAR with a view to indicating the possible utility of this technique for civil mapping applications. Theoretical performance will be compared with the results of actual trials using the experimental DERA C-Band single-pass system and a summary of expected performance will be given for the DERA Enhanced Surveillance Radar (ESR) airborne system which is due to become operational in the next few months.

1. INTRODUCTION.

The coupling of a high resolution radar instrument together with a height-finding capability offers the opportunity to gather a vast amount of detailed information on imaged terrain characteristics and individual features therein. An airborne Synthetic Aperture Radar (SAR) offers a capability to generate radar reflectivity maps of terrain areas at sub-meter spatial resolutions. The utility of such information for diverse earth observation applications is well documented in the literature which stretches back several decades. In more recent years the technique of height mapping using interferometric SAR has become well established and the performance limitations in terms of height estimation accuracy are to a large extent understood.

Topographic mapping using conventional airborne photogrammetric techniques are well established and routinely used for digital elevation map (d.e.m.) production. Limitations of this approach include the necessity for clear day-time weather, and the relatively time-consuming (and expensive) process of scanning and digitising photographs to produce the desired ortho-projections. In contrast, airborne SAR can operate in all weathers, day or night, and the interferometric height data is intrinsically captured 'on the fly', offering the potential for near real-time production of d.e.m.s. The main limiting factors on HFISAR accuracy are the need for very precise motion compensation and sufficient radar transmitter power to minimise the effects of thermal noise on the interferometric data.

In the present paper a brief summary of the theory behind airborne HFISAR will be presented, and examples of performance achieved with the DERA C-Band SAR will be given. The paper ends with a discussion of the expected performance and possible utility of the forthcoming DERA X-Band SAR when operating in HFISAR mode.

2. HEIGHT FINDING INTERFEROMETRIC SAR.

A conventional SAR obtains a high spatial resolution reflectivity map of an area by transmitting and receiving coded coherent microwave pulses which are then processed to form a two dimensional image (Figure 1). High resolution is obtained in the range direction by transmitting large bandwidth pulses, high resolution

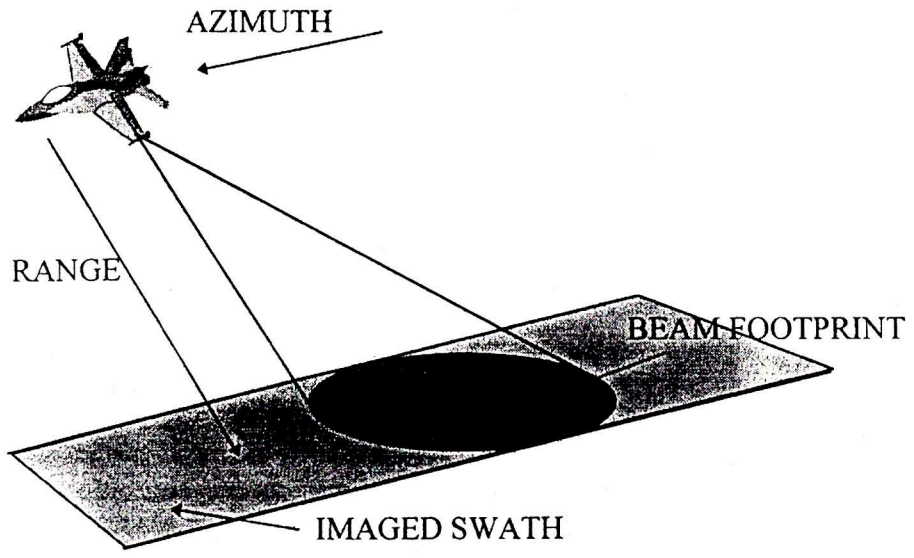

Figure 1: Synthetic Aperture Radar Imaging Geometry

is obtained in the orthogonal along-track direction by coherently combining radar returns from the ground over a long time interval as the aircraft overflies a scene. The resulting image is composed of elements (pixels) each of which is a complex number representing the summed amplitude and phase of all scatterers from some area of the ground. Each pixel covers an area equal in extent to the spatial resolution of the system. The map is inherently two dimensional, with points ordered in the range direction according to the round trip time of pulses scattered from them, and ordered in the along-track (azimuth) direction according to their relative positions down track. A consequence of this is that points at different ground ranges from the sensor may be assigned the same slant-range value if there is a significant height difference between them (Figure 2), a phenomenon termed 'layover'. A typical airborne SAR image is shown in Figure 4.

In the conventional case the amplitude of each pixel is displayed in the image (as in Figure 4). The phase, however, is discarded as this is expected to be a random number with no inherent information on the imaged scene.

In contrast to the conventional case, operation in HFISAR mode involves the formation of two SAR images, either by processing radar returns to two independent antennas which are separated in the cross-range direction (single-pass case), or by combining images obtained on two different imaging passes of a scene (dual -pass case.). The relative phase of the two measurements for a given pixel does then contain useful information which can be related to the height of the terrain contributing to that pixel. Due to the cyclical nature of phase, a process termed 'phase unwrapping' needs to be carried out prior to height estimation. details of this process can be found, for example, in [1].

A schematic of the imaging geometry for single pass HFISAR is shown in Figure 3. With comparison to Figure 2, it can be seen that the interferometric technique effectively breaks the range ambiguity associated with conventional SAR by obtaining an estimate of the radar 'look angle', as well as the range, to a point. Combination of the height estimates for each image pixel then results in a digital elevation map (d.e.m.) characterised by a spatial resolution (or grid spacing) determined by the radar signal bandwidth and along-track integration time, and by a height estimation accuracy in the third dimension.

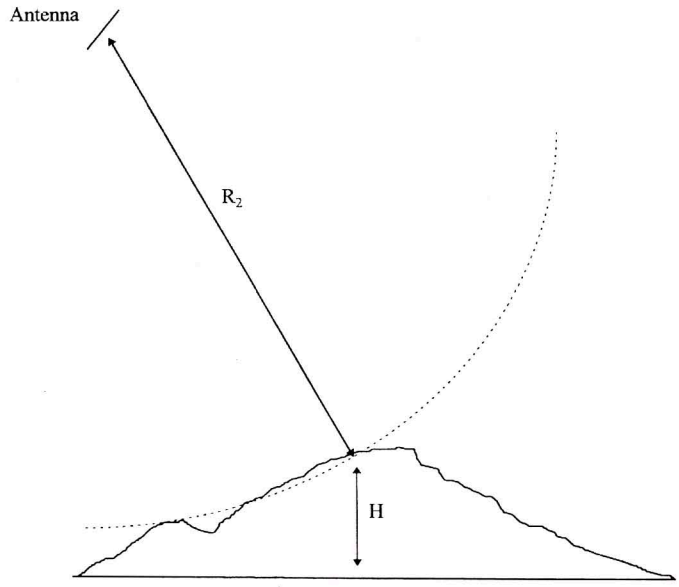

Figure 2 : Range overlay

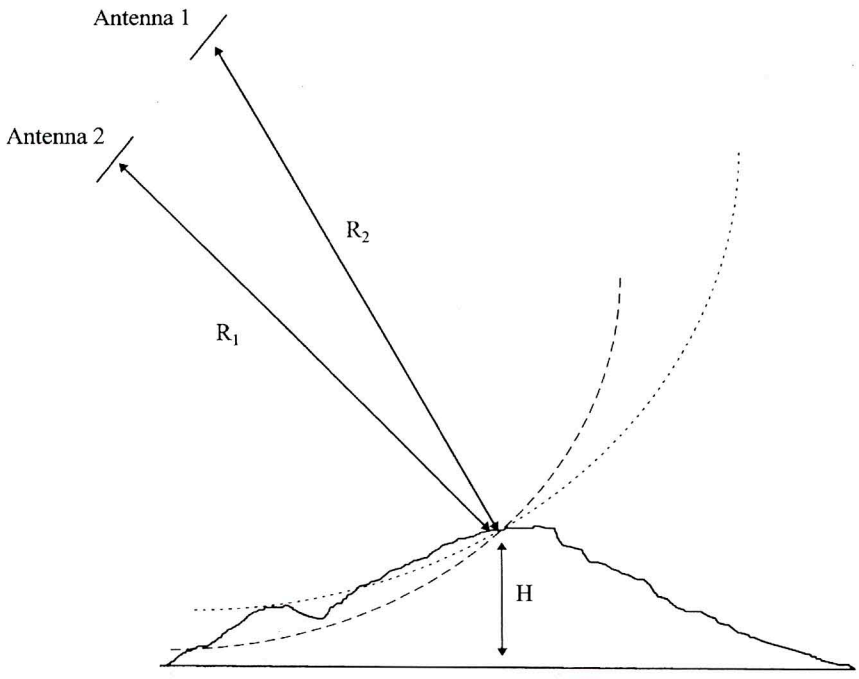

Figure 3 : HFISAR Imaging Geometry

The accuracy of height estimates is determined by the precision of knowledge of the various system parameters, such as antenna baseline and orientation, the accuracy of the motion compensation employed to reduce the effects of non-uniform aircraft motions due to turbulence etc., and the presence of thermal noise in the radar.

It is not intended in the present paper to discuss the theoretical relationships for height accuracy as a function of the above factors. A fairly complete treatment can be found in [2] for example. Rather, in the following, some examples of d.e.m.s obtained with the DERA HFISAR system will be presented in the context of large-scale civilian mapping applications. Achieved performance will be discussed, and expected performance figures will be given for the forthcoming DERA I-Band HFISAR system, the 'Enhanced Surveillance Radar' (ESR).

The DERA C-Band Interferometer

The recently decommissioned DERA C-Band SAR, flown on an Andover aircraft, has been used in a large number of trials as a test bed for HFISAR imaging. This system operated in dual antenna mode with a baseline separation of order 1.8 metres. The operating range of the system was limited by the restricted available on-board power of 9 W peak, which in turn limits the practical operating range to between 1.7 and 4 km, giving an instantaneous swath width of around 2 km. in ground range. Ultimate height estimation accuracy of the system was thus fundamentally constrained by limited signal to noise at far range.

A number of calibration trials were carried out to ascertain achieved height estimation performance for the system. Apart from limited signal to noise performance, the major degrading factors on performance are the effects of roll and possible errors in determination of baseline separation and platform altitude. Relative roll can be corrected from INU measurements to better than 0.05 degrees, corresponding to a residual relative height slope error of less than 2 metres over a swath width of order 2 km. This leaves a constant roll value which must be estimated from control points on the ground.

Platform altitude is measured on-board by a baro-altimeter, typically to an accuracy of order ± 10 metres, and also with p-code GPS which gives a comparable estimation accuracy. An additional method is to measure the time of nadir return to the radar, giving a height accuracy of order the range resolution of the system (2 metres) assuming the nadir ground patch is reasonably uniform.

Figure 4 : SAR Image of Brecon Beacons Region

Figure 5 Interferogram of Brecon Beacons Region

The concern for the present applications is with the height distortions caused by inaccurate altitude estimates rather than with errors in absolute height of points above mean sea level. The first two techniques allow distortion-free height estimation assuming that either the difference in ground elevation between nadir point and the first imaged point is not greater than around 50 metres (above which the measured interferometric phase to the first pixel becomes ambiguous modulo 2pi) , or that a known height point exists in the image. The third technique does not require these contingencies but does constrain the operating height of the system to be higher than the slant-range to the first imaged point (typically 1.7 km).

The antenna baseline length and orientation was measured by laser range measurements to millimetric accuracy. The corresponding residual height slope error is then around one metre across the full swath width.

The fundamental limitation to achievable height accuracy for the C-Band system is that imposed by thermal noise. This component of error may be significantly reduced by forming phase estimates by coherently averaging over a number of adjacent pixels (similar to amplitude multi-looking for conventional SAR speckle reduction). As the C-Band system is operated with a high PRF (10 kHz.) the over-sampling in azimuth could be exploited to achieve an effective signal to noise increase for the interferogram. If 25 looks are generated, then the residual rms height error fluctuation due to noise varies from around 0.5 metres at near range to around 5 metres at far range.

3. EXAMPLES OF HEIGHT ESTIMATION PERFORMANCE

Brecon Beacons Topography

A typical trials data set, obtained over demanding topography, is illustrated in Figures. 4 to 6. An area encompassing the Brecon Beacon mountain range was imaged in HFISAR mode and subsequently used to generate a digital elevation map of the area. Figure 4 shows the conventional SAR image of the area at a spatial resolution of around 6 metres. Some of the features visible in the image are the main mass of Corn Du at upper left, the summit of Pen y Fan in the lower part of the image, and the Upper Neudd reservoir at the upper right. The corresponding interferogram is shown

in Figure 5. The interferogram has been 'flat plane corrected' to take out fringing which occurs purely due to the particular side-looking geometry of the system.

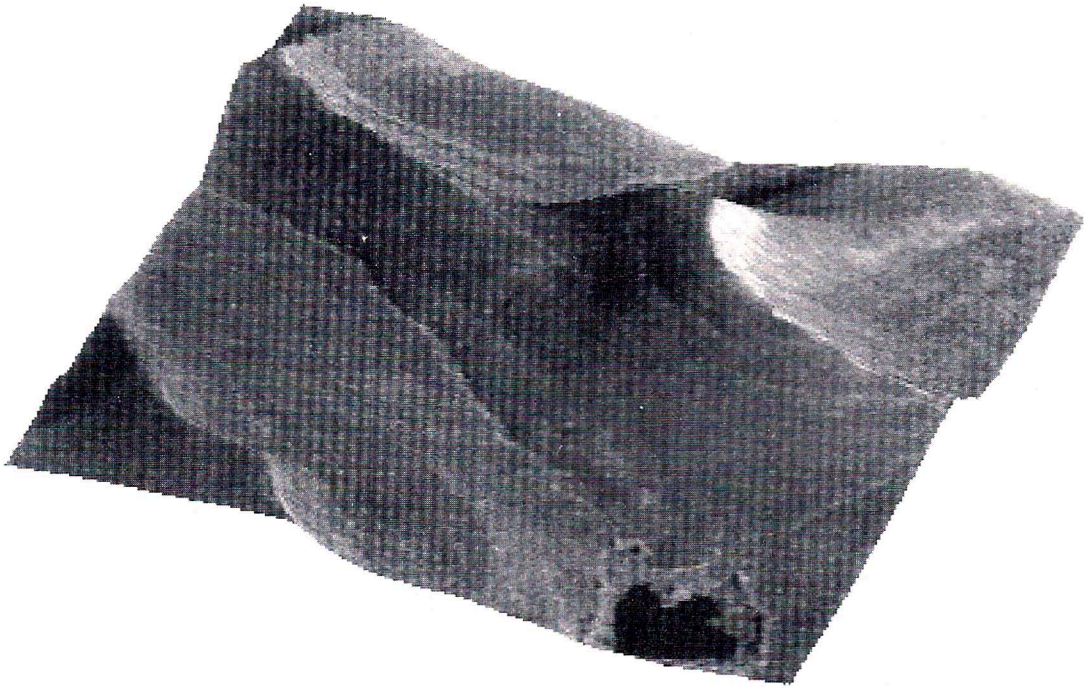

Figure 6 : Digital Elevation map with SAR Image Overlaid

Effectively, this leaves an interferogram which represents height deviations from a nominal flat-plane, the fringe lines can then be interpreted in a similar fashion to conventional map contour lines. Thus, the steep inclines of Corn-Du and Pen y Fan are clearly represented in the figure. Also visible is the noise dominated regions where radar shadowing occurs and also where radar backscatter is reduced due to specular reflection from the water surface of the reservoir. These potentially problematic regions are masked out prior to phase unwrapping using a template based on thresholding the radar intensity from the SAR image. Figure 6 illustrates the result of overlaying the SAR amplitude image on top of the d.e.m. This figure clearly illustrates the potential for combining the two types of information to aid in visual interpretation of the data.

The SAR derived d.e.m. has been compared to an Ordnance Survey d.e.m. of the area in order to indicate the achieved height accuracy across the image. One important difference between the two which needs to be taken into account is that the SAR d.e.m. is sensitive to culture height as well as topography, thus features such as trees and buildings will appear as differences between the two data sets.

Taking account of the above features, the measured height estimation accuracy's for this data set are on the order of 2 to 5 metres rms error over most of the image with an increased error, up to 15 metres, near the peaks of the mountain ranges, most likely due to mis-registration errors in these regions. The latter errors could be reduced by improving the image registration accuracy between the images.

Halifax Geological Formations

A second example of d.e.m. generation from trials data is shown in Figure 7. The system was used to collect HFISAR data over a region covering Wadsworth and Midgley Moor near Halifax. The region is of geological interest as the surface topography is strongly controlled by the underlying geology. The geological structure comprises thin horizontal sheets of rock which erode at different rates resulting in a stepped topographical expression [3]. The SAR generated d.e.m., which was

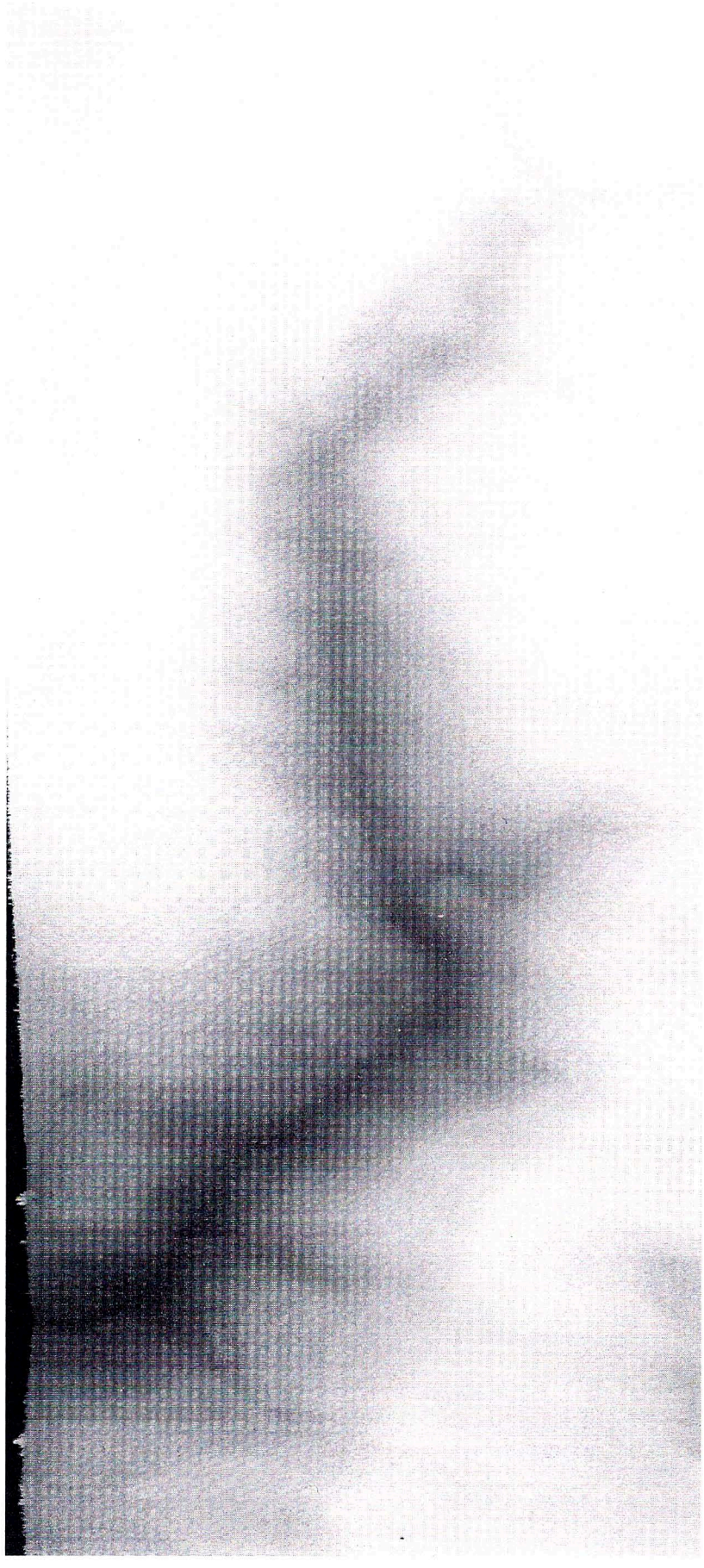

Figure 7 : Digital Elevation Map of Geological Region

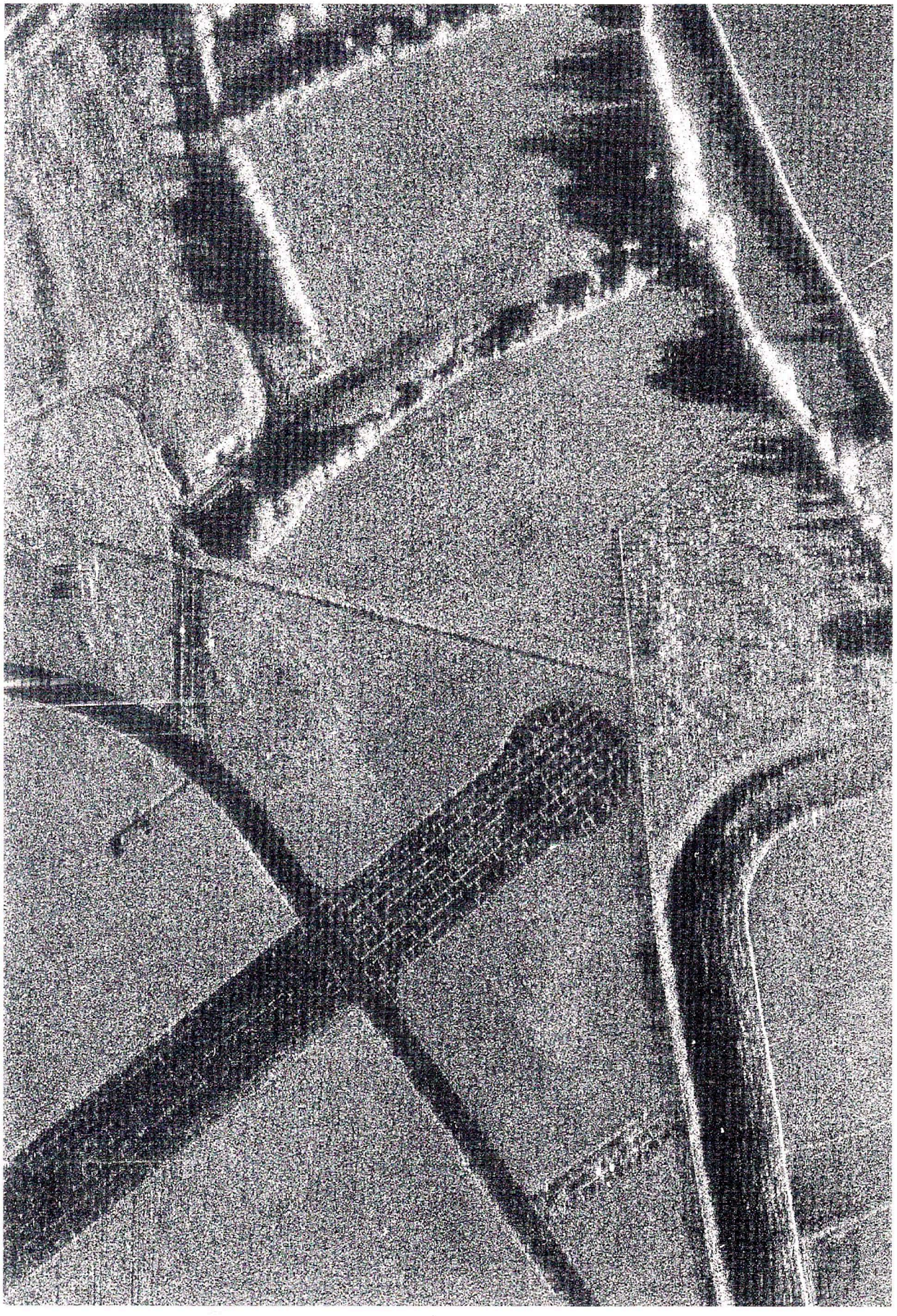

Figure 8 : High Resolution SAR Image of Pershore Airfield

processed to 6 m spatial resolution, clearly exhibits this characteristic step structure as illustrated in Figure 7. Other geological features of the area include land-slide regions and fault zones. Future work is planned to compare the SAR derived height data with that obtained by the British Geological Survey, using photogrammetric mapping, in order to assess achieved height reconstruction accuracy for the HFISAR technique over this area, and the utility of the technique for geological applications.

4. THE ESR SYSTEM.

The follow-on to the experimental C-Band SAR is a significantly higher performance system known as the Enhanced Surveillance Radar (ESR). This system, which is flown on a BAC 1-11 and is due for initial trials within the next few months, operates at I-Band (10 Ghz.) and is capable of producing imagery at a spatial resolution of 0.3 metres. The system has three small receive-only antennas positioned along the fuselage and a main transmit / receive antenna positioned below the central small one allowing HFISAR to be performed.

The amount of detail available in a SAR image of 0.3 metre spatial resolution is indicated in Figure 8. which was generated from data obtained with the now decommissioned DERA 'Canberra' X-Band SAR. In this image, which is a subset of an image of Pershore airfield, textural features are visible in the fields probably indicating the direction of plowing / planting, shadows from individual trees are clearly defined (top centre) as are vehicle tracks in the grass area towards the bottom right of the image. The criss-crossing lines on the runway itself are reflections from grass growing between the asphalt slabs comprising the (disused) runway surface.

The height reconstruction accuracy of ESR can only be properly assessed after trials data has been collected, however, the relatively large transmit power (15 kW. compared to 9 W for the C-Band SAR) implies that noise-limited height estimation performance should be on the order of tens of centimeters over one kilometer of swath. The coupling of this height estimation capability together with the high spatial resolution performance offers great potential for applications such as topographical mapping, flood plain monitoring, erosion monitoring, and subsidence mapping.

SUMMARY

The SAR research group at DERA (Malvern) operates an experimental SAR system for height mapping applications. Initial trials results indicate great potential for the technique for civilian mapping purposes. The potential will be greatly increased when the ESR system is commissioned within the next few months.

ACKNOWLEDGMENTS

The authors would like to thank Anthony Denniss and Andrew MacDonald of the British Geological Survey for providing geological information on the Halifax area, and David Belcher of DERA (Malvern) who processed the Canberra imagery.

References

[1] Goldstien, R.M., Zebker H.A., and Werner C.L., 'Satellite radar interferometry : Two dimensional phase unwrapping', Radio Sci. Vol. 23, pp. 713-720, 1988.
[2] Rodriguez, E. and Martin, J.M., 'Theory and design of interferometric synthetic aperture radars', IEE Proc-F, Vol. 139, No.2,April 1992.
[3] Denniss, A., British Geological Survey, Private Communication.