The LANDMAP project for the automated creation and validation of multi-resolution orthorectified satellite image products and a 1" DEM of the British Isles from ERS tandem SAR interferometry.

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ABSTRACT

A Digital Elevation Model (DEM) of the British Isles at 1" (~30m) and a set of orthorectified satellite image data products (from 0.3" to 1") is being created by the LANDMAP project using a multi-processor Solaris machine with some 0.65TB of on-line disk-space. This unique DEM is being created from multiple passes of ascending and descending tandem ERS Synthetic Aperture Radar data using commercially available software from Phoenix Systems Ltd. and GIS software developed to maximise ERS-tandem strip coverage.

The 1" DEM is being validated using a variety of different sources including (i) kinematic GPS profiles (see Cross et al., this conference) and (ii) Ordnance Survey® PANORAMA 50m DEM both of which have up to an order of magnitude higher vertical accuracy.

Dead reckoning is used with precise orbital elem,ents (PRCs) together with the CEOS GLOBE 30" global DEM to provide very accurate DEMs for individual strips without any need for Ground Control Points. These strips have then been manually checked for planimetric error against digital map data-sets such as the Ordnance Survey® OSCAR® road data-set and no significant shifts were detected. A consensus algorithm is being been developed to minimise artefacts due to atmospheric effects, phase noise errors and phase unwrapping errors.

The 1" DEM is being used to orthorectify all the IfSAR products (amplitudes and phase coherence) and these are then being mosaiced together into seamless image map products. These orthorectified IfSAR products will then been employed to register SPOT, LANDSAT-5 and LANDSAT-7 images . The resultant set of orthorectified images will then be mosaiced into a final image map product.

The resultant LANDMAP data products (including all data produced at individual stages) are available to anyone in the British academic community at no royalty fee cost for any purpose related to teaching, learning and/or research. The software developed for the LANDMAP project is also being made freely available (at Manchester University / MIMAS) to anyone in the UK academic community who is interested in mapping large areas using this approach. Web mapping technol.ogy is being employed to deliver the LANDMAP products to the UK academic community.

The LANDMAP approach heralds a new age for remote sensing research whereby geocoded and orthorectified image maps can be produced for anywhere on the planet WITHOUT the need for any expensive and time-consuming Ground Control Point acquisition.

1 INTRODUCTION

All applications of relevance to end users over land require geocoded data as an input, especially given the increasing prevalence of GIS analysis software and the trend of major software companies to provide interfaces to geocoded products. In order to exploit remotely sensed data, especially that viewed off-nadir such as SAR or SPOT, full orthorectification needs to be employed.

The Combined Higher Education Software Team (CHEST) in the UK, which provides centrally negotiated access to software and data for higher education in the UK, holds an archive of SPOT and Landsat-TM images, served to users from the MIMAS information service (see section 2.2). The Landsat archive is composed of a set of 32 images from the late eighties to the early nineties, covering the whole of the UK. The SPOT archive is composed of 152 images covering the whole of the British Isles from the early 1990s. The images are however only available in raw sensor geometry at present, proving a significant barrier to non-expert use of the datasets. The LANDMAP project (Muller et al., 1999) has therefore been funded by the UK Higher Education Funding Council of England's Joint Information Systems Committee (JISC) to increase the value of the CHEST satellite data archive by providing an integrated set of mosaiced, fully orthorectified images of the British Isles.

The othorectification process for existing visible/near-infrared sensors requires not only identified ground control points to account for planimetric inaccuracies in pointing knowledge of the sensors (typically several hundred metres for SPOT data) but also accurate Digital Elevation Models (DEMs). A stated aim of the LANDMAP project is that its products should be free of onward copyright or licensing issues. This means that all known elevation data sources were deemed unsuitable. Hence a DEM needed to be created as part of the LANDMAP project.

One possible source for such DEMs is the remote sensing technique of Synthetic Aperture Radar (SAR) interferometry (IfSAR) whereby topographic information is derived from measured phase differences between radar returns from a surface from two slightly different viewpoints (e.g. Henderson & Lewis, 1998).

The US DoD/NASA/DLR/ASI Shuttle Radar Topography Mission (SRTM) project, which flew in February 2000, will generate near global topography by IfSAR methods at a grid-spacing of 1 arc-second (≈30m). However, SRTM DEM data is restricted to the region 56ºS to 60ºN and all data outside of the conterminous USA (JPL, 1999) will only be made available at 3” (≈90m) and then only towards the end of 2002 (http://www.jpl.nasa.gov/srtm/) with Europe likely to be the last of the areas processed. DLR also plans to process their X-band single-pass SRTM data but although this will be available at 1” it is not global in coverage.

Currently DTED level 2 will be used to set the accuracy requirements. The DTED level 2 specification states an objective of absolute vertical accuracy of 30 metres at 90 %LE (NIMA (1999)) which is equivalent to 18.24m RMS assuming no systematic bias. This is insufficient to orthorectify images with resolutions of better than around 30m (Muller and Eales, 1990) . The quality of SRTM DEM products will probably be higher and is more likely to be in the range 7-15m RMS. However, this depends greatly on the number of repeat overpasses and the removal of all systematic biases with most regions in poorly mapped regions of Africa, South America and Australasia having only 1-2 passes.

Another source for interferometric SAR data are the two European Space Agency ERS satellites. In particular, the Tandem operation mode, where ERS-2 acquires images of the ground 1 day after ERS-1, as this provides good opportunities to reduce temporal decorrelation of the surface between acquisitions. ERS tandem data can, in exceptional circumstances, be used to generate DEMs with accuracies comparable to products derived from 1:10 000 scale maps (i.e. around 1m RMS) as demonstrated by Walker et al. (1999). The ERS tandem data acquisitions have provided global coverage to ±70°N. (Muller 1996) proposed that they could be used to generate a global 3” (≈90m) DEM with complete coverage, subject to gaps over most tropical forested areas and using multiple Tandem pairs to overcome atmospheric effects. It is of note that ERS IfSAR products could be used to extend the coverage of or further densify the SRTM DEMs as demonstrated by Muller & Mandanayake (1996).

The LANDMAP project aims to demonstrate how a wide area DEM can be generated fully automatically from multi-pass ERS tandem interferometric (IfSAR) pairs without any need for ground control points (GCPs), how wide area DEMs can be validated using kinematic GPS and how such a DEM and derived orthorectified IfSAR products can be used to generate multi-sensor geocoded products.

2 PROCESSING SCHEME

2.1 Interferometric Processing System

A commercial software system, called PulSAR™ (provided by Phoenix Systems) is used to produce focussed SAR image data products from level 0 transcribed radar signal data from ERS, provided here by the UK Defense Evaluation Research Agency (DERA) through NRSCL. (The system can also process datasets from RADARSAT and JERS-1).

PulSAR can be operated either interactively through a Graphical User Interface (GUI), or from the command line as a batch process. In the LANDMAP project, most data processing is performed as off-line batch processing on the MIMAS E3500 system (see section 2.2).

PulSAR provides two features that are of great importance to the LANDMAP project:

- Strip processing. PulSAR allows the generation of coherent SAR image strips of 5-600km in length, free of phase or geometric artefacts, where the usual scene length for ERS data is 100km.

- Accuracy of georeference. PulSAR has been engineered to ensure that image products can be accurately geo-located, given sufficiently accurate data for the platform orbit and the terrain height. For the ERS platforms, the absolute georeferencing accuracy of the system is on the order of 30 metres or better. The accuracy of the georeference is of great practical significance to this project, because it eliminates the need for the time-consuming and error prone manual definition of image ground control points. This is examined later in comparison with GPS profiles.

Pairs of focussed image strips are then fed into the interferometric processing software, the InSAR Toolkit (also provided by Phoenix Systems). This INSAR Toolkit is designed to support both ground surface deformation and DEM generation applications and consists of a suite of independent executables which can be operated in suitable sequences under control of a shell script, but can also be executed manually by command line input if required. The basic InSAR processing sequence for the LANDMAP project is illustrated in Figure 1.

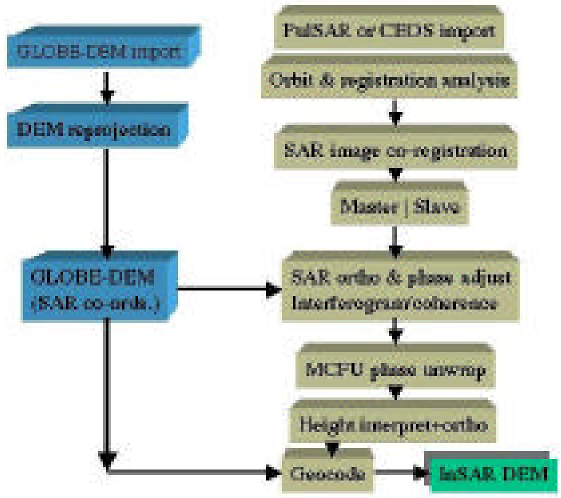

Figure 1. Schematic diagram of the InSAR Toolkit processing system

One of the other significant features of the LANDMAP InSAR processing scheme is the use of a low-resolution DEM (30 arc-seconds, ≈1Km postings) to eliminate errors associated with estimation of a vertical datum and residual InSAR phase trends. The 1km DEM is taken here from the CEOS-IGBP GLOBE project (Hastings, 1996)) available from http://ftp.ngdc.noaa.gov/seg/topo/globe.shtml

Eliminating vertical datum errors in the InSAR DEM data is of critical importance, because errors in the vertical datum couple strongly into planimetric projection errors, by a factor (derived from the radar incidence angle) for ERS of cot(23°). Hence a 100 metre error in the vertical datum results in a planimetric error of 235 metres. In a traditional approach the data needs to be unwrapped, translated to height, and assigned a vertical origin and corrected for possible slope errors by manual identification of control points. In the LANDMAP scheme, the height difference between the coarse DEM and the ground surface is assumed to be zero mean, and this allows the differential unwrapped phase to be processed fully automatically.

Highlights of the InSAR Toolkit which have been specially developed for the LANDMAP project are:

- Phase unwrapping can optionally be performed using the MCFU algorithm provided by ESA (Constantini, 1998)).
- A percolation analysis is performed to detect potential water areas which are eliminated from the phase unwrapping to reduce artefacts near and on water bodies. This water mask also eliminates areas where phase coherence is too low to yield unwrappable fringes.
- DEM generation operates on the unwrapped phase image to convert the unwrapped phase values to height. In order to eliminate the need to manually define a vertical datum, the LANDMAP scheme processes the data differentially relative to the coarse DEM. The resulting height data is orthocorrected within the SAR interferogram co-ordinate system.
- All output products, amplitudes, phase coherences, and DEMs are provided in geoTIFF format for import into standard data analysis and GIS packages and to facilitate subsequent automated mosaicing production.

2.2 Computing Facilities

A project of this magnitude involving 164 ERS tandem scenes of area 100x100 km^2 with generally 3 SAR acquisition pairs per location not only requires significant computing resources but also very significant storage and backup facilities.

MIMAS, the Manchester InforMation and Associated Services, is the premier of the three national academic data centres in the UK. MIMAS is a free service for higher education throughout the UK and primary funding is provided by JISC (http://www.jisc.ac.uk/) and the Economic and Social Research Council, ESRC (http://www.esrc.ac.uk/). MIMAS hosts a number of information services.

The broad aims of the service can be summarised as:

· to provide the UK academic community with the widest possible access to strategic datasets for teaching, learning and research;

· to promote effective use of these datasets in research, learning and teaching; and

· to provide a world-class data analysis service to the academic community.

MIMAS serves seven categories of datasets: Census , Government Surveys , Macro-Economic, Spatial , Scientific, Bibliographic, Electronic Journals, comprising over 50 actual datasets. The latest edition is the Web of Science (http://wos.mimas.ac.uk/). MIMAS also hosts a large spatial data resource including the Bartholomew digital map data, the 1981 and 1991 Census of Population digital boundary data, and extensive archives of satellite data from SPOT and Landsat.

MIMAS also provide additional support to EDINA, Edinburgh Data and INformation one of the other national online services for the UK higher education and research community. EDINA hosts Digimap, which is a new service that will deliver Ordnance Survey (http://www.ordsvy.com/) digital map data to UK Higher Education.

The MIMAS Spatial Service also provides, in addition to the datasets, support and advice on the latest versions of the following software resources: Arc/Info, ARCVIEW, Erdas, Imagine, ENVI, IDL, Rivertools, PCI Geomatics, and ERMapper.

The MIMAS computing facility currently consists of a number of co-operating computer systems: an Irwell E3500 with 23 366MHz Sparc processors, over 1TB of local disk space, 7GB memory, Tame 12 Processor system and Vault, 2 processor for 200GB disk mount and transfers. To make the data processing task feasible within a relatively short space of time (approximately 18 months), the LANDMAP system has been developed to run on the Irwell machine. The processing system will be supported on the machine after the end of the project itself for subsequent use by members of the UK academic community for large-scale IfSAR projects.

3 FIRST-PASS DEM GENERATION

3.1 Data Selection and Planning

Metadata concerning ERS scene availability is available from ESA through the DESCW system, while information concerning IfSAR pair baseline values is available separately from the German ESA data centre, D-PAF. A GIS import routine has been developed over the last three years which enables scene selection and queries to be made based on these data using industry standard GIS systems (ESRI's ARC/INFO and ArcView). Scenes were selected for the first-pass DEM using the following criteria:

· minimal number of strips to cover the British Isles to reduce processing time and to leave as many scenes as possible in the data budget for later patching of areas of poor accuracy;

· IfSAR perpendicular baselines between pairs of greater than 100m and less than 400m, for topographic derivation. (In one area of western Ireland scenes were only available with baselines of order 90m);

· groups of scenes acquired as close as possible together in time, preferably during Winter months to ensure "leaf-off" vegetation conditions to improve radar coherence.

Figure 2 shows a plot of the 82 ERS Tandem pairs selected for the first pass regional DEM. This first pass covers a range of dates from June 1995 through to August 1996, although the bulk were acquired between September 1995 and January 1996. The full list of scenes can be found on the project World-Wide Web site at http://www.landmap.ac.uk

An important part of the accuracy assessment of any DEMs such as the IfSAR-DEM, the GLOBE and any third party DEM data-sets is access to a high quality set of height measurements, free of copyright. Fortunately, kinematic GPS (kGPS) technology has now matured to such an extent where a national tour can be undertaken in a matter of a couple of weeks given sufficient advance planning. (Cross et al., this conference).

Again, GIS systems were employed in planning the kGPS acquisitions (Morley et al., this conference). Detailed planning was accomplished using both a national roadmap, free of copyright problems, and the ERS Tandem footprints for each strip. A tour of the British Isles was constructed to cover two weeks driving, completing a closed route each day around a kGPS base station. The resultant set of height points represent the optimal routes for assessing the accuracy of each strip. These profiles cross strip boundaries in the DEM mosaic, are located at opposite ends of strips to look for general tilt and bias effects, and cover a variety of topographies from the lowlands of East Anglia to the highlands of Scotland.

The tour was conducted during September 1999 and the routes are shown superimposed on the ERS Tandem footprints in Figure 2. It may be possible to acquire one further set of measurements in South Wales / the West Midlands of England which was missed out from the original tour due to operational difficulties.

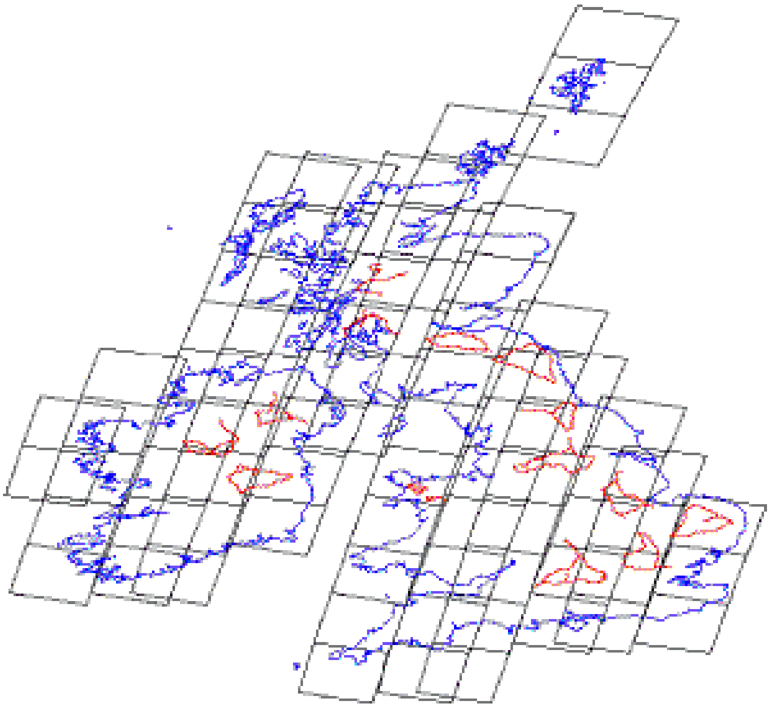

Figure 2 ERS Tandem IfSAR pair strips and frame boundary footprints (black) for the first-pass DEM generation, with kGPS tracks superimposed (red). There is only one IfSAR pair per footprint in the first-pass coverage

3.2 Data Processing

The 82 scene pairs shown above comprise some 53GB of raw SAR data. Initially, single 100x100km^2 scenes were processed as the automated batch processing system was developed, the systems debugged and initial accuracy assessments performed. However for the full first-pass processing, the data have been processed in strips. A practical limit, even on a machine such as Irwell, was reached in terms of memory and disk allocation during processing so that strips had to be limited to 500-600km in length (5-6 scenes), meaning that some of the longer strips in figure 2 had to be cut in two.

By the end of August 2000, all of the first-pass data has been processed. Some of the gaps are due to poor tape copies of the raw SAR data which are in the process of being replaced. Updates are reported on the project Web site (http://www.landmap.ac.uk). The second pass DEM consists of night-time (ascending pass) strips which are shown in Figure 3. Based on an analysis of the phase coherence and data gaps, up to 5 scenes for any particular frame will be ordered. The unreliability of media such as EXABYTE 8mm tapes continues to cause operational difficulties which any prospective IfSAR software user should be aware of.

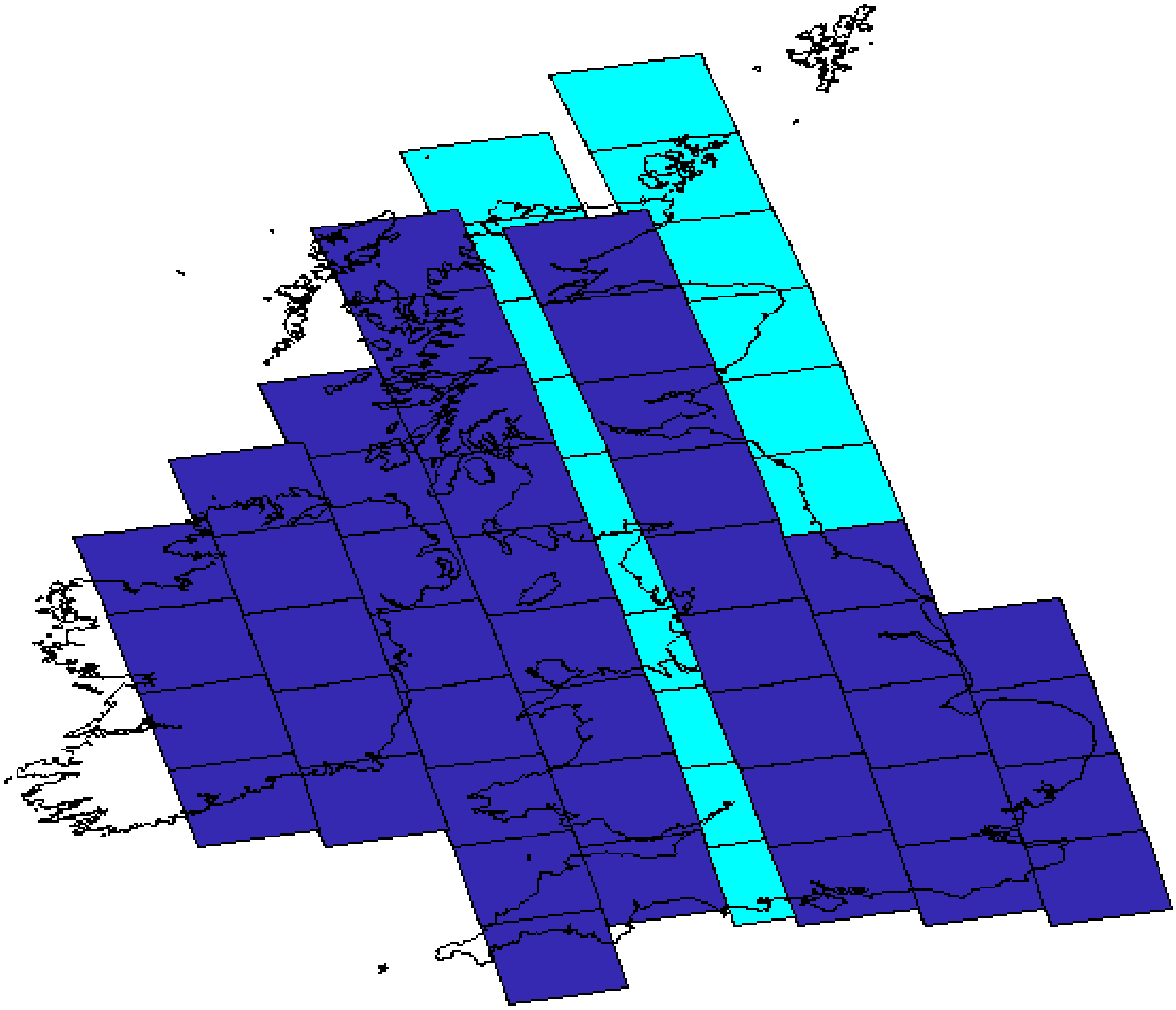

Figure 4 ERS Tandem IfSAR pair strips and frame boundary footprints (black) for the second-pass DEM

4 FIRST PASS DEM AND IFSAR IMAGE PRODUCTS

The First Pass IfSAR DEM was completed in June 2000 and is shown in Figure 5. Originally, it was envisaged that block adjustment would be required to fuse the DEM due to inaccuracies in the PRCs. However, experience with the creation of this DEM showed that the accuracy of the georeferencing was such that no tiepointing and adjustment was required. In addition, the poor computing performance of the phase unwrapping algorithm from (Constantini, 1998)) and severe artefacts when phase noise was too high resulted in the use of a tile-based algorithm. Residual tiling artefacts are planned to be eliminated by merging of the DEMs from the different passes. Inspection of Figure 5 shows that there are small gores due to the lack of overlap, gaps due to water bodies and areas of noise due to low phase coherence. Extensive quality assessment studies are currently underway some results of which will be reported in the next section and in companion papers by Cross et al., and Dowman et al. (2000).

Figure 5 First-Pass IfSAR DEM of the British Isles from the LANDMAP project.

The coarse resolution GLOBE DEM was employed to orthorectify the first pass IfSAR amplitude and Phase Coherence products and these individual strips have been mosaiced together using commercial software. At this stage no attempt was made to correct for across-track backscatter variations due to imaging geometry. Figure 6a shows a mosaic of the ERS-1 SAR amplitudes whilst Figure 6b shows the mosaic of the Phase Coherence. The final DEM is due to be completed in December 2000.

Some 500gb of disk-space was consumed in the creation of these products together with several CPU years of processing time. Most of the processing was performed by a single individual (A.H. Walker) after the initial production system was developed.

No atmospheric artefacts have been detected to date such as those described by [*Goldstein*, 1995] [*Tarayre and Massonnet*, 1996; *Zebker et al.*, 1997]. However, it is envisaged that systematic studies comparing the LANDMAP First Pass DEM and national mapping gridpoint interpolated contours will indicate some artefacts present.

To overcome problems in DEMs from atmospheric artefacts, [*Ferretti et al.*, 1999] developed a method combining unwrapped phases with different baselines to create a DEM free of any known atmospheric artefacts but the likelihood of sufficient numbers of ERS tandem passes with a wide enough range of Perpendicular baselines is low given the latitude of the UK.

It is planned that a further GLOBE-restituted mosaic will be made with LANDMAP products from the Second Pass coverage. The final orthorectified products will be created once the final DEM< is complete.

Figure 6a,b First Pass ERS-1 SAR amplitude mosaic (a) and Phase Coherence (b)

5 QUALITY ASSESSMENT

5.1 Planimetric Accuracy

The first-pass DEMs has been assessed for planimetric and altitudinal accuracy. Assessing planimetric accuracy by comparing kGPS data with the IfSAR DEMs has proved to be problematic. The kGPS trails are limited to lying on roads. To assess planimetric accuracy requires that features can be located which are sufficiently constrained in extent and identifiable in position in the DEM to be able to measure offsets of the kGPS trails from the features. Generally this could mean bridges or cuttings. However these are difficult both to find and to locate accurately enough. Planimetric accuracy has therefore been assessed by comparing the amplitude images after they have been orthocorrected using the GLOBE DEM with the kGPS trails and digital map data from the national mapping agency of the UK, the Ordnance Survey® (OS). In particular, the OS OSCAR® road asset management data have been used for comparisons.

Figure 4 shows an example overlay of kGPS data and OSCAR roadlines on an orthocorrected amplitude image. A concern in designing the system to use strip data was that estimation of the trend in the variation of the IfSAR baseline between the tracks along the strip, a key factor in determining an accurate reconstruction of the IfSAR geometry, is more important for strip datasets. The image extract in figure 7 is taken from near the far end of a 6 scene strip (approximately 600km long, orbits ERS1: 21940, ERS2: 2267) showing that the planimetric accuracy does not appear to degrade with distance along the strip. The roads, visible in the image, align well with the vector overlays.

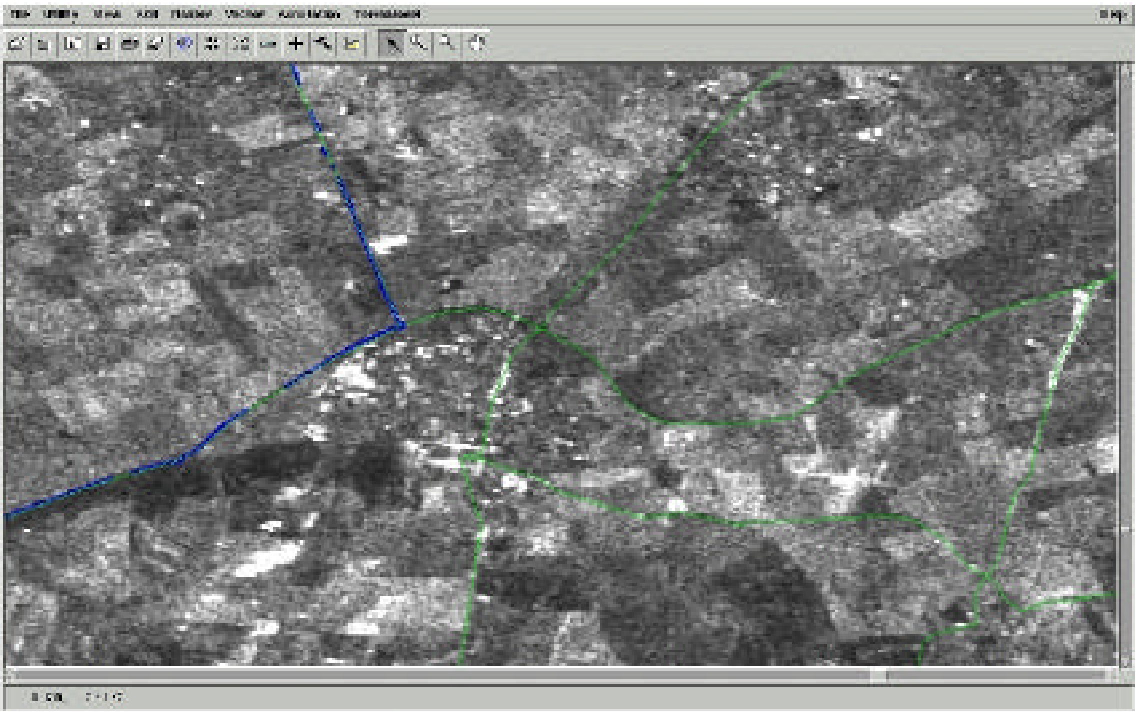

Figure 7 Amplitude image overlaid with kGPS trail in blue and the OSCAR® (Crown Copyright) road network data set in green

Measuring individual points locations has generally been found not to be reliable with SAR amplitude images due to difficulties in identifying single points as a result of speckle noise. Initially there were problems projecting the road dataset from the British National Grid into a WGS84 geographic coordinate system (the primary reference system for the IfSAR processing) as the GIS package used did not utilise parameters of a sufficient precision. The vector data were therefore exported and separately projected with inhouse software using improved parameters. Further examples can be found on the project Web site.

It is should also be noted that for the first-pass, the GLOBE DEM has been used as the reference DEM for phase flattening. Due to the coarse nature of this DEM (pixel spacing of 1km) some localised areas of the first-pass orthorectified radar images may not be as accurate as others. The processing system will therefore need to be run iteratively putting the output high resolution IfSAR DEM back into the processing chain in order to precisely orthorectify the amplitude and coherence images. Areas which are particularly likely to be affected are features such as motorway cuttings and embankments which may have a vertical height difference of many metres when compared against the GLOBE DEM. As noted above, a vertical inaccuracy results also in a planimetric shift after processing. Further detail is provided in Dowman et al. (2000).

5.2 Elevation Accuracy

Table 1 summarises a number of comparisons that have been made between two of the kGPS trails, days 1 and 14 of the tour (the southernmost trails in figure 2) and a number of DEMs. The two days' kGPS data cover a region to the West of London in the Thames Valley. Three scene pairs have been processed to produce three separate DEMs, labelled by ERS1 orbit number, 23006, 23858 and 23357. Note that pass 23006 is an ascending pass not shown in figure 2. Additionally, these three DEMs have been averaged together (by a simple mean) to produce a simple multipass DEM.

DEM	kGPS run	Number of points	Min (m)	Mean (m)	Max (m)	SD (m)
23006 (Asc)	Day 14	10522	-34.19	7.99	162.86	11.18
23858 (Desc)	Day 1	6094	-27.99	7.63	60.46	11.38
23357 (Desc)	Day 1	5993	-38.00	-5.86	30.54	7.87
23357 (Desc)	Day 14	6770	-34.27	-7.58	50.97	11.55
Multipass (2 Desc, 1 Asc)	Day 1	6802	-49.46	-4.57	55.94	9.79
Multipass (2 Desc, 1 Asc)	Day 14	10624	-73.34	-7.70	36.93	8.75
GLOBE	Day 1	9874	-51.10	-1.13	45.97	17.12
GLOBE	Day 2	11459	-51.37	-1.64	37.19	16.95
GLOBE	Day 14	16985	-63.91	-3.92	69.89	20.44
IOH (OS coordinates)	Day 1	9874	-18.95	-0.09	16.31	3.45
IOH (OS coordinates	Day 14	16985	-17.40	-0.52	47.50	3.88

Table 1 Differences (DEM-kGPS) between kGPS points from day 1 and 14 trails and various DEMs: IfSAR DEMS in the top section, the GLOBE DEM in the middle section; and the Institute of Hydrology/OS DEM in the bottom section.

The results show a complex pattern. Firstly, the coarse 1km GLOBE DEM does not compare well, as expected, with the high resolution kGPS point measurements with large differences but a small mean difference. An additional 50m DEM was available for comparison in this area created by the Institute of Hydrology by interpolation of OS 1:50 000 contour data with constraints to maintain correct river hydrology. Here the differences against the kGPS are much lower, with an almost zero mean difference. This provides some validation of the kGPS data themselves (and the improved projection to British National Grid co-ordinates).

A combination of factors affect the IfSAR DEM comparisons. The principal source of difference between the kGPS trails and the IfSAR DEMs is the different measurement surfaces for each. In the case of the kGPS, the measurement position is the position of the antenna attached to the car above the road. On the other hand the C-band ERS SAR tends to receive radar returns from near the top of any canopy, for example trees around the road. Figure 8 shows the kGPS trail from day 14 versus heights extracted from the 23006 DEM (and hence is the equivalent for the first row in table 1). As can be seen, there are regions of significant vertical offset and others where the measurements agree closely. The 162m maximum offset in the table is probably due to an erroneous kGPS point (around point 250 in figure 8).

It is should be noted that for the purposes of orthorectification, the primary purpose for the LANDMAP DEM, a top-of-canopy DEM is preferable. The standard deviations of the differences versus the IfSAR single-pass DEMs even with the surface cover effects are generally 11-11.5m and show an improvement due to multipass averaging. This should then be acceptable for orthorectification processing.

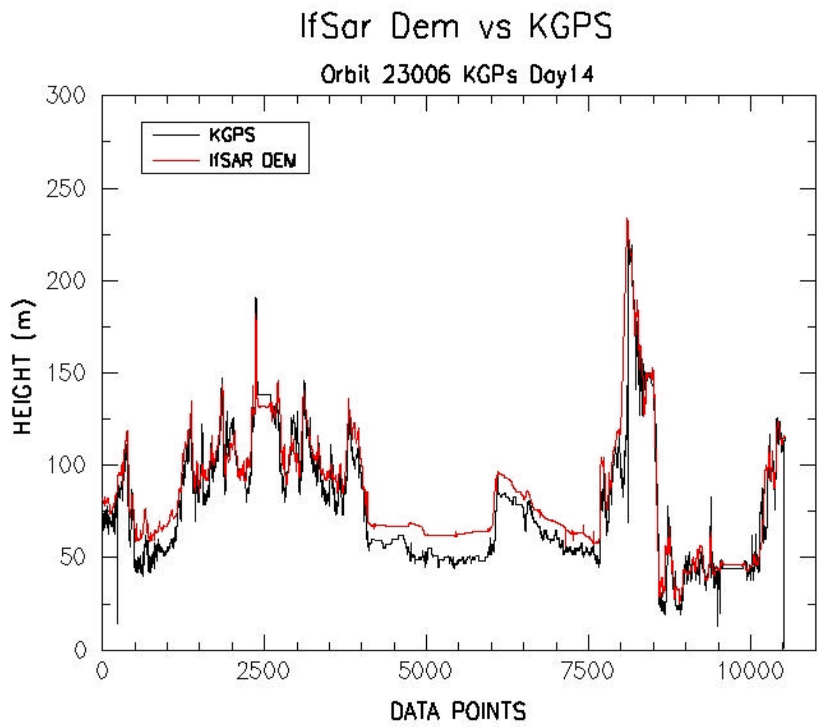

Figure 5 kGPS elevation measurements versus ERS1 orbit 23006 IfSAR single-pass DEM (red).

6 CONCLUSIONS

We have demonstrated a new IfSAR processing system which is capable of strip processing of ERS data to produce products of high planimetric accuracy and surface height comparisons of 11m standard deviation for single-pass DEMs including vegetation cover offsets, or 3.5m standard deviation versus map-based DEM data. The system does not require the use of ground control points. LANDMAP will release the final multi-pass British Isles DEM in early 2001 using newly developed software based on ARCIMS and .the OpenGIS Web Mapping testbed (Kitmitto et al., this conference)

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