GPS Validation of IfSAR Digital Elevation Models from LANDMAP

P. Cross, R. Keenan, J. Barnes, N. Anthis, K. Chugani*, A. Walker,
J-P. Muller and K. Kitmitto§

Department of Geomatic Engineering
University College London
London, England WC1E 6BT
United Kingdom
Email: pcross@ge.ucl.ac.uk
** Selektra Limited §Manchester Computing*

1 Introduction

In order to validate LANDMAP image and elevation products, two fieldwork campaigns totalling 23 days duration were carried out to collect kinematic GPS (KGPS) data throughout the British Isles. When processed, these data yielded almost 9,500 kilometres of accurately co-ordinated 3-D profiles that could be used for quality assessment purposes, i.e. to validate the accuracy of the LANDMAP [*Muller et al, 1999, 2000*] products.

This paper briefly describes all activities pertaining to the GPS validation tasks including route design, observing procedure and data processing tasks. Example results are provided relating to the accuracy of kinematic GPS methods along with some initial results of the comparisons between the first pass IfSAR DEM and the KGPS profiles.

2 Route Design

Design of the IfSAR-DEM validation profiles for the first fieldwork campaign was done as part of an MSc project at UCL, [*Proctor, 1999*] and is discussed in [*Morley et al, 2000*]. All of the profiles followed were selected for their optimal sky visibility, not only in terms of data collection from GPS satellites but also to permit easy identification from the SAR and SPOT satellite imagery. Where possible, the routes included motorways and major trunk roads that generally afforded unobstructed satellite visibility. Inevitably, due to the limited road network in some areas, for example the Lake District and the Scottish Highlands, it was necessary to traverse routes that were less than ideal in terms of satellite visibility. The second fieldwork campaign had slightly different objectives (see §6) and was designed in a more *ad hoc* manner.

3 Validation Tasks

Validation of the kinematic GPS observation strategy was carried out to the west of London *(western section of M25 orbital motorway and M40 towards Oxford),* in which a number of valuable lessons were learnt regarding the antenna type, recording rates, signal tracking and driving style. In particular it was learnt

- that an antenna suitably mounted on the roof of the vehicle would afford optimum satellite visibility and tracking conditions; however the presence of reflected signals entering the antenna would have to be reduced,
- routes following motorway sections would afford the greatest average density of data points given their 'relatively' unobstructed satellite visibility,
- recording GPS observations at a 1-second data interval would afford sufficient point spacing at motorway speeds, approximately 20 metres,
- for identification purposes, motorways afforded clear linear features visible on images which would aid in validation purposes, and
- that the driving manner should reflect the satellite coverage and observing rate. After losing lock onto the GPS satellites when passing under a bridge for example, the vehicle speed should be reduced (dynamics minimised) so as to reduce the presence of data gaps in the profiles and quickly return lock onto the satellites.

As there was no requirement for real-time positioning, radios were not necessary - all the observations could be processed at a later time.

4 Equipment Used

Differential GPS was used to meet the objectives of the validation exercise. Ideally it was required that the positioning accuracy was one order of magnitude (ten times) better than that of the satellite imagery. The DGPS positioning technique allows the accurate positioning of a mobile GPS receiver 'relative' to a second GPS receiver which occupies a point of known 3-D co-ordinates in the WGS-84 reference frame. As the co-ordinates of the reference station and all GPS satellites are known, it is possible to determine the errors caused by satellite ephemeris errors and atmospheric refraction of the GPS signals. From the assumption that, over short distances, these errors are also common to the measurements made by the mobile receiver, the application of scalar corrections to the mobile's observed pseudoranges yields a significantly more accurate user position.

The GPS receivers used in both campaigns were Leica Geosystem's System 500 [*Leica*] and MC1000 unit as well as a Javad Eurocard receiver system [*Javad*]. Both systems comprised geodetic quality receivers capable of observing and recording code pseudoranges and carrier-phases on both GPS frequencies, as well as two GPS antennas.

The antenna was mounted atop the vehicle on a roof-rack system ensuring that the vehicle did not obstruct the antenna's sky visibility in any way. The mobile receiver was located inside the survey vehicle, a large estate car, for ease of operator interface.

Leica choke-ring antennas were selected specifically for both campaigns as they featured some advanced multipath mitigation capabilities, which would afford a considerable reduction in the number of incorrect position solutions yielded during processing. Multipath is the phenomena whereby additional GPS signals enter the antenna having been reflected off nearby structures (e.g. buildings, motorway furniture, high-sided vehicles and the survey vehicle roof), as well as those that have travelled a direct path.

For further information regarding GPS equipment, observing and processing techniques, the reader is referred to the University of Colorado's 'Global Positioning System Overview' website, [*Dana, 1999*].

5 Campaign 1 - Circular Kinematic GPS Profiles

The first campaign, carried out in September 1999, required the GPS profiles for 14 pre-defined circular routes, as shown in Figure 1 below. This suited a 'Real-time Kinematic' (RTK-GPS) survey technique in which both GPS code pseudorange and carrier-phase measurements are recorded.

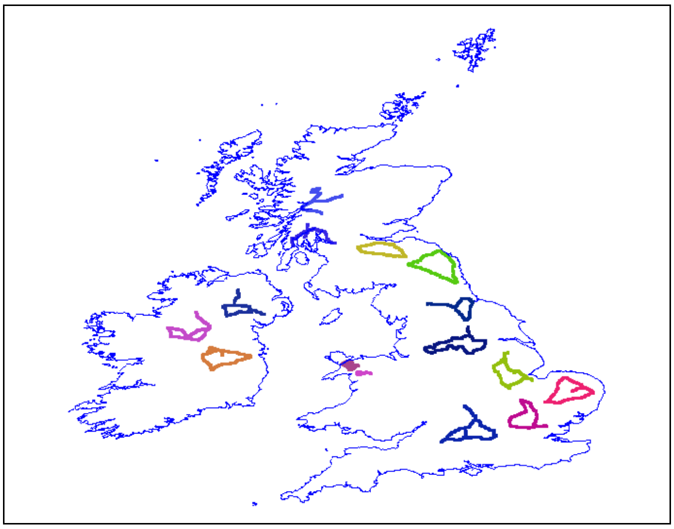


Figure 1. Distribution of the Circular Profiles observed using RTK-GPS during Campaign 1 - September 1999. Each coloured loop represents one of the 14 circular profiles observed with RTK-GPS.

The observing schedule was such that the reference receiver was established at a location deemed to be the centroid of the day's profile. By doing this it meant that the baseline distances from the 'local' reference receiver to the mobile receiver would be kept to a minimum thus preventing an unwanted accumulation of distance-dependent errors, caused mainly by atmospheric effects. The mobile receiver was then driven along each predefined route recording GPS observations at a rate of one every second.

Once the profile was traversed, on average a distance of 320 kilometres, the local reference station team was picked up and the entire team travelled to the site of the next profile, to prepare for the next day's survey. Also at this time, GPS datasets from both the local reference and mobile receivers were checked for errors before being archived to optical disc.

During the 14 days of this first campaign, the mobile team covered almost 6,460 kilometres with the predefined circular profiles representing some 4,480 kilometres of that total.

6 Campaign 2 - Linear Kinematic GPS Profiles

The second campaign, which took place during May / June of 2000, had a different set of objectives to the first campaign and therefore the observing schedule was restructured to accommodate these. This time, the fundamental objective was to observe some long linear GPS profiles that would span a number of satellite pass-strips focusing on areas of strip overlap and permitting some checking of the strip matching procedures using orthorectification techniques. A plan showing the coverage of the first ERS data pass is shown in Figure 2 below.

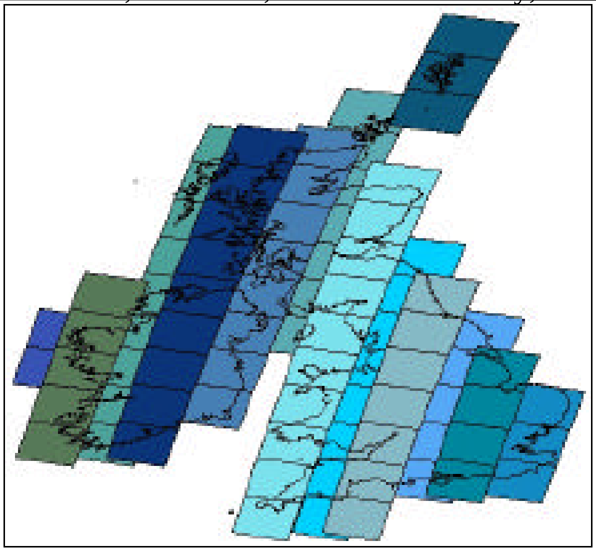


Figure 2. LANDMAP Data Coverage for the British Isles from the 'First Pass' of the ERS satellite.

The establishment of a 'local' reference receiver station alongside each section of these proposed transects, as shown in Figure 3, would have been too demanding in both time and logistics so an alternative processing approach was decided upon. The observing procedure was identical to that of the first campaign with the exception that the 'local' reference receiver remained in the same location for the entire duration of the campaign. A high-precision geodetic GPS receiver was established at a point of known co-ordinates at University College London where it collected GPS observations for the 9 days of this second campaign. The mobile receiver was driven along the require profiles recording GPS data at a 1Hz rate, again corresponding to a point spacing of about 20 metres.

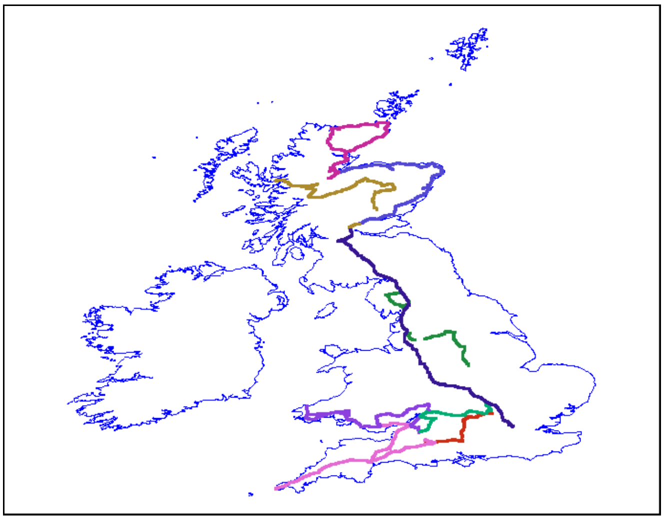


Figure 3. Linear Profiles observed using Differential Code Pseudorange GPS during Campaign 2 - May / June 2000. Each different coloured profile represents one day's GPS observations.

The routes followed for this second campaign contained a number of features as requested by the LANDMAP processing team that would aid them in their orthorectification tasks. One particular request was that a number of profile crossovers should be performed at major road junctions. At such junctions, two or three kilometres of additional observations were recorded on the feeder roads for the junction in question. Such manœuvres provided the processing and imaging team with a greater number of features to identity and refer to during their quality assessment routines. The nature of the road network in some areas meant that several long stretches of road were recovered or intersected which would afford additional error checking.

As in Campaign 1, all datasets from the mobile and reference receivers were subject to preliminary quality checks and then written to optical disc on a daily basis. Nearly 5000 kilometres were driven in the 9 days of the second campaign incorporating both Land's End, in south west England and John 'O' Groats, in north east Scotland.

7 Data Processing

All GPS data collected in both campaigns was post-processed at UCL, eliminating the obvious difficulties of having to maintain constant telecommunications between the reference and mobile receivers.

Leica's SKI-Pro GPS processing software was used to determine 3-D co-ordinates of the mobile antenna in the WGS-84 reference datum from dual-frequency GPS code pseudorange and carrier phase measurements.

Data from the first campaign was post-processed in an RTK-GPS mode that made use of the more precise carrier-phase observations over the shorter distance baselines. With the successful resolution of these carrier-phase ambiguities, this method was capable of yielding 'fixed ambiguity' positions accurate to 2 cm in plan and 5cm in height (95% of the time). In times of greater carrier-phase signal noises, the processing may be able to compute a lesser accuracy 'float ambiguity' position good to 5-10 cm in plan and 20-30 cm in height (95% of the time). The position solutions output from such processing routines are known as fixed and float solutions, respectively.

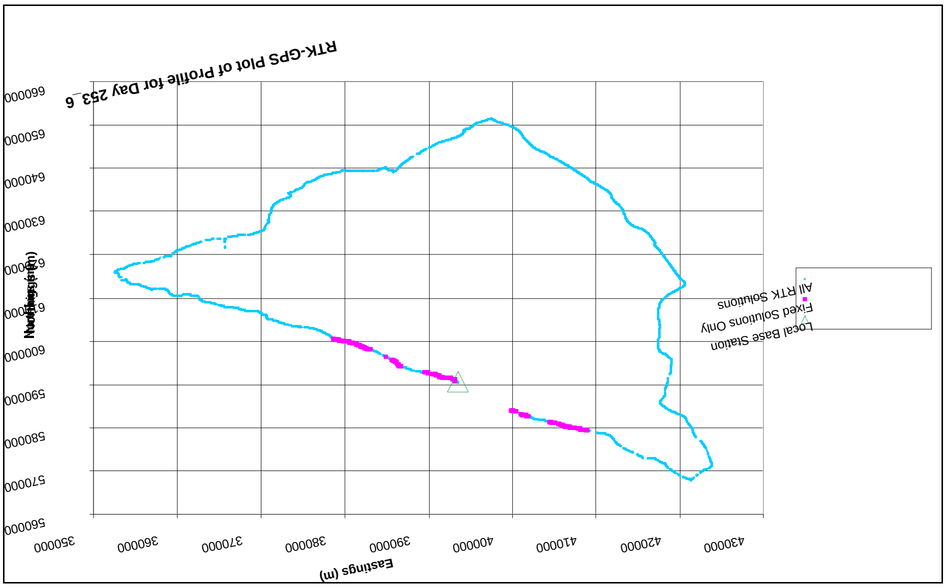


Figure 4. The RTK-GPS Trajectory as computed for Day_253_6, Campaign 1 with an overlay of the fixed RTK solutions as computed within 20 km of the Local Base Station.

The profile, shown as Figure 4, relates to the RTK trajectory computed for Day 253_6. Also included, as the thicker lines, are the fixed ambiguity solutions as computed within 20 km of the local base station. Note that the broken segments of the trajectory are mainly due to loss of lock on the GPS satellites preventing the computation of the mobile antenna's position. For the 10,681 points on this loop, fixed solutions were obtained for 23%, and float solutions for 15%, making nearly 38% 'successfully' processed in total. A success rate of 35-40% was typical for all RTK-GPS profiles observed in Campaign 1.

Results for the second campaign were derived from a differential code GPS positioning (DGPS) technique that nominally uses the code pseudorange measurements only. This code-only technique is usually applied to long-range positioning where it becomes increasingly difficult to resolve successfully the carrier-phase ambiguities within an RTK-GPS position computation; this is due mainly to the ionospheric and tropospheric refraction effecting an increase in the levels of carrier-phase signal noise. However techniques have been developed whereby the carrier-phase measurements are used to smooth out some of the high-frequency noises in the code pseudoranges. With the relevant atmospheric models, phase-filtered code DGPS positioning can provide positions with an accuracy of approximately 1.5 metres in plan and 3 metres in height (95% of the time).

Over 173,000 points were processed and passed onto the LANDMAP validation team from the first campaign, as were 180,000 points from the second campaign. In total, for the two campaigns, over 353,000 point positions were successfully processed for the 9,500 kilometres of the recorded profiles making this a sizeable dataset for DEM validation purposes. Other academic institutions are invited to make use of this GPS dataset for academic research purposes - please refer to the LANDMAP website [*LANDMAP*] for further details. The average spacing, as calculated from these statistics, was around 25 metres between each point.

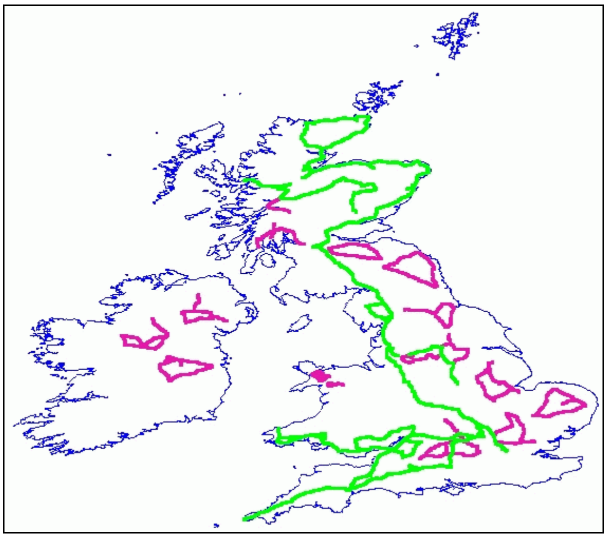


Figure 5. The combined coverage of the GPS profiles observed in both campaigns. Circular profiles from Campaign 1 are shown in purple and those linear profiles observed during Campaign 2 are illustrated in green.

The following three plots, Figures 6, 7 & 8, show time-series comparisons of the accuracies yielded by different processing methodologies for a subsection of one circular loop, Day 253_6 in Northumbria. Due to the hemi-spherical configuration of the GPS constellation, the height component is the least well-known within any form of GPS positioning. In order to preserve space in this publication, the results displayed refer to the height component only, which is of significant relevance to the majority of research applications these LANDMAP DEMs will be implemented in. Horizontal error components can generally be expected to half of their height counterparts.

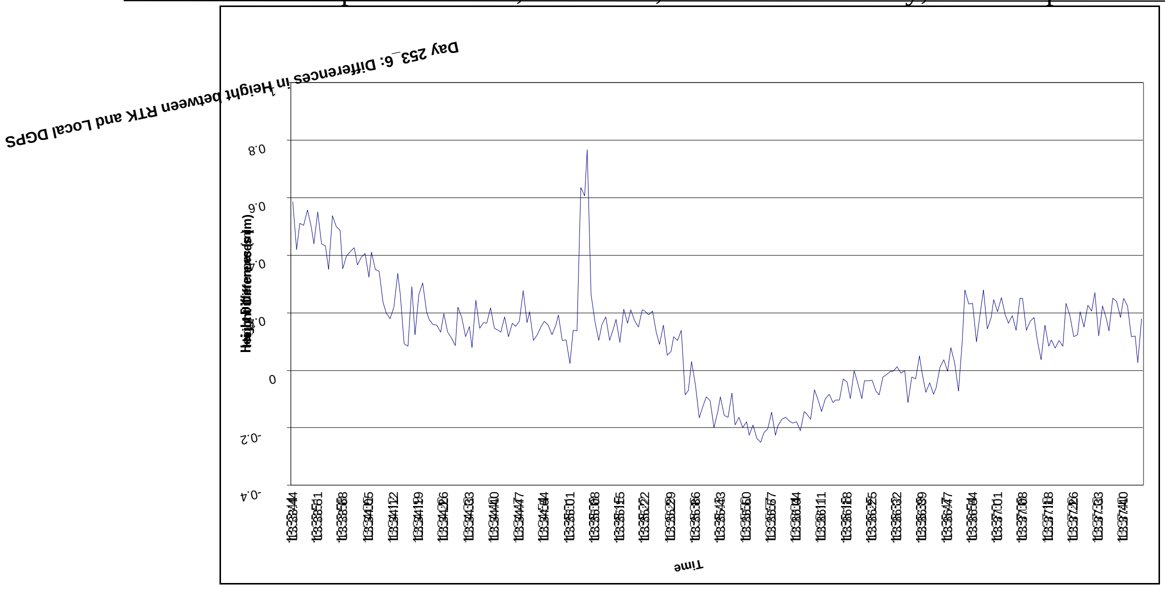


Figure 6. Differences in Height between RTK and Local Code DGPS Positions as derived from the Local Base Station, Day 253_6.

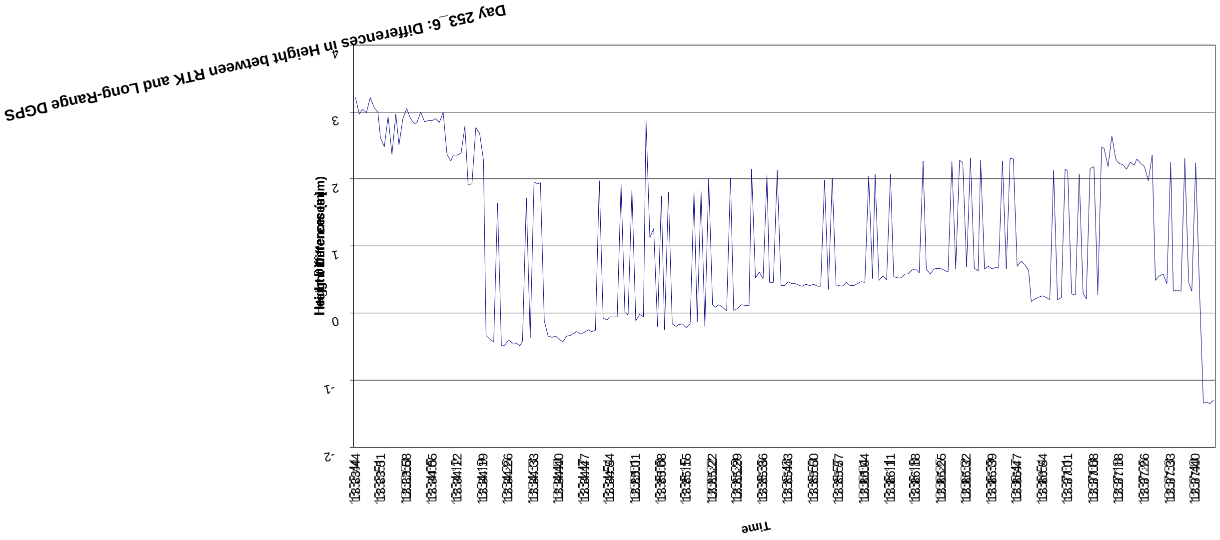


Figure 7. Differences in Height between RTK and Long-Range Code DGPS Positions as derived from the UCL Base Station, Day 253_6.

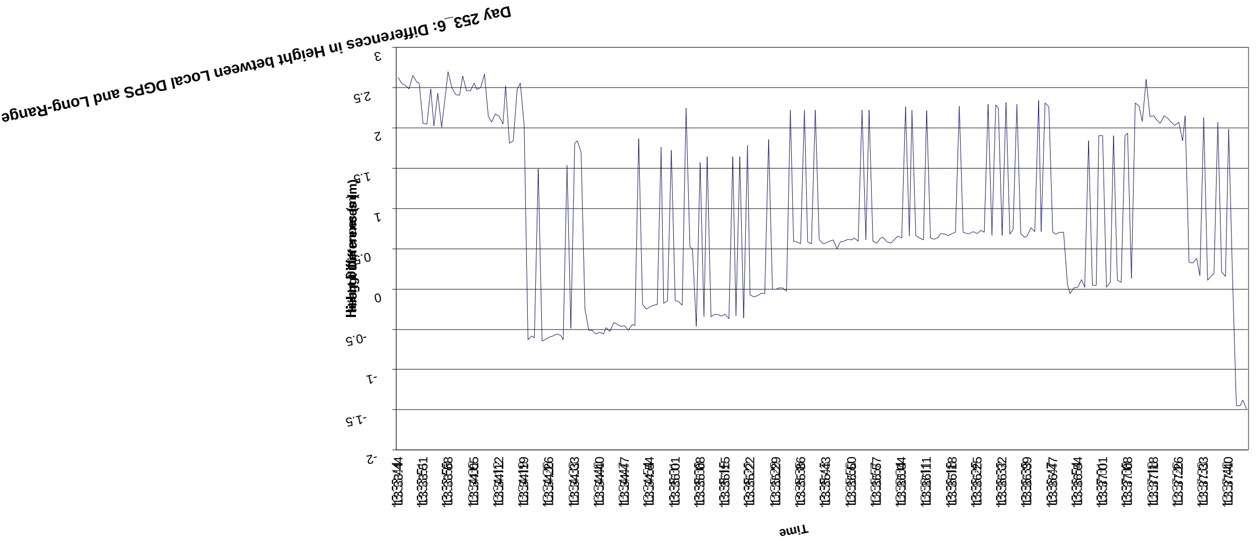


Figure 8. Differences in Height between Local and Long-Range Code DGPS Positions as derived from the Local and UCL Base Stations, Day 253_6.

For these plots, the mobile receiver was approximately 15 and 443 kilometres from the local and UCL reference stations respectively. The differences between the short and long-range DGPS positions as shown in Figure 8 can be mainly attributed to residual distance-dependent errors such as the ionosphere and the troposphere.

The sharp jumps seen in the time series of Figures 7 and 8 correspond to the difficulties encountered by the reference and mobile receivers in maintaining lock on common GPS satellites. This 'scatter' effect was especially noticeable on the longer length baselines whereby the satellite geometries relative to two antennas could be significantly different. It is also possible that some jumps are due to incorrect ambiguity estimation in the phase GPS solutions.

The typical accuracies achievable with short-range and long-range DGPS are shown in Table 1 as follows, for a subsection of the Day 253_6's trajectory. They have been determined relative to the 'truthing' RTK trajectory.

Day 253_6: RTK versus		**Mean (m)**	**Min (m)**	**Max (m)**	**St Dev (m)**
Short-Range DGPS	Plan	0.09	0.00	0.29	0.04
	Height	0.15	-0.53	0.86	0.19
	Vector	0.18	-0.53	0.91	0.19
Long-Range DGPS	Plan	1.84	0.52	4.54	0.80
	Height	0.97	-2.11	4.79	1.13
	Vector	2.08	-2.17	6.60	1.38

Table 1. Typical Accuracies of the Different GPS Processing Methodologies used in LANDMAP KGPS Processing, as derived from a subsection of Day 253_6's trajectory.

At the time of writing, the three profiles observed in Eire have not yet been fully analysed in terms of the accuracies achievable under different processing methodologies, as the co-ordinate conversion software requires some additional datum transformation parameters.

8 Deliverables to LANDMAP SAR processing team

For the purposes of truthing and verifying the LANDMAP IfSAR DEM and orthorectified imagery using GPS positions, it was necessary to perform the comparisons in the same reference frame. Using the programmes developed by UCL Positioning Research Group *[UCL PRG]*, the GPS co-ordinates were converted from WGS-84 into the UK National Grid for local reference purposes and then reduced them to WGS-84 geoid heights using the EGM96 geoid model. The results for each day's route were provided in the following three formats: -

1) WGS-84 position and WGS-84 ellipsoidal height

As output by Leica SKI-Pro

2) WGS-84 position and WGS-84 geoid heights using the EGM96 geoid

As calculated using WGS-84 ellipsoidal height and correction coefficients for the EGM96 Geoid -- ' WGS84 Geoid Height Computation' [*UCL PRG*]

3) UK National Grid position and WGS-84 geoid heights using the EGM96 geoid

As using WGS-84 position and the transformation parameters to UK National Grid -- 'WGS84 to UK National Grid Computation [*UCL PRG*]

9 Initial Results from GPS and IfSAR Profile Comparisons

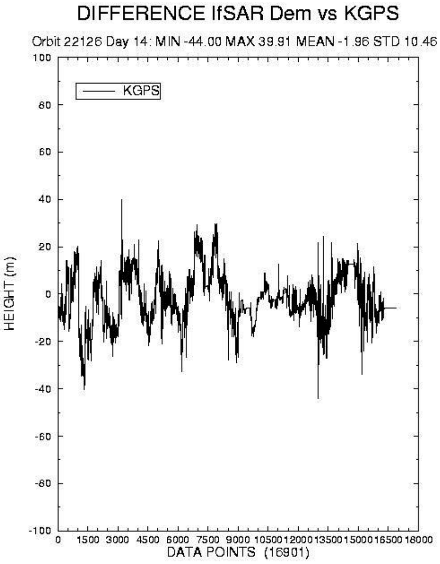
Table 2 below shows the status of the quality analysis of the first pass DEM [*Muller et al, 1999, 2000*] against the kinematic GPS (KGPS) profiles. The statistics refer to the difference in height between the first pass DEM and KGPS.

Number	KGPS ID	# Points	Min (m)	Max (m)	Mean (m)	Std Dev (m)
1	2	11331	-43.3	26.7	-9.4	11.8
2a	1	8164	-42.6	49.5	-3.1	13.8
2b	3	12368	-84.4	98.8	8.6	17.2
2c	14	6489	-91.7	37.3	3.0	9.4
3a	3	11174	-54.7	36.3	10.5	15.9
3b	14	16901	-44.0	39.9	-2.0	10.5
4a	4	9394	-75.0	172.3	-2.4	20.1
4b	5	8752	-41.2	71.1	-0.8	15.5
4c	6	5708	-72.8	16.8	-20.0	14.1
5a	5	5947	-48.3	54.6	-3.7	15.2
5b	6	11503	-118.3	60.0	-11.2	23.0
5c	13b	402	-45.9	76.3	5.2	23.7
6a	7	8358	-100.9	211.8	-7.5	27.9
7	13a	5543	-118.2	169.2	21.2	43.6
10	12	5318	-29.3	55.6	9.3	15.0
11a	11	15388	-57.39	56.6	0.2	19.6
11b	12	8456	-18.1	87.9	27.5	17.2

Table 2. Status of the Quality Analysis of the First Pass DEM against the KGPS Profiles.

It must be noted that these results have been derived from the first pass approximation of the IfSAR DEM, and that with further iterative processing, the final IfSAR-DEM product will be of higher quality. Two profiles observed in Scotland (day 8 and 9) are currently subject to some further investigation as to the long-range DGPS method hence their omission from Table 2.

Figure 9 illustrates the differences in height between the IfSAR generated DEM generated as compared to the 'truth' KGPS profile. The standard deviation of the 16,901 height differences for this profile is 10.5 metres (at the 68% confidence level).



Figures 9. Plot of Height Differences (in WGS-84) between the IfSAR DEM and KGPS profile for Day 14 [Day 263].

10 Conclusions

The methods of RTK-GPS and DGPS have been shown to be very capable of providing co-ordinated 3-D profiles to the required specification for validation purposes. Subsequently, the initial comparisons of the first pass approximation DEM, as derived from IfSAR observations, show a mean agreement to 8.5 metres and a mean standard deviation of 17.6 metres with the truth GPS profiles. With the further processing and analysis of the IfSAR datasets being undertaken at UCL, these results are expected to be improved.

11 References and Bibliography

DANA, P, (1999), '*Global Positioning System Overview*', http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

JAVAD Positioning Systems, http://www.topconps.com

LANDMAP, official website for the LANDMAP project, http://www.landmap.ac.uk

LEICA Geosystems, http://www.leica-geosystems.com

MORLEY, J. et al (2000), '*GIS techniques employed for the LANDMAP Project.*', paper in LANDMAP Special Session, RSS 2000, Leicester University.

MULLER, J.-P., et al. (1999), '*The LANDMAP project for the creation of multi-sensor geocoded and topographic map products for the British Isles based on ERS-tandem interferometry*'. Proc. Second International Workshop on ERS SAR Interferometry on "'Advancing ERS SAR Interferometry from Applications towards Operations'".10 – 12 November 1999, Palais des Congrès, Liège, Belgium. http://www.esa.int/fringe99/

MULLER, J.-P., et al. (2000), '*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*', paper in LANDMAP Special Session, RSS 2000, Leicester University.

PROCTOR, D., (1999), '*A Route Planner Validating the SAR-Generated DEMs*', MSc thesis, Department of Geomatic Engineering, University College London, August (1999).

POSITIONING RESEARCH GROUP, Department of Geomatic Engineering, University College London, http://www.ge.ucl.ac.uk/research/positioning