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SINGLE RECEIVER HEIGHTING USING THE ACTIVE STATIONS OF THE NATIONAL GPS NETWORK OF GREAT BRITAIN

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ABSTRACT

Precise height determination using a single GPS receiver is now possible, following the establishment of GPS networks that include active stations with typical separations of about 100km. A method is described to determine precise heights when using a single GPS receiver and active stations of the National GPS Network of Great Britain. From the computation of the heights of 188 GPS stations distributed across the British mainland, a precision of 1.5cm was attained. This was achieved using only 4 hours of dual frequency static GPS data, but with scientific GPS processing software to mitigate systematic error effects.

INTRODUCTION

National GPS networks with active stations are now commonplace in most countries of the developed world, for instance in Great Britain **[6]**, **[8]**, Sweden **[13]**, Switzerland **[22]** and the Netherlands **[26]**. Such networks typically include active stations, at a spacing of about 100km, with precisely determined coordinates and permanent, continuously operating, dual-frequency GPS receivers. These active stations provide a framework of control points that enable a user equipped with a single GPS receiver to obtain precise, homogeneous, geocentric coordinates, by processing the GPS data they have collected in combination with data from one or more active stations. If sufficient coordinate precision is attainable, such single receiver positioning presents itself as a tool for determining both plan coordinates and heights, which is a viable alternative to the use of conventional survey techniques. These include both traditional techniques, such as triangulation and levelling, and techniques that require the use of multiple GPS receivers.

Until the advent of active stations as part of national GPS networks, the precise coordinate determination of a GPS station required the occupation of at least one additional station of known coordinates, necessitating at least two GPS receivers. In Great Britain, this was achievable by occupying one or more ‘passive stations’ of the National GPS Network, whose coordinates were determined in the European Terrestrial Reference System 1989 at epoch 1989.00 (ETRS89 e89.00) through the European Reference Frame (EUREF) GB92 campaign **[7]** and its subsequent densification. However, the Ordnance Survey of Great Britain (OSGB) state that the use of passive stations will only allow the determination of ETRS89 e89.00 coordinates to an accuracy of 5 to 10 cm **[19]**. Alternatively, relative positioning could be carried out with respect to active stations that form part of the International GPS Service (IGS) global network. However, the relatively sparse distribution of IGS stations means that precise single receiver positioning using only IGS stations is a challenging task. This is mainly due to the long baselines involved, which reduce the number of common error sources that can be eliminated by using data differencing techniques.

In this paper, the computation of the precise coordinates of 188 GPS stations distributed across the British mainland is described, based on the use of a single GPS receiver and a network of 16 active stations. Particular emphasis is placed on the determination of heights, which presents the biggest challenge when using GPS over baselines of hundreds of kilometres. The GPS stations used were close to fundamental benchmarks (FBMs) maintained by the OSGB, who collected the data and contracted the University of Nottingham to compute ETRS89 e89.00 station coordinates as part of their current coordinate positioning policy **[19]**. Two sessions of 4 hours of GPS data were collected per ‘FBM station’ during January, February and March 1999, using a single GPS receiver. In every case, the GPS antenna height was altered and re-measured between the two sessions, enabling the height quality from 4 hours of GPS data to be assessed and antenna height blunders to be detected.

The data used in this paper pre-date the official launch (June 2000) of the 30 active stations now operated by OSGB as part of the National GPS Network **[6]**. Hence the first computational task was to determine the ETRS89 e89.00 coordinates of the 16 active stations that were operational at this time. Following this, ETRS89 e89.00 coordinates were estimated for the 188 FBM stations, by relative positioning with respect to a number of these active stations. In the GPS data processing, particular emphasis was placed on the mitigation of systematic error effects, notably due to satellite orbits, antenna phase centre variations, tropospheric delay, Earth body tides, ocean tide loading and integer ambiguity resolution.

A brief description of the network is first provided, followed by details of the coordination of the active stations. The single receiver positioning strategy is then described along with the methods used for quality assessment. Based on these, the results from the FBM stations are analysed and conclusions drawn on the quality of the heights obtained when using the strategy with only 4 hours of GPS data.

NETWORK DESCRIPTION

The distribution of the 16 active stations and the 188 FBM stations is shown in Figure 1. The active stations were selected to provide as even a distribution across the British mainland as possible. About 67% of the FBM stations were located within 100km of an active station, and 94% within 150km.

As stated previously, the data for the FBM stations were collected in early 1999, before the establishment of all 30 of the active stations now operated by OSGB as part of the National GPS Network. Hence for this study, the active stations were collated from the first eleven OSGB active stations, four stations that were operational for scientific purposes **[8]** and the Herstmonceux IGS station. All of the active stations selected were equipped with choke ring antennas and dual frequency, geodetic GPS receivers, that recorded data with a maximum of 30 seconds sampling interval and a minimum elevation cut-off angle of 15 degrees.

COORDINATION OF THE ACTIVE STATIONS

To determine the highest quality ETRS89 e89.00 coordinates for the active stations, all available data from January, February and March 1999 were collated. The processing strategy adopted followed the guidelines detailed in **[25]** for EUREF extension campaigns. Firstly, the coordinates of the active stations were computed in the International Terrestrial Reference System (ITRS) at the campaign observational epoch by processing with respect to IGS stations. Then the ITRS coordinates were transformed to ETRS89 e89.00 using the parameters detailed in **[2]**.

A series of discrete, 24 hour, daily network solutions were computed that incorporated all active reference stations at which data were available for the day considered, and the European IGS stations Kootwijk, Onsala, Villafranca and Wettzell.

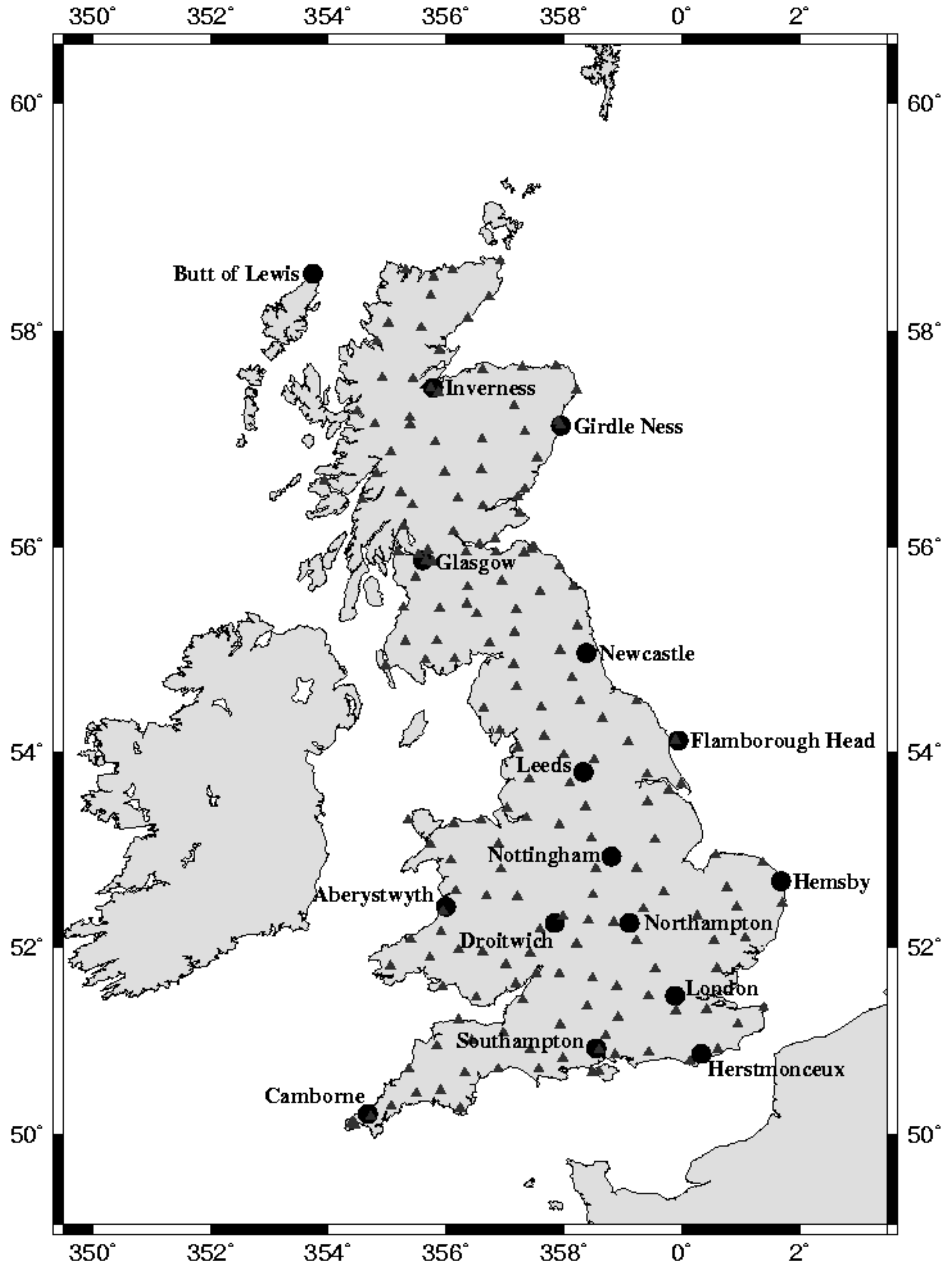

Fig. 1. The active stations (denoted by circles) and the FBM stations (denoted by triangles) distributed across the British mainland

These IGS stations were selected to provide good network geometry with respect to Great Britain, and also since they all have long established station coordinates and velocities, spanning many successive realisations of the ITRS. In addition, they can be considered to be ‘global’ IGS stations, ie their data are analysed independently by three IGS Analysis Centres, and they have often been either fixed or at least their data included in the computation of the IGS precise ephemerides. The complete network of stations used to determine the coordinates of the active stations is shown in Figure 2.

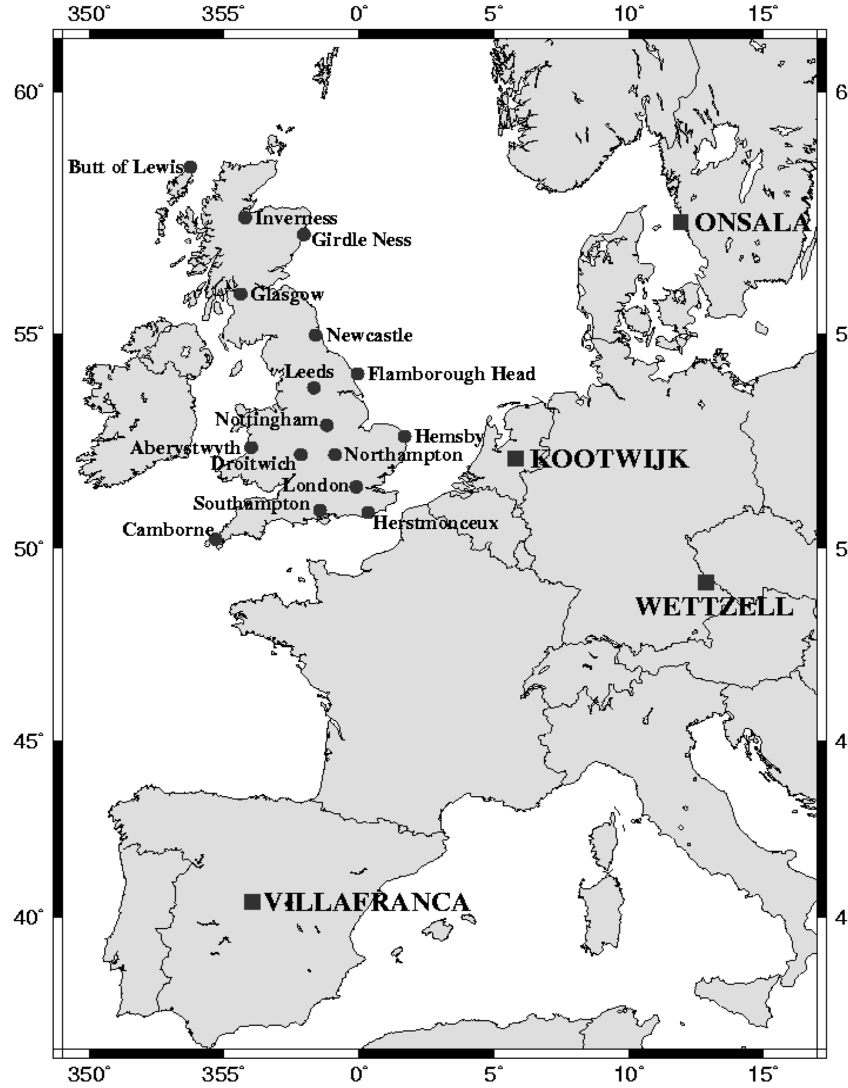

Fig. 2. Network of European IGS stations used (denoted as squares) used to determine the coordinates of the active stations (denoted as circles)

The GPS Analysis Software (GAS) **[24]** developed in-house at the University of Nottingham was used to compute each daily network solution, using the so-called 'ionospherically free' linear combination of the L1 and L2 carrier phase data. The data were equally weighted and an integer fixed solution was computed when possible. The mitigation of systematic error effects not eliminated by the double differencing techniques used in GAS was considered carefully.

Satellite orbital errors were mitigated by holding fixed the coordinates of the satellites obtained from the final IGS precise ephemeris, which has a quoted accuracy of 5cm **[12]**. Antenna phase centre variations were mitigated by the application of the IGS models **[20]**, although choke ring antennas were used as standard throughout the network.

Tropospheric delay effects were mitigated in each daily network solution by modelling the hydrostatic zenith delay (using the Saastamoinen model **[21]** with empirically generated meteorological data) and estimating, as an unknown, the residual (‘wet’) zenith delay at each station. To overcome the time varying nature of the troposphere, these were estimated as discrete parameters every 3 hours. In the formation of the observation equation ‘partials’, the hydrostatic and wet zenith tropospheric delays were mapped to the relevant station to satellite elevation angle using the Niell mapping function **[18]**.

Solid Earth tide effects were corrected according to IERS Standards **[16]**, whilst ocean tide loading effects were corrected for constituents M2, S2, N2, K2, K1, O1, P1, Q1, Mf and Mm, according to IERS Conventions **[17]**. Hence the ocean tide loading parameters were computed based on the purely hydrodynamic ocean tide model FES94 **[15]**, convolved with loading Green’s functions of the Earth’s rheology **[11]**.

In each daily network solution, the reference frame was defined by fixing the final IGS precise ephemeris and by highly constraining the ITRF96 epoch 1999.00 coordinates **[3]** of the four European IGS stations. This approach assumed negligible relative movement between the four European IGS stations over the short (three months) interval considered.

Table 1. *Data availability and coordinate repeatability for the active stations.*

Active Station	**No. of Days Data**	**Coordinate Repeatability (mm)**		
		North	**East**	**Height**
Aberystwyth	64	3	10	10
Butt of Lewis	11	3	12	7
Camborne	68	3	7	9
Droitwich	51	3	7	8
Flamborough Head	18	3	7	8
Girdle Ness	9	3	8	8
Glasgow	22	6	8	9
Hemsby	65	3	7	10
Herstmonceux	60	3	8	11
Inverness	29	5	7	10
Leeds	45	5	5	8
London	51	3	8	10
Newcastle	50	4	6	8
Northampton	51	3	5	7
Nottingham	77	3	6	8
Southampton	58	3	8	8

Once computed, all of the daily network solutions were combined to form a weighted mean solution, and hence the final coordinates for each active station. The *precision* of these coordinates was assessed by computing the root mean square of the differences between each daily solution and the weighted mean, ie the coordinate repeatability. These are listed in Table 1, together with the number of days of data used per active station.

It can be seen from Table 1 that, except for the East component for Butt of Lewis and the height component for Herstmonceux, the coordinate precisions obtained for the active stations were all less than or equal to 10mm in all three coordinate components.

To provide an assessment of the *accuracy* of the coordinates determined for the active stations, the estimated ITRS96 e99.00 coordinates for Herstmonceux were compared with the published ITRF96 e99.00 coordinates **[3]**. Coordinate differences in the North, East and height components of 2mm, 7mm and 3mm were obtained respectively. This suggests that the coordinate accuracies obtained for the active stations were also less than 10mm in all three coordinate components.

Having assessed the precision and the accuracy of the ITRS96 e99.00 coordinates for the active stations, these were transformed to ETRS89 e89.00.

SINGLE RECEIVER POSITIONING STRATEGY

For each FBM station, two sessions of 4 hours of GPS data were collected, using a single GPS receiver. ETRS89 e89.00 coordinates were estimated for each of the sessions as part of a *sessional solution*. These were computed by processing a 4-station network, incorporating radial baselines from the FBM station to three active stations. The first baseline was formed between the FBM station and the nearest active station, and the second baseline was formed between the FBM station and the second nearest active station. Lastly, a third baseline from the FBM station to the most distant active station was included. Only those active stations that had data for the same observation window as the FBM station were considered when selecting these baselines.

In a sessional solution, the ETRS89 e89.00 coordinates of the nearest active station were fixed, to enable the determination of the ETRS89 e89.00 coordinates of the FBM station. Here it is important to note that as part of the adopted strategy, the coordinates of the second nearest and the most distant active stations were not fixed. In fact, these two stations were included in the network for other reasons.

The role of the second nearest active station was to provide an indication of the likely quality of the coordinates of the FBM station. The estimated coordinates of the second nearest active station, based on 4 hours of common GPS data, were compared with the *known* ETRS89 e89.00 coordinates, computed as detailed in the previous section. This provided an initial indication of the likely quality of the coordinates for the FBM station, since the effect of any poor quality data at the FBM station would propagate directly to the estimated coordinates of the second nearest active station.

The role of the furthest active station was in the mitigation of tropospheric delay effects. The computations for each sessional solution were carried out using GAS. With the exception of tropospheric delay, all of the systematic errors were mitigated in the same way as described for the coordination of the active stations in the previous section. Due to the sheer quantity of data from the 188 FBM stations, and the variety of FBM station to nearest active station separations (distances ranged from 3km to 198km), a generic, automated strategy that would optimally mitigate tropospheric delay effects in all sessional solutions was required.

Whilst simple data differencing would be sufficient to mitigate tropospheric delay effects on the shorter baselines and in periods of little tropospheric activity, when different tropospheric characteristics arise at the two ends of a baseline this approach is inadequate. In these cases, it is normal to estimate tropospheric zenith delay parameters as part of the solution. In each sessional solution, the 'wet' tropospheric zenith delay was estimated, per station, as a first order polynomial **[9]** to account for both the spatial and temporal variability in tropospheric behaviour.

The inclusion of data from the most distant active station should enable increased decorrelation between per station parameters estimated via least squares, and should also enable 'absolute' values to be estimated for the tropospheric zenith delays, due to the significantly different mapping functions at longer station separations **[10]**. Using a strategy in which absolute, rather than just relative tropospheric zenith delays are estimated, increases the scope for quality control. Such increased confidence in tropospheric delay mitigation is valuable, since a tropospheric zenith delay error manifests itself approximately threefold to a station height error **[4]**.

QUALITY ASSESSMENT OF THE FBM STATION COORDINATES

One estimate for the *precision* of the FBM station coordinates could be obtained from the variance-covariance matrices. However, it is well known that such formal errors derived from GPS data processing are over-optimistic. To overcome this, it is suggested in **[14]** to scale the elements of the variance-covariance matrix by a factor between 3 and 5. In this study, the coordinate formal errors were scaled by a factor of 4.

Since only two sessional solutions were processed for each FBM station the computation of coordinate repeatabilities (successfully used to assess the precision of the estimated coordinates of the active stations) could not be used to assess the precision of the FBM station coordinates. Instead, a direct comparison of the coordinates estimated in the two sessional solutions was used as an indication of coordinate precision.

Focusing on the height component, the F-test (2-tail test) was used to determine whether the height estimates from the two sessional solutions differed significantly. The global congruency test outlined in **[5]** was utilised, in which the difference in the two height estimates dh and its variance σ_{dh}^2 are formed based on the height estimates $h1$ and $h2$, with corresponding variances σ_{h1}^2 and σ_{h2}^2 :

$$dh = h1 - h2 \tag{1}$$

$$\sigma_{dh}^2 = \sigma_{h1}^2 + \sigma_{h2}^2 \tag{2}$$

where it is assumed that $h1$ and $h2$ are uncorrelated.

The global congruency test's hypothesis is that the expectation, $E\{dh\} = 0$, which is tested using the test statistic T:

$$T = (dh/\sigma_{dh})^2 \Big/ (r.\sigma_0^2) \tag{3}$$

where r is the rank of σ_{dh} and σ_0^2 is the unit variance. In this case, r is equal to unity for a single point and σ_0^2 is assumed equal to unity. Hence, the test statistic T becomes:

$$T = (dh/\sigma_{dh})^2 \tag{4}$$

This was tested against the F-test, ie $F = f(dh, m-n, \alpha)$, where $m-n$ are the degrees of freedom and α is the significance level. In each sessional solution used to compute the FBM station coordinates, the 4-station network involved approximately 80 unknown parameters and several thousand GPS observations. Although not all of these observations were independent, the number of degrees of freedom was doubtless greater than 100, hence it can be assumed that $m-n$ tended to infinity for the purposes of this test. Therefore choosing a 5% significance level:

$$F(1, \infty, 5\%) = 3.84 \tag{5}$$

For a 2-tailed test, $F = 7.68$. Consequently, for the null hypothesis to be accepted then $T < 7.68$. Where the null hypothesis was rejected for an FBM station, the heights obtained from the two sessional solutions were deemed to be significantly different.

As previously stated, the role of the second nearest active station was to provide an indication of the likely quality of the coordinates of the FBM station. To provide an assessment of the *accuracy* of the coordinates determined for an FBM station, the coordinates estimated for the second nearest active station, based on 4 hours of GPS data, were compared with the values based on many days of data (as detailed in the previous section). In the case of the height component, this direct comparison of estimated heights with 'truth' heights at the second nearest active station was taken as an indication of the *accuracy* of the FBM station heights estimated in the sessional solution.

RESULTS FOR THE FBM STATIONS

Using the single receiver positioning strategy, ETRS89 e89.00 coordinates were estimated for the 188 FBM stations. In this section, the quality of coordinates determined using the strategy is assessed based on the criteria outlined in the previous section.

Outlier Detection

Of the 188 FBM stations, ten were found to have significantly different height estimates from their two sessional solutions. Table 2 presents the quality assessment for these ten stations in terms of the height precisions for both sessions (σ_{h1} and σ_{h2}), based on the height formal errors scaled by a factor of 4; differences for the North (*dN*) and East (*dE*) coordinate components; height differences (*dh*) and corresponding standard errors (σ_{dh}); and estimates of height accuracy for both sessions, based on the height results for the second nearest active station.

From Table 2, the FBM stations denoted as outliers 9 and 10 have the lowest height difference (about 5cm) and would simply appear to be statistical outliers. For each of the other eight FBM stations deemed to be outliers, the height precision and accuracy can be used to provide indications of the problems that may have occurred during the field observations.

Table 2. *Quality assessment for the ten FBM stations deemed to be outliers.*

Outlier Number	Height Precisions		Plan Differences		Height Differences		Height Accuracies	
	σ_{h1} (cm)	σ_{h2} (cm)	*dN* (cm)	*dE* (cm)	*dh* (cm)	σ_{dh} (cm)	Sess 1 (cm)	Sess 2 (cm)
1	2.0	1.6	1.5	0.8	11.1	2.4	2.4	0.9
2	1.6	0.8	0.9	1.4	38.3	1.8	0.2	1.1
3	1.2	1.2	0.7	0.2	5.7	1.8	3.4	1.3
4	1.2	2.0	1.0	0.1	7.0	2.3	0.3	1.0
5	1.6	4.4	1.4	11.5	11.8	4.5	2.4	4.0
6	1.2	1.2	1.4	0.7	9.7	1.7	4.2	1.3
7	1.2	1.2	0.9	0.4	26.9	1.5	3.2	0.7
8	4.4	5.2	0.1	9.9	25.3	6.8	11.3	17.7
9	0.8	1.2	0.4	0.4	4.7	1.6	1.7	1.0
10	0.8	1.2	0.5	0.3	5.0	1.4	1.9	0.7

Firstly considering outlier 8, the large East differences of 9.9cm, the large height difference of 25.3cm and the height accuracies of 11.3cm and 17.7cm suggest that there may have been a problem with the GPS data at this station.

With outlier 1, the plan differences were only 1.5 and 0.8cm and the height accuracies were only 2.4cm and 0.9cm. However, the height difference was 11.1cm. This suggests that the data at the FBM station and the nearest two active stations were of an acceptable quality, since any poor data at these stations would degrade the estimated coordinates of the second nearest active station. In this case, it is most likely that an antenna height measurement error occurred at the FBM station in one or both of the 4 hour sessions. The same assessment can be made for outliers 2, 4, 6 and 7.

In a similar way, the large height difference of 11.8cm obtained for outlier 5, coupled with height accuracies of 2.4 and 4.0cm, could suggest an antenna height measurement problem at this station. However, considering the large East difference of 11.5cm, the complete antenna set up may be in question.

The assessment for outlier 3 is interesting, since the height difference is lower (5.7cm), but is coupled with height accuracies of 3.4cm and 1.3cm. This may be an indication that the tropospheric delay was not successfully mitigated, which would be explained by the fact that this station was coordinated using only the nearest and second nearest active stations, due to encountering very noisy data during the pre-processing at all of the active stations.

Coordinate Quality

Of the 188 FBM stations, 178 were found to have acceptable height estimates in their two sessional solutions. The coordinate qualities of these stations are summarised in Table 3 which gives percentile values for all of the quality parameters, including the coordinate differences between the two sessional solutions; the height precisions for both sessions (σ_{h1} and σ_{h2}), based on values taken from the variance-covariance matrix and scaled by a factor of 4; and estimates of height accuracy for both sessions, based on the height results for the second nearest active station. Table 3 also shows the maximum distance from the FBM station to the nearest active station for each percentile.

Table 3. *Quality assessment for 178 FBM stations, expressed as percentiles.*

Percentile	Distance (km)	Coordinate Differences			Session 1		Session 2	
		dN (cm)	dE (cm)	dh (cm)	σ_{h1} (cm)	Height accuracy (cm)	σ_{h2} (cm)	Height accuracy (cm)
50th	80	0.4	0.3	1.1	1.2	1.1	1.2	1.5
60th	90	0.5	0.4	1.3	1.2	1.5	1.2	1.9
70th	105	0.5	0.5	1.6	1.2	1.9	1.6	2.2
80th	120	0.7	0.6	2.6	1.2	2.5	1.6	2.9
90th	145	0.9	0.8	3.3	1.2	4.2	1.6	3.9
95th	165	1.1	1.2	4.1	1.6	5.7	2.0	5.0
100th	200	2.2	3.6	5.8	2.4	8.4	4.8	9.1

From Table 3, it can be seen that 70% of the FBM stations were located within 105km of the nearest active station that was fixed in the sessional solutions. The subsequent height precision obtained at 70% of the FBM stations is about 1.5cm, as defined by the scaled height formal errors and the differences in height between the two sessional solutions. This encouraging height quality is substantiated by the fact that the height accuracy estimates for 70% of the FBM stations are less than about 2cm.

CONCLUSIONS AND DISCUSSION

It has been shown that using 4 hours of data collected with a single GPS receiver and data from active stations that form part of the National GPS Network of Great Britain, it is possible to determine ellipsoidal heights to a precision and accuracy of about 1.5cm.

The height estimates and an assessment of their quality were obtained by using data from three active stations. These included the nearest active station, which was fixed in the solution, the second nearest active station, to enable an assessment of coordinate accuracy, and the furthest active station, to assist in the mitigation of tropospheric delay and ensure the highest quality height determination.

The single receiver positioning strategy described could be used by surveyors to obtain similar high quality height estimates in any region where networks of active stations exist at similar separations to those in Great Britain.

However, it should be noted that the data used in this study were recorded using top-of-the-range geodetic, dual frequency GPS receivers and choke ring antennas at both the FBM stations and the active stations. This avoided the mixing of antenna types in any of the solutions, which can cause a significant degradation in height if sufficient quality models for antenna phase centre variations are not applied in the processing software (eg **[23]**). In addition, the scientific GPS processing software used throughout this study enabled the estimation of time varying tropospheric zenith delay parameters, the modelling of ocean tide loading effects and the correct decorrelation of observations in a simultaneous multi-baseline network solution, as detailed in **[1]**. Such features are not necessarily present in all commercial GPS processing softwares, which would result in a degradation in height determination.

The above statement should, therefore, be extended to say that the single receiver positioning strategy described could be used by surveyors to obtain similar high quality height estimates in any region where networks of active stations exist at similar separations to those in Great Britain, and where an appropriate GPS processing software package is used.

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