





FURTHER TESTING OF COMMERCIAL NETWORK RTK GNSS SERVICES IN GREAT BRITAIN (NETRTK-2)

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1 Introduction

An earlier study of Network RTK performance conducted by Newcastle University in 2008, "NetRTK-1", focused mainly on the performance of Network RTK towards the geographic and topographic extremities of the GB network, with other factors given less prominence. The goals of this second Network RTK GNSS study (NetRTK-2) were to analyse, for both GPS-only and GPS+GLONASS positioning (Goal G1), the performance of the three commercial Network RTK services available in Great Britain, namely Leica SmartNet, Topcon TopNet+ and Trimble VRS NOW (Goal G2). The SmartNet service is usually based on the Master Auxiliary Concept (MAC), but also has the capability to operate in Virtual Reference Station (VRS) mode, whilst TopNet+ and VRS NOW operate using the VRS positioning concept. Edwards et al (2010) and references therein provide details of the two concepts. In this study, consideration was given to both static (i.e. collection of Network RTK positions when the receiver is stationary) and rover modes i.e. single epoch positioning to simulate a detail survey (Goal G3), and the impact of base station failures, e.g. for users on the edge of the network (Goal G4). It was required to determine the accuracies (including whether manufacturer-reported figures are reliable) and repeatabilities attainable, and compare them with satellite availability and PDOP for all three systems in these positioning and survey modes, under each of the following specific conditions:

- (a) Within the confines of the OS Net® base station network, in a variety of environmental conditions (i.e. ranging from open sky to densely urban) and with at least three visits to each survey control station at different times of day (Requirement R1a).
 - (b) For at least two survey stations, the performance of each of the SmartNet, TopNet+ and VRS NOW services must be assessed using receivers from each of Leica, Topcon and Trimble, to demonstrate compatibility (**Requirement R1b**).
- 2 50 km outside the boundaries of the OS Net base station network, but in open sky conditions only (**Requirement R2**).
- 3 Within the confinements of the OS Net base station network, but when a local base station failed (open sky conditions) (**Requirement R3**).

This report details how the above requirements were met and the project goals fulfilled, including the establishment of an appropriate test network (incorporating 22 control stations sampling a range of environmental conditions), the tests carried out and resulting analysis. Finally conclusions and recommendations for best practice are included.

Throughout this report, the following terminologies are used:

Survey point: Fixed ground marker such as a road nail or Feno marker, over which a tripod or detail pole may be unambiguously and repeatably placed / set up.

Environment category: Survey points are placed into four categories (easy, moderate, difficult and severe), according to their locations' environmental conditions (skyline obstructions, building facades and ground reflectors likely to cause multipath, etc.) and hence suitability for high quality GNSS positioning.

Test (sub-) network: A set of survey points, comprising either a single environment category (test sub-network) or all environment categories (test network).

Survey area: An area approximately 1 km2 in extent, incorporating the test network and hence survey points of all environment categories.

Static (stationary) mode: Denotes the collection of Network RTK solutions every second but whilst the antenna is mounted on a stationary ('static') tripod. Note that this is not the same as conventional static GPS for the establishment of control survey points, in which long spans of carrier phase data would be collected and post-processed (as was done in section 2.2.1 for the providing the truth coordinates).



The control survey fieldwork was carried out from 8-22 August 2011, with the Network RTK tests themselves carried out from 23 August to 14 September 2011. Unless otherwise stated, 'Leica' Network RTK observations/results denote the use of the SmartNet service with a Leica GS10 receiver and AS10 antenna; 'Topcon' observations/ results denote the use of the TopNet+ service with a Topcon HiPer II receiver/antenna; 'Trimble' observations/results denote the use of the VRSNow service with a Trimble R8 receiver/antenna.

2 Survey test network

2.1 Network design and establishment

To meet the four goals and two requirements, a 22 point test network was established in a survey area of approximately 1 km2 in and around Riverside Park, Chester-le-Street, County Durham, UK (approximate National Grid coordinates 428300 mE, 550300 mN), that incorporated a variety of environmental conditions, from open sky to urban canyon (meeting Requirement R1a). This enabled the effects to be assessed of different survey conditions on positional quality (Requirement R1a) that could be encountered in realworld GNSS surveying, as well as the impact of GPS+GLONASS over GPS-only (Goal G1). The 22 point network shown in Figure 1 comprised four sub-networks of 5-6 points each (marked by road nails or drilled holes in existing substantial, permanent monuments such as inspection cover rims), grouped according to the environmental category represented (easy, moderate, difficult or severe). Examples of each point category are shown in Figure 2 and defined broadly as:

- i) **Easy:** Points with an open sky view in all directions, and no nearby buildings or extensive paved/water surfaces likely to cause multipath.
- ii) Moderate: Points with a fairly open sky view, perhaps with tree-line obstructions imposing an elevation mask up to 20° in some directions, and/or extensive nearby paved or water surfaces to the south, giving rise to limited ground multipath.
- iii) Difficult: Points with sky view restricted to elevations >25° in one or two directions by low/medium rise buildings within 10-30 m in plan, likely to raise PDOP and cause some multipath, or partially under tree canopy.
- Severe: Points with sky view restricted to elevations >30° in three or more directions by high rise buildings within 20-40 m in plan, likely to increase PDOP considerably and cause extreme multipath.





Figure 1. Google Earth image showing distribution of survey points around Chester-le-Street Riverside Park survey area. Points are labelled according to the environment category: red = E (easy), purple = M (moderate), yellow = D (difficult), orange = S (severe).



Figure 2. Sample of survey points, denoted by the rucksack's location, in (anti-clockwise from top left) 'easy', 'moderate', 'difficult' and 'severe' category survey environments.



The Chester-le-Street location ensured that the tests were carried out within the confines of the OS Net base station network (i.e. the survey area was bounded on all sides by NCAS, MORO, CARL, WEAR, RICM, LOFT), and around 15 km from the nearest base station (NCAS). This meant that our tests encompassed a user-to-nearest base station distance of 15-20 km, typical of that most commonly experienced by field surveyors, as derived by analysing a grid of land locations in Great Britain (cells separated by 30" in latitude and longitude). Figure 3a indicates that the median distance from the nearest OS Net base station is 22 km (inter-quartile range 15-29 km). However, for the 6% of cells designated as "urban" (Figure 3b, where the majority of survey activity is likely to take place, and the requirement for precision is likely to be higher), the median distance is 17 km (inter-quartile range 1024 km). Further filtering to consider only the larger conurbations (just under 2% of the total area), reduces the median distance to 12 km (range 7-18 km; Figure 3a). We therefore judge that a distance of 15-20 km from the nearest OS Net base station is most representative of actual commonly-experienced field conditions.



Figure 3a. Cumulative histogram of distances between grid cells in Great Britain and the nearest OS Net base station (black curve). Note that the distance axis is logarithmic. Yellow through red curves show the cumulative histograms for urban cells only, for increasing concentrations of urbanisation.





Figure 3b. Major urban areas in Great Britain shaded by their distances from the nearest OS Net base station (shown as blue circles).

2.2 Control point observation and analysis

To enable the accuracy of the coordinates computed using the three Network RTK services to be assessed, truth coordinates of all 22 points in the test network were computed, using GPS for the category easy and moderate sub-network points and terrestrial network survey for the environment category difficult and severe sub-network points. Due to restricted sky visibility and multipath, GPS was not considered suitable for the determination of truth coordinates for most of the difficult and severe environment category survey points, and hence traditional total station distances, horizontal angles and spirit levelling were used instead for these points. This necessitated the computation of a 7 parameter conformal transformation, in order to relate the ETRF89 geocentric coordinates obtained for those points coordinated using GPS, with the local planar system coordinates obtained for those points coordinated using terrestrial observations (for this purpose, the entire network was observed using horizontal angles, distances and spirit levelling). Thus the coordinates of all points coordinates.



2.2.1 Static GPS observation and analysis

To accomplish the GPS-based truthing, a local GPS base station was established within the 1 km2 survey area (at point E1), which was occupied for 8 hours on four different days using a Leica GS15 GNSS receiver/antenna. Two Leica GX1230 receivers with LEIAX1202 antennas were then deployed in parallel to occupy the remaining category easy and moderate points (plus two category difficult points) at least three times for 1 hour, as detailed in Table 1. Note that point E6 was only coordinated using terrestrial observations.

Survey point	Thu 11 Aug 2011 (DOY 223)	Fri 12 Aug 2011 (DOY 224)	Mon 15 Aug 2011 (DOY 227)	Tue 16 Aug 2011 (DOY 228)
E1	1x8 hr	1x8 hr	1x8 hr	1x8 hr
E2	1x1 hr		1x1 hr	1x1 hr
E3	1x1 hr		1x1 hr	1x1 hr
E4	1x1 hr	1x1 hr	1x1 hr	
M1	1x1 hr	2x1 hr	1x1 hr	
M2	1x1 hr	1x1 hr	1x1 hr	1x1 hr
M3	1x1 hr		2x1 hr	
M5	1x1 hr	1x1 hr	1x1 hr	
M7			1x1 hr	2x1 hr
M8		1x1 hr	1x1 hr	1x1 hr
D3	1x1 hr		1x1 hr	1x1 hr
D4	1x1 hr		1x1 hr	1x1 hr

Table 1. GPS control observation schedule, showing number of 1 hour sessions observed on which date

The GAMIT scientific software (Herring et al, 2010) was used to process the control GPS data, first determining ETRF89 coordinates for the local base station E1, by processing relative to the nearest five OS Net base stations NCAS, LOFT, MORO, RICM and WEAR, whose published ETRF89 coordinates were held fixed, together with final IGS orbits and clocks. Dual frequency observations were always used, with an elevation cut-off angle of 10°, applying the IGS models for absolute satellite and receiver phase centre variations, the IERS2003 Earth tide model, TPXO7.2-based ocean tide loading corrections, and estimating zenith tropospheric delays every 2 hours, together with one set of gradients, and using the GMF mapping function. An elevation dependent reweighting of the observations based on residuals from an initial solution was adopted. ETRF89 coordinates for the remaining 11 category easy/moderate/difficult points were then coordinated relative to this local base station, using the same GAMIT processing options, but due to the very short (< 1 km baselines) only L1 data were used and no tropospheric delays were estimated. The sessional solutions were then combined using the GAMIT ancillary module GLOBK, to produce a weighted mean set of coordinates, which had a precision of around 2-3 mm in plan and 5 mm in height.

2.2.2 Terrestrial observation and analysis

3-d traversing was undertaken for the entire 22 point network, plus an additional (unused) point S8 and the inclusion of an additional reference object point for orientation (the flag pole on Lumley Castle, approximately 800 m north-east of the survey area, was adopted). The network was observed as three primary traverses, namely E2-E3-M8-M1-D1-S1-S2-S9-S7-E4-E1-E2; E2-E1-E4-M5-E6-S8-M2-E2; E2-D2-M7-D5-D6-M3-D3-S6-D4-M1-M8-E3-E2 (Figure 4). At least four rounds of horizontal and vertical angles were observed at each point, and additional cross braces were observed wherever possible, which led to horizontal angular misclosures of 18", 25" and 12" respectively for the three primary traverses, with corresponding proportional misclosures of 1:30,000, 1:29,000 and 1:41,000 respectively. The corresponding 3-d traverse height misclosures were 6, 3 and 6 mm respectively, but spirit levelling was



also undertaken around the entire network, resulting in height misclosures for the three primary traverse loops of 0, 0 and 3 mm respectively. All horizontal angles and distances from the observed traverses, plus the bracing observations and the spirit levelled height differences, were then input to a 3-d least squares network adjustment to determine the final terrestrial local system planar ENU coordinates for the test network, with the resulting error ellipses shown in Figure 4, drawn from typical Easting and Northing standard deviations of 3-8 mm and 3-11 mm respectively. The height standard deviations were around 0.5 mm. These were obtained after the unit variance for the network adjustment equalled 1.1, by assigning observational precisions (weights) of 10" to the mean horizontal angles from the four rounds, 5 mm to the horizontal total station distances, and 0.5 mm to the levelled height differences.





2.2.3 GPS to terrestrial coordinate transformation

Since the GPS-based coordinates for the 12 points analysed using GAMIT were in ETRF89, and the coordinates for all 22 points from the analysis of the terrestrial observation data were in a local ENU planar system, a least squares 7 parameter conformal transformation was undertaken, using the common 12 points with both ETRF89 and local ENU coordinates. The RMS of the residuals from the least squares transformation computation was 7 mm, demonstrating the high level of consistency of both methods of survey point coordination. Applying these transformation parameters to the 22 points with local planar system ENU coordinates led to the 'truth' ETRF89 coordinates for all points of the test network, with which the Network RTK coordinates could be directly compared.



3 Environmental effect tests

To assess the performance of the three Network RTK services ('service providers') in a range of environmental conditions, our 22 point test network was occupied both in rover (i.e. detailing) single-epoch mode, and when the antennas were stationary (termed 'static'). For these scenarios (and all subsequent test scenarios), the tests were carried out twice: first using GPS-only, and then repeated at the same sidereal time the next day i.e. 86154 s later (as found to be optimal by Ragheb et al (2009)) using GPS+GLONASS. This ensured that the GPS satellite geometry was the same when assessing the impact of the additional GLONASS observations. On presenting the results for these (and all subsequent tests), only integer-fixed solutions with manufacturer-reported CQ values of less than 50 mm in plan and 100 mm in height were used, together with a PDOP of less than 3 to ensure good satellite geometry and solution robustness in harsh environments such as urban canyons, as adopted by Edwards et al (2008). However, for the environment tests, results when using a PDOP filter of 5 are also shown, to more closely align with a typical manufacturer suggested mask. The availability statistics presented (for both PDOP masks) therefore represent the percentage of filtered solutions obtained in relation to the original number of observations expected for the defined experiment and its time window.

3.1 Environmental effects: Rover occupation

Using a roving detail pole to obtain a single epoch of data per occupation, each of the test network's 22 points was occupied for both GPS-only and GPS+GLONASS, per service provider. For each service provider, the points were occupied in quick succession, and each environment category sub-network was occupied in turn, such that the 5-6 points per category were occupied within a few minutes of each other and hence geometry effects are similar. This was then repeated three times later in the day (at different satellite geometry), and then at the same sidereal times the next day for GPS+GLONASS. The RMS of the coordinate differences obtained between the Network RTK solution and the truth (i.e. accuracy) from each point's four occupations was computed per provider for each of GPS-only and GPS+GLONASS, with the median RMS differences per environment category listed in Table 2 and presented graphically in Figure 5.

It can be seen from Table 2 and Figure 5 that the results from all three services are approximately commensurate when the solutions pass the three filters adopted, with GPS-only horizontal accuracies of around 15 mm and height accuracies of around 20-30 mm, with small accuracy improvements arising from the addition of GLONASS. For the solutions that passed all CQ and PDOP filters, the RMS accuracies obtained for the different environment categories do not noticeably degrade as the environment becomes more severe (as perhaps might be expected), but the solution availability does. All three providers exhibit a gradual reduction in solution availability from easy through to severe, for GPS-only. Encouragingly, solution availability for each category improves considerably when GLONASS observations are also used.



- **Table 2.** Environmental effects, rover mode results for GPS-only and GPS+GLONASS solutions. Median RMS accuracies per coordinate component for Leica, Topcon and Trimble listed, for each of the easy (E), moderate (M), difficult (D) and severe (S) categories, based on four separate single-epoch occupations per service provider of each of the 5-6 points per category. Median percentage solution availabilities (Av) are also shown, after CQ and PDOP filtering. All RMS values are given in mm. The results are presented twice, with (a) and (b) denoting the application of PDOP filters of 3 and 5, respectively.
- (a) PDOP filter of 3

	Leica					Topcon				Trimble			
	N	E	υ	Av	N	Е	υ	Av	N	E	υ	Av	
GPS-	only												
Е	13.4	16.7	16.9	75	19.4	11.1	28.3	95	16.9	9.8	17.7	100	
м	21.9	13.1	18.3	66	17.6	13.9	29.1	87	16.6	8.7	25.2	70	
D	8.6	15.1	19.4	25	22.1	18.7	30.6	41	10.7	18.4	21.0	66	
S	4.2	6.3	23.9	20	22.9	9.6	32.2	30	12.9	18.7	24.1	45	
GPS+	GLONASS												
Е	13.7	13.7	13.4	95	12.7	12.8	13.0	75	8.9	15.0	9.6	95	
м	9.8	11.7	12.3	95	9.7	12.2	18.7	66	10.6	15.4	14.4	100	
D	11.1	9.3	19.6	87	15.8	11.2	14.1	70	14.2	14.8	15.3	100	
S	13.3	7.2	11.0	60	33.0	22.3	23.9	55	37.4	9.8	30.7	85	

(b) PDOP filter of 5

		Leic	a			То	pcon	Trimble				
	N	E	υ	Av	N	Е	U	Av	N	Е	U	Av
GPS-	only											
Е	14.2	18.4	16.9	85	19.4	11.1	28.3	100	16.9	9.8	17.7	100
м	20.0	12.4	18.5	83	17.6	13.9	29.1	87	16.2	8.1	23.9	91
D	15.3	14.2	27.9	54	22.4	16.6	40.7	58	12.2	17.1	20.6	91
s	4.1	7.0	25.5	25	22.9	9.6	32.2	30	35.6	20.1	25.2	60
GPS+	GLONASS											
Е	13.7	13.7	13.4	95	12.7	12.8	13.0	75	8.9	15.0	9.6	95
м	9.8	11.7	12.3	95	9.7	12.2	18.7	66	10.6	15.4	14.4	100
D	10.8	10.2	19.6	91	15.8	11.2	14.1	70	14.2	14.8	15.3	100
s	13.8	14.9	16.4	70	19.9	34.5	64.4	65	37.4	9.8	30.7	95





Figure 5. Environmental effects, rover mode results for GPS-only (left) and GPS+GLONASS (right) solutions. Median RMS accuracies per coordinate component for Leica (blue), Topcon (green) and Trimble (red), for each of the easy (E), moderate (M), difficult (D) and severe (S) categories, based on four separate single-epoch occupations per service provider of each of the 5-6 points per category. Median percentage solution availabilities after CQ and PDOP filtering are also shown. The results are presented twice, with (a) and (b) denoting the application of PDOP filters of 3 and 5, respectively.



3.2 Environmental effects: Stationary ('static') occupation

For all tasks that incorporated the collection of data from a stationary ('static') antenna, a tripod was set up over the point with the three antennas mounted on the same bar used by Edwards et al (2008, 2010) as shown in Figure 6, such that the different service providers could be directly compared. With the aid of a total station, the bar was orientated to an adjacent network point. Given that the bearing from occupied to adjacent point was known, together with the antennas being 250 mm apart, East and North coordinate differences could be readily computed. Hence this offset was transformed and applied to the Topcon and Trimble ETRF89 reported coordinates, so to be directly comparable with the ground marker truth coordinates. 45 mins of single epoch Network RTK observations were collected for GPS-only on one day, then repeated with GPS+GLONASS the next. Two points per category were occupied, and the RMS coordinate differences between the Network RTK based coordinates and the truth coordinates computed (i.e. accuracies), per coordinate component, with the results listed in Table 3 and shown in Figure 7. Note that for a couple of points, some of the RMS differences are slightly greater than denoted on the common bar chart scale used throughout all figures to enable direct comparisons between each test. To provide an indication of repeatability attainable, as well as accuracy, in Table 4 and Figure 8 the coordinate standard deviations per point are provided.



Figure 6. Bar used for mounting of antennas for all 'static' tests.



Table 3. Environmental effects, 'static' mode results for GPS-only and GPS+GLONASS solutions. RMS accuracies per coordinate component per service provider are given per point occupied (two points from each of the easy (E), moderate (M), difficult (D) and severe (S) categories). All solutions have been CQ and PDOP filtered, with availabilities (Av) denoting the proportion passing all filters and hence included in the RMS statistics. -999.9 denotes no observations passed the CQ and DOP filters (although for S7 Topcon GPS+GLONASS, it was due to a data transfer human issue). The results are presented twice, for the application of PDOP filters of 3 and 5, respectively.

(a) PDOP filter of 3

	Leica					Topcon				Trimble			
	N	Ε	U	Av	N	E	U	Av	N	E	U	Av	
GPS-or	nly												
E2	31.1	22.0	45.2	99	29.2	23.4	40.1	78	16.8	12.2	29.4	98	
E4	27.1	19.0	46.3	53	37.8	16.9	45.4	56	18.6	13.3	15.6	70	
M1	19.5	10.2	21.9	77	27.2	14.0	29.0	53	15.5	9.2	21.2	73	
M5	20.1	10.9	29.8	100	24.7	10.4	33.9	85	27.1	12.7	39.2	99	
D1	16.9	11.8	53.0	100	28.6	29.7	69.1	58	18.6	20.0	50.7	98	
D4	24.8	14.3	34.0	88	40.8	18.4	37.5	98	27.6	26.0	40.8	77	
S2	24.2	36.5	13.0	2	30.5	20.2	22.0	26	-999.9	-999.9	-999.9	0	
s7	16.3	19.6	35.7	47	31.4	14.0	26.7	73	11.6	12.2	33.8	9	
GPS+GI	LONASS												
E2	20.8	19.8	26.6	91	15.2	24.2	22.9	84	7.5	15.3	17.9	89	
E4	12.6	9.6	15.3	100	13.5	12.4	19.3	68	11.7	9.5	14.0	91	
M1	21.0	14.2	55.4	92	14.3	11.8	54.4	99	11.7	11.9	41.6	99	
M5	25.6	10.6	29.4	100	16.3	9.8	36.0	73	24.3	9.0	31.5	98	
D1	21.4	24.6	42.5	97	27.9	27.5	55.5	49	28.9	30.8	40.0	97	
D4	12.1	12.8	45.5	85	9.7	15.4	49.8	86	11.1	18.3	24.8	99	
S2	25.1	27.1	38.2	55	26.7	28.2	35.4	48	29.0	49.9	22.1	0	
S7	13.9	21.9	24.7	99	-999.9	-999.9	-999.9	0	15.2	19.9	19.5	74	

(b) PDOP filter of 5

	Leica					Торсо	on		Trimble			
	Ν	Ε	U	Av	N	E	U	Av	N	E	U	Av
GPS-0	nly											
E2	31.1	22.0	45.2	99	29.2	23.4	40.1	78	16.8	12.2	29.4	98
E4	27.6	15.1	42.5	97	41.0	15.8	48.7	66	23.2	11.7	21.3	99
M1	24.1	9.4	25.7	100	48.3	12.3	41.0	79	20.6	8.7	23.2	99
M5	20.1	10.9	29.8	100	24.7	10.4	33.9	85	27.1	12.7	39.2	99
D1	16.9	11.8	53.0 3	100	27.6	27.4	76.7	84	18.6	20.0	50.7	98
D4	26.6	14.8	32.9	100	40.8	18.4	37.5	98	32.2	23.9	38.3	98
S2	54.1	30.5	19.6	67	30.5	20.2	22.0	26	43.2	6.1	45.3	5
S7	17.8	19.2	35.8	89	31.4	14.0	26.7	73	16.7	10.4	43.5	30
GPS+G	LONASS											
E2	20.8	19.8	26.6	91	15.2	24.2	22.9	84	7.5	15.3	17.9	89
E4	12.6	9.6	15.3	100	13.5	12.4	19.3	68	11.7	9.5	14.0	91
M1	21.1	14.1	55.9	100	14.3	11.8	54.4	99	11.7	11.9	41.6	99
M5	25.6	10.6	29.4	100	16.3	9.8	36.0	73	24.3	9.0	31.5	98
D1	21.4	24.6	42.5	97	27.9	27.5	55.5	49	28.9	30.8	40.0	97
D4	12.1	12.8	45.5	85	9.7	15.4	49.8	86	11.1	18.3	24.8	99
S2	23.8	27.7	35.2	81	26.7	28.2	35.4	48	29.0	49.9	19.3	0
S7	13.9	21.9	24.7	99	-999.9	-999.9	-999.9	0	15.1	19.9	22.1	76





Figure 7. Environmental effects, 'static' mode results for GPS-only (left) and GPS+GLONASS (right) solutions. RMS accuracies per coordinate component are shown per point occupied (two points from each of the easy (E), moderate (M), difficult (D) and severe (S) categories), for each of the Leica (blue), Topcon (green) and Trimble (red) services. All solutions have been CQ and PDOP filtered, with availabilities denoting the proportion passing all filters and hence included in the RMS statistics. The results are presented twice, for the application of PDOP filters of 3 and 5, respectively. The absence of Topcon S7 GPS+GLONASS results is due to a data transfer human issue.



Table 4. Environmental effects, 'static' mode results for GPS-only and GPS+GLONASS solutions. Repeatabilities (standard deviations) per coordinate component per service provider are given per point occupied (two points from each of the easy (E), moderate (M), difficult (D) and severe (S) categories). All solutions have been CQ and PDOP (value of 3) filtered, with availabilities (Av) denoting the proportion passing all filters. -999.9 denotes no observations passed, except S7 Topcon GPS+GLONASS is missing due to a data transfer human issue.

	Leica					Topcon				Trimble			
	Ν	Ε	U	Av	N	Ē	U	Av	N	E	U	Av	
GPS-or	nly												
E2	8.8	10.9	24.9	99	14.4	10.2	19.6	78	13.5	11.9	14.7	98	
E4	26.9	11.8	41.5	53	31.3	10.1	23.6	56	13.8	10.3	15.3	70	
M1	12.8	6.5	20.8	77	14.1	9.0	23.1	53	9.2	7.3	17.5	73	
M5	11.7	9.0	15.1	100	12.6	9.4	21.3	85	14.7	9.1	18.1	99	
D1	9.3	10.1	22.4	100	26.9	29.0	66.7	58	14.7	14.9	22.8	98	
D4	22.9	9.5	34.0	88	14.2	8.5	35.1	98	14.1	9.3	38.2	77	
S2	17.6	5.4	10.4	2	28.9	10.7	21.3	26	-999.9	-999.9	-999.9	0	
S7	16.3	7.4	26.3	47	29.1	9.8	26.4	73	10.3	5.5	12.5	9	
GPS+G	LONASS												
E2	15.4	12.9	26.2	91	11.9	7.5	21.2	84	7.5	5.0	17.0	89	
E4	8.6	7.1	14.2	100	10.7	7.9	17.9	68	8.4	6.9	14.0	91	
M1	10.4	12.3	37.0	92	9.7	9.0	31.9	99	9.5	6.3	32.0	99	
M5	17.2	10.3	22.2	100	12.6	9.8	11.6	73	15.9	9.0	22.3	98	
D1	16.1	21.0	36.0	97	9.0	10.3	19.7	49	17.6	16.9	27.1	97	
D4	11.7	12.8	20.2	85	8.9	6.7	27.2	86	11.1	8.0	16.8	99	
S2	24.9	9.7	23.1	55	24.3	8.3	20.0	48	13.9	4.3	9.0	0	
S7	13.4	4.3	16.2	99	-999.9	-999.9	-999.9	0	15.1	7.8	19.5	74	



Figure 8. Environmental effects, 'static' mode results for GPS-only (left) and GPS+GLONASS (right) solutions. Repeatabilities (standard deviations) per coordinate component are shown per point occupied (two points from each of the easy (E), moderate (M), difficult (D) and severe (S) categories), for each of the Leica (blue), Topcon (green) and Trimble (red) services. All solutions have been CQ and PDOP (using a value of 3) filtered, with availabilities denoting the proportion passing all filters. The absence of Topcon S7 GPS+GLONASS results is due to a data transfer human issue.



As with the Environment Rover tests, the addition of GLONASS improves the solution availability for all three providers, including even the easy category. The RMS values for the 'static' tests are slightly higher than obtained for the rover tests, which is attributed to collecting a larger data sample, and that each point was only occupied at one particular time of day, which only enabled one particular satellite geometry to be experienced.

On considering coordinate repeatability alone, i.e. from inspecting Figure 8 compared with the RMS accuracies shown in Figure 7, it can be seen that all three providers exhibit similar performance, with 10-20 mm horizontal and 20-30 mm height standard deviations.

3.3 Effect of PDOP filters

Inspection of Figures 5 and 7 shows that for the GPS-only case, reducing the PDOP limit to 3 (as recommended by Edwards et al (2008, 2010)) rather than the manufacturer often recommended limit of 5 can increase the robustness of determined coordinates under challenging conditions i.e. difficult and severe categories, but reduces the solution availability. This does not however usually reduce productivity in open/benign environments where PDOP values between 2 and 3 predominate. The GPS+GLONASS results meanwhile, are largely unaffected by the choice of a PDOP mask of 3 or 5, demonstrating how the augmentation of GPS with GLONASS enables a low PDOP value to be obtained in most circumstances, with the GPS+GLONASS solutions rejected being due to high CQ values instead.

3.4 Rover occupation: Single versus multiple measurements

For the Trimble kit when collecting data using Trimble's 'Topo point' mode, as typically used by a detail surveyor (and hence as used for all 'rover' occupations throughout this report), it is not possible to record a single measurement, even when this is stipulated on the controller (as was done throughout all tests for each of the Leica, Topcon and Trimble kit). Instead, multiple measurements are collected, with the modal value being two throughout the rover mode occupation results detailed in this report. To assess the effect of multiple measurements (typically two), 1 hour of 'single' measurements in 'Topo point' mode were collected on a 'static' tripod at Newcastle University using a Trimble R8 receiver and the VRSNow (GPS-only) service. These were repeated the next sidereal day but using 'Rapid point' mode, which does result in a single measurement only. The differences from the static-GPS established ETRF89 truth coordinates are shown in Figure 9, with North, East and Up RMS differences of 13.7, 3.1 and 9.0 mm respectively for Topo point, and 11.6, 4.0 and 7.6 mm respectively for Rapid point. These are very similar, and strongly suggest that the benefit of recording multiple measurements when making 'single epoch' measurements is negligible.

Note that for all 'static' tests described in this report, the Trimble receiver was set to operate in 'Continuous Topo' mode, which resulted in one measurement only per single 1 Hz coordinate recorded.





Figure 9. Trimble 'Topo point' single measurement versus 'Rapid point' single measurement.

4 Receiver interoperability tests

Receiver / service provider interoperability was assessed by testing in turn each of the Leica, Topcon and Trimble receivers using Network RTK corrections from each of the SmartNet, TopNet+ and VRS NOW Network RTK services. This was accomplished in rover mode, for the five points of two sub-networks (environment categories easy and difficult) using GPS-only, and then repeated the next day using GPS+GLONASS. The RMS coordinate accuracies for each of the five category occupations, per receiver per service provider, are tabulated in Table 5 and shown in Figure 10. Note that for the use of the Trimble kit with the SmartNet service, the Smartnet VRS corrections rather than MAC-based corrections were used, adhering to the manufacturer's recommendations as explained in section 1.

It can be seen from Figure 10 that, particularly for the height component, when all three manufacturers were able to access the Network RTK service considered, very similar RMS accuracies were obtained, for both the easy and difficult environment categories. These were commensurate with the results from the Environment Rover tests, i.e. around 10-20 mm in horizontal and 20-30 mm in height.



Table 5. Receiver interoperability, rover mode results for GPS-only and GPS+GLONASSsolutions. RMS accuracies (in mm) per coordinate component per manufacturer,based on single-epoch occupations of each of the 5-6 points of the easy (E)and difficult (D) categories, using in turn each of the SmartNet, TopNet+ andVRSNow Network RTK services. Percentage solution availabilities (Av) are alsoshown, after CQ and PDOP filtering. -999.9 denotes no observations passedthe CQ and DOP filters for the particular category/service/manufacturer.

			Leica	a			Topco	on		Trimble			
		N	Ε	U	Av	N	E	U	Av	N	Ε	U	Av
GPS-only													
SmartNet	Е	-999.9	-999.9	-999.9	0	-999.9	-999.9	-999.9	0	19.3	16.7	9.6	60
TopNet	Е	19.8	11.7	24.2	100	16.4	11.0	12.3	80	7.3	11.9	21.0	100
VRSNow	Е	5.2	26.8	0.9	20	12.3	11.8	11.8	60	12.5	14.3	8.5	40
SmartNet	D	12.8	22.0	13.8	100	-999.9	-999.9	-999.9	0	15.2	19.2	18.0	100
TopNet	D	15.3	14.2	20.1	83	9.6	18.6	14.0	66	13.7	6.8	25.2	33
VRSNow	D	14.8	17.6	28.9	100	19.8	17.7	23.8	100	14.8	14.5	21.3	83
GPS+GLONA	ASS	3											
SmartNet	Е	17.6	16.7	8.8	100	-999.9	-999.9	-999.9	0	7.1	13.3	7.9	100
TopNet	Е	16.1	11.2	26.6	100	11.6	5.7	13.8	100	16.2	5.5	17.3	100
VRSNow	Е	13.7	14.2	16.2	100	26.9	9.8	17.7	40	5.0	14.6	18.1	100
SmartNet	D	13.1	22.3	17.7	100	-999.9	-999.9	-999.9	0	12.3	21.7	16.6	100
TopNet	D	17.1	13.1	16.2	100	13.8	9.3	17.4	100	14.6	8.0	10.7	100
VRSNow	D	8.2	12.0	35.8	83	23.4	15.9	23.3	83	10.8	12.4	34.3	100



Figure 10. Receiver interoperability, rover mode results for GPS-only (left) and GPS+GLONASS (right) solutions. RMS accuracies per coordinate component per manufacturer (denoted by the blue, green and red for Leica, Topcon and Trimble receivers respectively), based on single-epoch occupations of each of the 5-6 points of the easy (E) and difficult (D) categories, using in turn each of the SmartNet (S), TopNet+ (T) and VRSNow (V) Network RTK services. Percentage solution availabilities are also shown, after CQ and PDOP (value of 3) filtering.



5 Network boundary effect tests

To test via simulation the performance of the three service providers when operating outside the network boundaries, the three manufacturers each created a sub-network comprising the OS Net base stations denoted by the solid circles in Figure 11. Thus collecting data around our Chester-le-Street survey area with such a network configuration simulated the effect experienced by a user approximately 50 km outside the network's extents.



Figure 11. Network of OS Net stations used (solid circles) to simulate the effects of working outside the network boundaries, with the Chester-le-Street test area denoted by the cross.

5.1 Network boundary effects: Rover occupation

In rover mode, the five category easy points were occupied once each with GPSonly per service provider, then once each with GPS+GLONASS. The RMS coordinate accuracies are listed in Table 6, and shown in Figure 12.



Table 6. Network boundary effects, rover mode results for GPS-only and GPS+GLONASS solutions. RMS accuracies per coordinate component for Leica, Topcon and Trimble respectively, based on single-epoch occupations of each of the five points of the easy category. Percentage solution availabilities are also shown, after CQ and PDOP filtering. -999.9 denotes no observations passed the CQ and DOP filters for the particular manufacturer. No values are provided for the GPS-only Leica (data transfer human issues) and Trimble solutions (hardware failure).









5.2 Network boundary effects: 'Static' occupation

In 'static' (stationary) mode, the five category easy points were occupied once each with GPS-only per service provider, then once each with GPS+GLONASS. The RMS coordinate accuracies per point are listed in Table 7 and shown in Figure 13, but graphically capped at 40 mm in horizontal and 80 mm in height.

The Topcon height values are off the scale in all cases, including GPS+GLONASS, and the Leica height is in one case (GPS-only E2). These large RMS values arise since when considerably outside the network extents as here, the Topcon system resorts to single baseline solutions (as does the Leica). Comparing with Figure 7, there is only limited degradation in the performance of the Trimble when operating outside the network both for GPS-only and GPS+GLONASS, i.e. solution availability degrades, whereas the Leica has degraded height and North component RMS accuracies. However, it is interesting that GLONASS not only improves the performance of the Leica when operating outside the network, but it also improves the performance when operating outside the network, improving the height RMS accuracy to 20-30 mm in three of the five points considered.

Table 7. Network boundary effects, 'static' mode results for GPS-only and GPS+GLONASS solutions. RMS accuracies per coordinate component for Leica (blue), Topcon (green) and Trimble (red) are given per point occupied (all points from the easy (E) category only). All solutions have been CQ and PDOP filtered, with availabilities (Av) denoting the proportion passing the filter and hence included in the RMS statistics.

	Leica					Topcon				Trimble			
	N	E	U		N	Ē	U		N	E	U		
G													
E1	45.5	8.4	33.6	99	10.2	11.7	167.3	100	10.	7 6.1	12.4	36	
E2	109.1	31.9	114.7	95	12.1	10.0	149.9	100	11.	7 8.9	14.2	99	
E3	24.1	21.9	25.2	96	302.9	537.1	162.4	48	12.	1 7.3	25.4	99	
E4	106.5	15.5	91.5	67	29.4	11.3	166.1	82	11.	1 9.9	29.5	70	
E6	71.5	23.8	55.8	93	7.3	5.6	110.5	99	7.	7 23.9	29.9	98	
GG													
E1	7.2	9.0	22.5	100	23.5	7.1	168.9	79	10.	2 12.9	29.9	69	
E2	24.7	42.7	29.3	100	14.4	24.1	154.1	99	12.	2 13.0	26.6	99	
E3	6.5	7.6	16.1	100	13.7	15.6	115.9	100	12.	4 7.4	25.3	99	
E4	7.6	27.0	41.9	98	21.6	12.7	116.6	98	14.	6 17.6	23.5	84	
Ε6	10.2	12.5	64.6	100	13.8	13.4	116.1	97	11.	2 21.2	34.1	99	





Figure 13. Network boundary effects, 'static' mode results for GPS-only (left) and GPS+GLONASS (right) solutions. RMS accuracies per coordinate component for Leica (blue), Topcon (green) and Trimble (red) are given per point occupied (all points from the easy (E) category only). All solutions have been CQ and PDOP filtered, with availabilities denoting the proportion passing the filter and hence included in the RMS statistics.

6 Local base station failure effect tests

To test via simulation the performance of the three providers when operating when a local base station fails, the service providers disabled the two base stations nearest to Chester-le-Street, namely NCAS and WEAR.

6.1 Local base station failure effects: Rover occupation

In rover mode, the five category easy points were occupied once each with GPSonly per service provider, then once each with GPS+GLONASS. The RMS coordinate accuracies are listed in Table 8 and shown in Figure 14.

For the Leica data, a network service interruption at the time of data collection inevitably led to high CQ and PDOP values, resulting in no solution passing the filters, as can be seen in Table 8 and Figure 14. All the Topcon and Trimble solutions passed the CQ/PDOP filters, with perhaps slightly degraded performance in the horizontal component compared with the Environmental Rover tests shown in Figure 5, but similar height RMS accuracies of 20-30 mm, with no noticeable improvement obtained with the addition of GLONASS.



Table 8. Local base station failure effects, rover mode results, for GPS-only and
GPS+GLONASS solutions. RMS accuracies (in mm) per coordinate component
per manufacturer, based on single-epoch occupations of each of the five points
of the easy category. Percentage solution availabilities (Av) are also listed, after
CQ and PDOP filtering. -999.9 denotes no observations passed the CQ and
DOP filters for the particular manufacturer.



Figure 14. Local base station failure effects, rover mode results, for GPS-only (left) and GPS+GLONASS (right) solutions. RMS accuracies per coordinate component per manufacturer (denoted by the blue, green and red respectively), based on single-epoch occupations of each of the five points of the easy (E) category. Percentage solution availabilities are also shown, after CQ and PDOP (value of 3) filtering.

6.2 Local base station failure effects: 'Static' occupation

In 'static' mode, the five category easy points were occupied once each with GPSonly per service provider, then once each with GPS+GLONASS. The RMS coordinate accuracies per point are listed in Table 9 and shown in Figure 15.

It can be seen from Figure 15 that almost all the solutions passed the CQ/PDOP filters for the static local base station failure tests. The addition of GLONASS improved the availability for all three manufacturers, as well as in general improving slightly the RMS accuracies, except for both Topcon and Trimble at E1, where the height RMS accuracy worsened. The results are not substantially different from the easy category Environment 'Static' results shown in Figure 8, suggesting that the services can still cope quite well in the scenario of a local base station failing. The missing values for Leica for point E4 arose due to a data transfer human issue, whilst the slightly lower E6 North accuracies for Topcon and Trimble are attributed to suspected bar orientation uncertainties.



Table 9. Local base station failure effects, static mode results for GPS-only and GPS+GLONASS solutions. RMS accuracies (in mm) per coordinate component for Leica, Topcon and Trimble are given per point occupied (all points from the easy (E) category only). All solutions have been CQ and PDOP filtered, with availabilities (Av) denoting the proportion passing the filter and hence included in the RMS statistics. -999.9 denotes missing data (due to a data transfer issue).

		Lei	ca		Торсс	n		Trimble				
	N	E	U	Av	N	E	U	Av	N	E	U	Av
GPS-	-only											
E1	14.9	7.6	20.2	97	12.3	13.9	23.8	100	5.5	8.2	12.9	99
E2	13.2	16.9	24.0	99	15.8	10.5	31.1	100	28.4	12.2	34.2	83
E3	19.5	25.6	21.7	56	19.4	13.7	26.3	96	16.3	25.2	36.3	64
E4	-999.9	-999.9	-999.9	0	15.9	15.0	36.5	75	16.8	17.2	44.0	72
Ε6	8.4	21.5	58.9	82	9.4	27.4	27.6	99	9.0	72.4	54.1	99
GPS-	GLONASS											
E1	8.9	9.4	45.7	100	10.8	7.0	35.9	100	11.5	9.9	48.7	99
E2	9.7	12.3	13.9	100	14.4	15.6	16.7	100	15.4	12.3	23.1	99
EЗ	11.7	7.8	16.6	100	11.6	10.1	15.0	100	15.2	16.5	20.3	99
E4	9.0	16.7	18.9	100	17.2	12.6	19.5	100	15.3	19.7	27.3	99
Ε6	8.9	18.2	18.3	99	20.6	34.0	32.2	99	10.3	64.6	21.2	98



Figure 15. Local base station failure effects, static mode results for GPS-only (left) and GPS+GLONASS (right) solutions. RMS accuracies per coordinate component for Leica (blue), Topcon (green) and Trimble (red) are given per point occupied (all points from the easy (E) category only). All solutions have been CQ and PDOP (value of 3) filtered, with availabilities denoting the proportion passing the filter and hence included in the RMS statistics. No results are presented for Leica E4 GPS-only due to data transfer issues.

7 Assessment of CQ values

To assess the reliability of manufacturer-reported CQ values, the Environment 'Static' mode results were analysed, by considering the accuracies obtained for the Up component and comparing with the manufacturer-reported 1D CQ values. These were selected rather than the 2D CQ values for conciseness and since no directional or ellipse minor axis is provided with the manufacturer CQ values to enable direct comparison with the East and North errors. For one survey point per category, these have been plotted against each other directly in Figures 16a-d, together with the respective accuracy:CQ ratios plotted against time (note the use of a logarithmic scale). In contrast to the other tests, all epochs were included, not just those passing the CQ and PDOP filters, which included some float solutions. If the CQ values are totally reliable, the upper pane plots should plot as a straight line with a slope of 45 degrees, whilst the CQ ratios should equal one (a lower value suggests too pessimistic CQ values, whilst a higher values suggests too optimistic CQ values). The axis limits chosen for Figure 16 ensure that all data points are incorporated, with the exception of the severe category plot, which is shown again separately (in Figure 16e), since the accuracies and reported CQ values were much greater than the 100 mm limits sufficient for the other three points shown.

It can be seen from Figure 16 that, on the whole, the Up component CQ values are fairly indicative of the actual accuracy obtained, which matches the findings of Edwards et al (2008). However, for the severe category case, the GPS+GLONASS Trimble reported CQ values are too optimistic, although both actual accuracy and reported CQ were often at the level of several metres, and a surveyor would be correct to not use the position when such large values arose anyway (and when float solutions arose). In general, GPS+GLONASS CQ values tend to be slightly over-optimistic compared with the GPS-only counterparts.

Figure 16a. For point E4 (easy category), Up coordinate accuracy versus 1D reported CQ values (top panes), and CQ ratio (accuracy/1D CQ) plotted against time in the lower panes. Plots are shown for both GPS-only (G) and GPS+GLONASS (GG) for Leica (L, blue/cyan), Topcon (To, green/yellow) and Trimble (Tr, red/purple).

Figure 16b. For point M1 (moderate category), Up coordinate accuracy versus 1D reported CQ values (top panes), and CQ ratio (accuracy/1D CQ) plotted against time in the lower panes. Plots are shown for both GPS-only (G) and GPS+GLONASS (GG) for Leica (L, blue/cyan), Topcon (To, green/yellow) and Trimble (Tr, red/purple).

Figure 16c. For point D1 (difficult category), Up coordinate accuracy versus 1D reported CQ values (top panes), and CQ ratio (accuracy/1D CQ) plotted against time in the lower panes. Plots are shown for both GPS-only (G) and GPS+GLONASS (GG) for Leica (L, blue/cyan), Topcon (To, green/yellow) and Trimble (Tr, red/purple).

Figure 16d. For point S2 (severe category), Up coordinate accuracy versus 1D reported CQ values (top panes), and CQ ratio (accuracy/1D CQ) plotted against time in the lower panes. Plots are shown for both GPS-only (G) and GPS+GLONASS (GG) for Leica (L, blue/cyan), Topcon (To, green/yellow) and Trimble (Tr, red/purple).

Figure 16e. Zoom of plot of Up coordinate accuracy versus 1D reported CQ values (top panes), and CQ ratio (accuracy/1D CQ) plotted against time in the lower panes for point S2 (severe). Plots are shown for both GPS-only (G) and GPS+GLONASS (GG) for Leica (L, blue/cyan), Topcon (To, green/yellow) and Trimble (Tr, red/purple).

8 Summary and recommendations

A 22 point test network was established across an approximately 1 km2 survey area in Chester-le-Street, County Durham, encompassing a range of survey environments, from open sky (category 'easy'), through to 'moderate', 'difficult' and the urban canyon ('severe'), with which to test the performance of the three commercial Network RTK service providers in Great Britain, namely Leica SmartNet, Topcon TopNet+ and Trimble VRSNow. Following the findings of Edwards et al (2008), solutions were only accepted in the tests if they were integer-fixed, the PDOP was less than three, and the horizontal and vertical CQ values were less than 50 mm and 100 mm respectively, such that the accepted positions followed those from the previous best practice guidelines. The Chester-le-Street survey area was located around 15-20 km from the nearest Ordnance Survey base station (NCAS), and was therefore representative of the most typical user to base station distance experienced by a surveyor in Great Britain. The control 'truth' coordinates of the test network points were obtained by both static GPS (processed using the GAMIT scientific software) and terrestrial survey (traversing and levelling), with the resulting coordinates precise to around 5 mm in all three components.

The performance of the three services in different **environmental conditions** was tested in both rover (detailing, single epoch) and 'static' (stationary antenna mounted on a tripod with 45 min of single second Network RTK positions collected) modes. For the solutions that passed the filters imposed, the RMS accuracies obtained for the three services were approximately commensurate at around 15 mm in horizontal and 20-40 mm in height for GPS-only, with small accuracy improvements arising with the addition of GLONASS. The key impact GLONASS had was to improve the availability i.e. the percentage of solutions passing the CQ and PDOP filters, in particular for the more challenging environments. In terms of repeatability rather than accuracy, for all three providers, horizontal standard deviations of 10-20 mm and 20-30 mm height standard deviations were obtained.

Receiver interoperability was assessed, namely the ability and compatibility of each of the Leica, Topcon and Trimble receivers to obtain Network RTK solutions using each of the SmartNet, TopNet+ and VRSNow correction services. This was assessed for the easy and difficult category points in rover mode, and when the particular receiver considered was able to access the service in question, very similar RMS accuracies were obtained for each receiver, and commensurate with the 10-20 mm horizontal and 20-30 mm height RMS accuracies obtained from the environment tests.By testing using corrections provided from sub-networks of base stations, it was found that GLONASS typically (but not in all cases for all manufacturers) improved the RMS accuracy obtained when working on the **network boundaries**, to 20-30 mm for three of the five points considered, and improved the availability for the case of a simulated **local base station failure**.

Based on these, the follow conclusions are drawn and recommendations made:

- 1 The use of GLONASS improves the solution availability in more challenging environments and should be used in all such scenarios, for both rover and static mode occupations. Even position solutions in more favourable environments are improved by the addition of GLONASS.
- 2 The addition of GLONASS results in small accuracy and precision improvements.
- 3 In general, if the receiver can access the Network RTK provider service considered, similar positions are obtained using each of the Leica, Topcon and Trimble kits.
- 4 GLONASS may be used to mitigate any degradation caused by working on the network boundaries or if the nearest base station fails.
- 5 Overall, CQ height values are fairly indicative of the actual height accuracy. When positioning in severe environments however, some CQ values were found to be over-optimistic, and similarly GPS+GLONASS CQ values tended to be slightly over-optimistic compared with the GPS-only counterparts.

9 References

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