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An examination of commercial network RTK GPS services in Great Britain

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With thanks to Mr Martin Robertson for
technical support and management of fieldwork

Key stakeholders

The Survey Association
Ordnance Survey
Leica Geosystems
Trimble
Royal Institution of Chartered Surveyors

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Foreword

This document has been produced as part of a drive to provide surveyors, engineers and their clients with guidelines for the use of network RTK GPS in land surveys. It has been produced by a joint working group – Ordnance Survey, Newcastle University, Leica, Trimble and The Survey Association (TSA).

The document has been written primarily with two goals in mind:

1. To quantify the achievable accuracy.

2. To provide a basis from which to draw out best practice guidance for those using the various commercial network RTK solutions.

Previous guidance notes such as the *RICS Guidelines for the Use of GPS in Surveying and Mapping* published in June 2003 have covered many aspects of GPS use. With the rapidly advancing technological edge of GPS surveying, not all aspects could be covered by previous guidelines. This document provides the basis for the extension of previous guidance to cover network RTK GNSS.

Back in 2007 the TSA, as a trade association of survey and mapping companies, became aware of litigation against its members as a result of accuracy using network RTK GPS in the UK. The chairman of the TSA technical committee raised these concerns with other major stakeholders, i.e. Ordnance Survey who provide and maintain the national network of continuously operating GPS active stations, and Leica Geosystems and Trimble who are correction service providers based on the Ordnance Survey data. An initial meeting of the major stakeholders plus representatives of other GPS suppliers and users identified poor levels of user awareness of best practice to achieve best accuracy and an unrealistic expectation of achievable accuracy.

The major stakeholders agreed to fund an independent study to address these two issues. Newcastle University were appointed and a final scope agreed.

The intention has always been to try to improve awareness and to get *best practice guidance* published as widely as possible. The publication has been jointly badged by The Survey Association, Ordnance Survey, Leica Geosystems, Trimble, and the Royal Institution of Chartered Surveyors (RICS).

This publication would not have been possible without the funding and help provided by The Survey Association, Ordnance Survey, Leica Geosystems, Trimble and RICS. We wish to acknowledge them for this joint approach to arrive at a workable solution.

Neil Harvey
President – The Survey Association

Executive summary

Commercial network RTK has been available in Great Britain since early 2006 and was borne out of the Ordnance Survey's densification of its permanent array of active GPS receivers known as Ordnance Survey OS Net® (OS Net). Currently two commercial providers, Leica Geosystems and Trimble, are licensed by Ordnance Survey to offer Great Britain's geomatics community access to coordinate solutions in real-time with sub-metre to centimetre accuracy levels. Leica Geosystems' network RTK solution known as 'SmartNet' is based on the so-called Master-Auxiliary Concept (MAC), (Euler et al, 2004) whereas the Trimble solution known as 'VRS NOW' is based on the Virtual Reference Station (VRS) approach (Vollath et al, 2000). The body of work presented in this report seeks to address a number of questions relating to the overall performance of SmartNet and VRS NOW and specifically focuses on:

- Accuracies attainable from both systems at a range of representative locations that users may experience.
- Coordinate repeatabilities attainable from the two systems.
- System performance at the geographical extents of the active station network.
- System performance when significant height differences exist between the OS Net reference stations and the roving site.
- Examine the potential for enhanced network RTK solutions through the integration of additional satellite constellation signals, e.g. GLONASS.

In order to assess the above, eight test locations were identified at different geographic locations throughout Great Britain and subsequently a series of tests was performed at each during the period March-April 2008. At each test site, precise coordinates ('truth' values) of both SmartNet and VRS NOW GNSS antennas were determined, and subsequent network RTK solutions from each were compared and statistically analysed to provide independent quantification of overall network RTK system performance. The ultimate goal of this testing/analysis was to provide the surveyors and engineers utilising centimetre-level solutions with an *impartial* and *independent* best practice user guide that extends beyond that currently available, e.g. the *Guidelines for the Use of GPS in Surveying and Mapping* published by Royal Institution of Chartered Surveyors (2003) and of course the manufacturers' own guidance and advice.

Prior to data analysis of the manufacturers' solutions, precise coordinates solutions for each of the test sites were determined. Three antennas (SmartNet, VRS NOW and additional Newcastle University Leica antenna in the centre) were set up at each test site on a fixed bar mounting arrangement with inter-antenna separations of 250 mm. The coordinates of the Newcastle University central antenna were determined via Bernese v5.0 (Dach et al, 2007) processing relative to the five nearest Ordnance

Survey active stations, with the ETRF89 coordinates of four held fixed. East, North and Up coordinate residuals from this processing are generally at the few millimetre (mm) level (majority less than 5 mm) with just five instances exceeding 10 mm. Then 'truth' values of the SmartNet and VRS NOW antenna were determined relative to the central antenna using the Leica GeoOffice Software. Over such short baselines all standard atmospheric biases will cancel thus providing an excellent set of benchmark coordinates for use in subsequent analysis.

Data analysis was preceded by the application of two filters applied to each of the network RTK providers' solutions. Firstly, all solutions with instrument-reported quality measures in excess of 50 mm in plan and 100 mm in height were removed. Subsequently, solutions with a Dilution of Precision (DOP) value of greater than or equal to 3 were also removed. In the majority of cases, the imposition of both these filters retained around 95% of all solutions from both SmartNet and VRS NOW for further analysis. Following the application of each of the above filters a number of tables of statistics, time series and histogram plots were produced for each provider's solution at each site (Appendix 1). It should be noted that as the aim of this work is the production of best practice guidance encompassing both the currently available network RTK systems the results of all analyses have been anonymised.

From the various analyses undertaken, it can be concluded that both commercial network RTK systems are currently operating at similar levels of accuracy overall. The application of simple coordinate quality and DOP filters in real time can greatly improve the accuracy of both SmartNET and VRS NOW in challenging multipath environments; however, in relatively benign environments no significant loss of productivity or accuracy is suffered. The key here is for the surveyor/engineer to pay close attention to coordinate quality (CQ) indicators provided on the equipment. Analysis of these has shown that in the main, both network RTK systems deliver coordinates that are of better accuracy than indicated in real-time which should engender confidence in the user. However, under conditions of severely limited satellite visibility and multipath, both network RTK solution types can give over-optimistic CQ values. In general it can be concluded that currently commercial network RTK services in Great Britain are achieving accuracies at around the 10 – 20 mm level in plan and 15 – 35 mm level in height (one sigma). Even when working at the extents of the Ordnance Survey active network, e.g. the coastal zone, surveyors/engineers can have a good deal of confidence in network RTK solutions. For example, from the limited tests performed in this work, rms errors in such locations range between 10–15 mm, 7–32 mm and 18–30 mm in the North, East and Up directions respectively. However, in such localities and indeed at other locations within Great Britain (e.g. Scotland, Wales and the South West of England), the user can still be in excess of 50 km (mean distance) from the nearest four OS Net sites. Under such conditions surveyors/engineers may wish to consider the adoption of averaged window solutions as described below.

The use of a single averaged window solution (user definable in the manufacturer's equipment) can significantly improve the levels of accuracy compared with a single epoch network RTK solution. Testing performed in this report has determined that rms errors can be reduced by around 5 mm, particularly in the Up coordinate component, through the adoption of the mean of two 3-minute averaged windows separated by 20 minutes. The separation of the two windows was also investigated and found not to yield significant improvement beyond 45 minutes.

Due to the nature of receiver locations comprising OS Net, the user may find themselves at an altitude significantly above or below the surrounding OS Net sites. This geographical offset has implications for commercial network RTK systems' ability to effectively model/estimate and ultimately remove residual atmospheric effects and in particular tropospheric bias. Testing at representative locations has determined that both commercial network RTK providers are able to mitigate residual tropospheric errors to a large degree. However, where height differences between the user and the nearest OS Net base stations exceed 250 m surveyors should consider the adoption of windowing techniques.

As other satellite constellations (e.g. GLONASS and Galileo) mature, more signals become available for integration into network RTK solutions. This work examined, at one point only, the effect of the GLONASS signal on such solutions. Results from this very early study should not be over-interpreted but would appear to suggest that the additional GNSS signals increase the availability of network RTK solutions especially in challenging environments such as the urban canyon. However, these initial results, although not conclusive, do not suggest improvements in accuracy and indeed imply a slight degradation. Further testing of this aspect is recommended following the ongoing replenishment of active station infrastructure and of the GLONASS constellation.

The periodic redistribution of water due to the ocean tides loads the Earth's surface, resulting in time-varying *ocean tide loading* (OTL) displacement. The complicated Great Britain coastline and shallow seas result in variabilities in OTL, from up to ±60 mm in height displacement and ±20 mm in plan displacement over a 6 hour period in the South-West Peninsula, to about a third of this range throughout much of eastern Great Britain. Again, limited testing at an OTL-susceptible site suggests that network RTK reduces OTL errors to within the limits of system noise throughout the majority of mainland Britain. However, further testing, especially at sites in the South-West, would be required to establish this more rigorously. This is recommended.

The above experiments and analysis have allowed a series of recommendations for practitioners to be developed (Section 7) and these will be used to form the body of best practice guidance. Clearly, this guidance is time delimited and future developments in commercial network RTK may well require update to these guidelines.

1. Introduction

1.1 Background

Since 1998, Ordnance Survey has gradually increased the number of *active* GPS stations to more than 100 with a target of ~110 (Figure 1). The key driver behind this increase has been the desire for the Ordnance Survey to move towards a real-time kinematic (RTK) GPS coordinate solution sufficient in accuracy (3-5 cm) to allow efficient and timely update of Great Britain's large scale mapping. This so-called 'OS Net' (Ordnance Survey OS Net®) is effectively a densification of the original *active* station network allowing Ordnance Survey personnel to achieve accuracies sufficient for its map update programme. A network approach enables the reference to rover separation to be increased beyond the single baseline traditional RTK limit of ~20 km (above which differencing of observations no longer sufficiently mitigates atmospheric and orbit errors with the result that ambiguity fixing is generally rendered less successful), by broadcasting atmospheric and other corrections to the rover from the set of reference stations. Briefly, OS Net is used to provide real-time information to Ordnance Survey surveyors using just one 'roving' GPS receiver combined with a mobile phone data card thus allowing coordinate determination at the required accuracies.

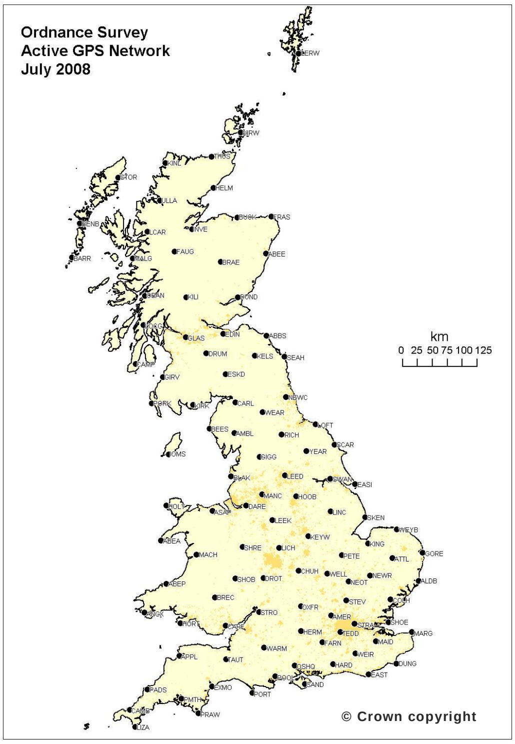

Figure 1. OS Net reference station network.

As a result of the development of OS Net, Ordnance Survey has recently entered into a number of third party partnerships bringing commercially available network RTK solutions to Great Britain's surveying/engineering sectors. The first partnership, announced in late January 2006, was between the Ordnance Survey and the surveying and engineering equipment manufacturer Leica Geosystems (Leica Geosystems, 2006a). Leica Geosystems offer a National RTK network solution called 'SmartNet'. This announcement was quickly followed in March 2006 by a second partnership between Ordnance Survey and the equipment manufacturer Trimble Navigation (Trimble, 2006). Both VRS NOW and SmartNet solutions are derived from OS Net raw data.

Both the Trimble and Leica network RTK systems have been designed to provide 'centimetre level' real-time positioning anywhere in Great Britain, provided mobile phone coverage is available. Initial coordinate accuracy testing (using the Trimble VRS system) by Ordnance Survey (2005) has indicated that coordinate rms accuracies in the order of 11, 14 and 34 mm (East, North and Up directions) are obtainable. Leica SmartNet promotional materials (Leica Geosystems, 2006b) state their system *'performs 1-3 cm RTK surveys'*, although no distinction is made as to the comparative accuracies of different coordinate components. An examination of frequently asked questions on the Leica SmartNet (http://smartnet.leica-geosystems.co.uk/SpiderWeb/frmIndex.aspx, accessed September 2008) reveals the following statement;

> *'Assuming the standard GPS RTK protocols and best practice methods are employed for maximum precision i.e. good satellite coverage, good geometry of precisions, low multipath environments etc, SmartNet typically achieves an RTK rmse accuracy of 10-20 mm plan and 20-30 mm height, in Great Britain' (Leica Geosystems, 2007).'*

For the Trimble VRS NOW system, a similar web search (http://trl.trimble.com/docushare/dsweb/Get/Document-277828/022543-080E_R8VRS_DS_0507_lr.pdf, accessed September 2008) reveals quoted accuracies for their R8 GNSS receiver of 11 mm + 1 ppm (horizontal) and 20 mm + 1 ppm (vertical) (Trimble, 2007), although a report published in their journal Technology and More (2005) reveals actual tests using their North Carolina, USA, VRS system that yield rms performance at the level of 15, 12 and 45 mm (East, North, Up directions).

A review of the literature would appear to suggest the accuracies of Great Britain's two current commercial network RTK GPS systems are similar, but there is currently a dearth of independent information providing an independent review of the range of achievable accuracies over the variety of situations realistically experienced by surveyors and engineers.

2. Scope of study

The scope of this study has been deliberately kept focussed as there are myriad circumstances in which one could assess network RTK performance. Thus five analysis aspects/objectives for Leica SmartNet and Trimble VRS NOW were identified:

1. Determine overall three-dimensional accuracies attainable at a range of locations.

2. Determine coordinate repeatabilities attainable at a range of locations.

3. Examine performance at the geographical extents of the system.

4. Examine system performance when significant height differences exist between the OS Net reference stations and the roving site.

5. Examine the potential for enhanced network RTK solutions through the upgrade of OS Net infrastructure to GPS + GLONASS receivers.

The above objectives were investigated through a series of controlled field experiments and subsequent data analysis.

A further aim of this project is the dissemination of its findings to the broader geomatics community through the formulation of an *impartial* and *independent* Great Britain network RTK 'user guide'. The lack of openly-published information on the performance of the commercial network RTK GPS systems in Great Britain and indeed Europe make this project particularly timely and relevant to the surveying, engineering and mapping communities. It should be noted that whilst the capabilities of both commercial network RTK systems will be critically examined, this report does not attempt to directly rank the services with respect to one another, but rather to provide impartial and objective indicators of the typical measurement quality attainable by any system.

3. Fieldwork

To meet the objectives outlined in Section 2, a series of field experiments was undertaken at a range of locations across England and Wales (Figure 2). To simplify site selection a series of passive Ordnance Survey network stations (OS Net) meeting a set of selection criteria was chosen. Initial test design criteria were based on distance of the test site from the nearest OS Net active station, the site's elevation and general aspect i.e. open or urban, and comprised:

1. Within 20 km, low elevation, open aspect
2. Within 20 km, low elevation, urban aspect
3. As for (2) but with GLONASS corrections
4. Within 60 km, low elevation, coastal, edge of network
5. Within 60 km, low elevation, coastal, edge of network but with potential for ocean tide loading effects
6. Within 60 km, low elevation, surrounded by actives
7. Within 30 km, high elevation, close to (6)
8. Within 30 km, large elevation difference to nearest active.

The above initial criteria resulted in the following Ordnance Survey passive sites being selected (Table 1). Table 1 shows the range of distances from the test site to the nearest four Ordnance Survey active stations, the rms of these baseline distances, the mean height difference between the test site and the four active sites and the rms of the height differences. It should also be noted that sites GRAV and GRAG are the same physical location and this site is not an Ordnance Survey passive site. This site was selected specifically to provide a challenging urban environment for a comparison between GPS only and GPS/GLONASS network RTK solutions. Figure 2 shows the Ordnance Survey network of active stations and the locations of the test sites chosen.

Table 1. Test sites selected based on initial selection criteria.

Site	**CALL**erton Grange	**GRAV**esend (GPS/GLONASS)	**GRAG** (Same as GRAV)	**STMG** (St. Margarets)
Date observed	17/03/08	19/03/08	20/03/08	21/03/08
Dist to nearest 4 Ordnance Survey active stations	10 - 67 km	22 - 50 km	22 - 50 km	28 - 61 km
rms baseline distance	51 km	35 km	35 km	48 km
Mean height difference	53 m	21 m	21 m	-81 m
rms height difference	144 m	26 m	26 m	82 m
Site	**TRET**io	Church **STRE**tton	**TUSH**ingham	**GWYN**fryn
Date observed	24/03/08	25/03/08	17/04/08	18/04/08
Dist to nearest 4 Ordnance Survey active stations	27 - 119 km	22 - 72 km	31 - 69 km	45 - 80 km
rms baseline distance	70 km	48 km	50 km	64 km
Mean height difference	-56 m	-255 m	16 m	-254 m
rms height difference	76 m	257 m	108 m	279 m

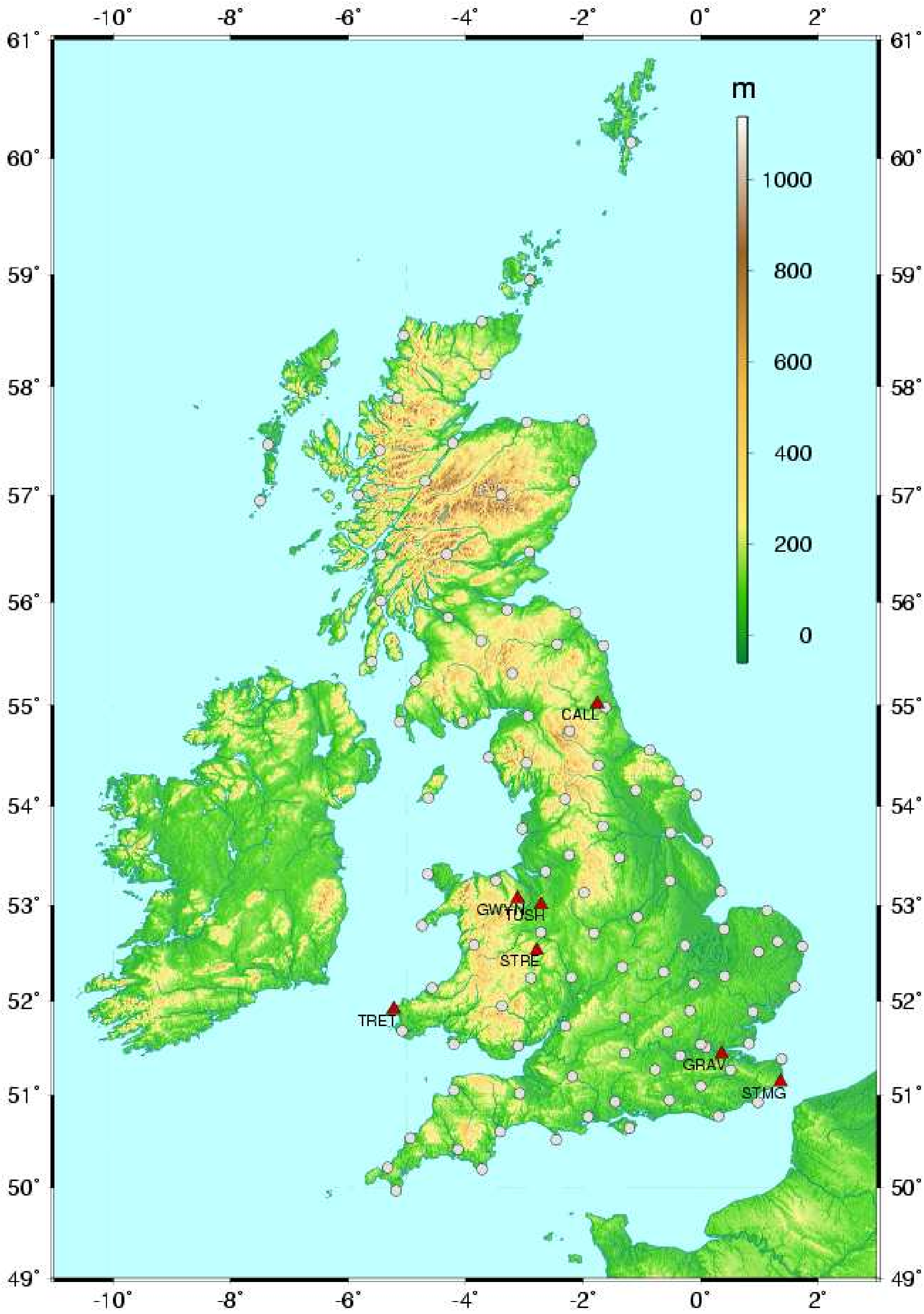

Figure 2. OS Net active stations (lighter circles) together with network RTK test sites (red triangles).

A total of seven sites yielding eight test data sets (GRAG is the additional test used to examine combined GPS/GLONASS performance) were identified across England and Wales (Figure 2) as meeting the criteria outlined above. At each of the sites a tripod was set up over the Ordnance Survey passive site marker and each manufacturer's antenna was set up on a bar (Figure 3) with fixed inter-antenna distances of 250 mm. In the centre of the bar was a third antenna connected to a Leica GX1230 (Ncl_rec) dual frequency receiver. This receiver was used to record static data for the determination of site coordinates using the Bernese v5 scientific GPS processing software. At each test site the mounting bar was centred such that the Ncl_rec antenna was over the station marker and approximately orientated to North using a magnetic compass to provide equipment configuration repeatability.

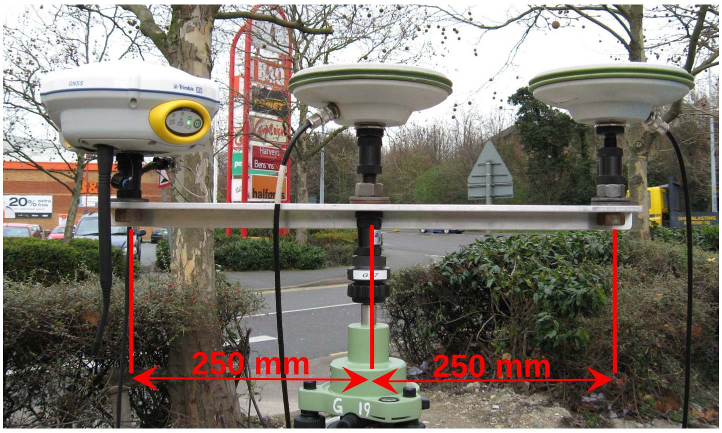

Figure 3. Equipment configuration showing inter-antenna distances.

Prior to fieldwork commencing it had been agreed that each manufacturer would configure their RTK equipment such that the highest number of fixed solutions would be recorded for later analysis. These settings necessarily involved parameters that would not normally be advised for general surveying purposes. The following summarises the primary parameters set:

Trimble VRS NOW equipment parameters

- Elevation Mask: 10°
- PDOP: 99
- Horizontal and vertical quality limits set to 100 mm

Leica SmartNet equipment parameters

- Elevation Mask set to 10°
- No further instrument parameters were set to ensure that all fixed points were recorded.

At least 6 hours of network RTK solutions were collected to allow for a significant geometry change in the satellite constellation and to provide a long time span of data for analysis. Furthermore, this hardware configuration and observing procedure helped to minimise any biasing at different sites due to varying satellite geometrical configurations. The Ncl_rec instrument also collected 6 hours of static data for later post processing.

4. Data processing and test methodologies

4.1 Data processing

Whilst ETRF89 coordinates are already available for all sites occupied except for GRAV, the stability of Ordnance Survey passive network sites is uncertain so the coordinates of these sites were initially recomputed using data from the mid-mounted receiver (Ncl_rec) as a 'sanity' check on processing procedures and to provide a means of determining precise 'truth' coordinates for the SmartNet and VRS NOW antenna. During the Bernese v5.0 processing of the central antenna the following parameter settings were selected to provide coordinates of the highest quality:

- Processing was performed relative to the five nearest OS Net active sites, with the ETRF89 coordinates of the best four held fixed.
- IGS final precise orbits were used
- Final station coordinates were based on network processing as opposed to individual baseline solutions
- Final coordinates were based on accumulated solutions using 180 second data interval
- Antenna phase centre offsets and elevation-dependent variations were modelled using the IGS absolute values
- An elevation cut-off angle of 15° was imposed
- Elevation-dependent weighting was implemented. This parameter setting down-weights observations from lower elevation satellites in the final solution.
- Ambiguity resolution was attempted
- Ocean tide loading effects were corrected using the FES2004 ocean tide model
- Earth body tides were modelled
- Ionospheric free observable was used to generate the final coordinate solutions
- Tropospheric zenith delays were computed every 2 hours at each station and the Niell (1996) mapping function was used

Figure 4 shows the geographic locations of all test sites together with the vectors to the nearest five active OS Net stations used in the Bernese processing. It should be noted that in the final solution the coordinates of four of the five OS Net stations fixed, following closely the EA 'E1 point' processing strategy (Environment Agency, 2004). Table 2 provides summary information following the Bernese processing for each test site including distance to each OS Net station, final residuals and the percentage of L1 and L2 ambiguities resolved in the final solution. Following the Bernese processing the newly determined precise coordinates for each test site were used to determine 'truth' coordinates for the antennas used by the SmartNet and VRS NOW systems.

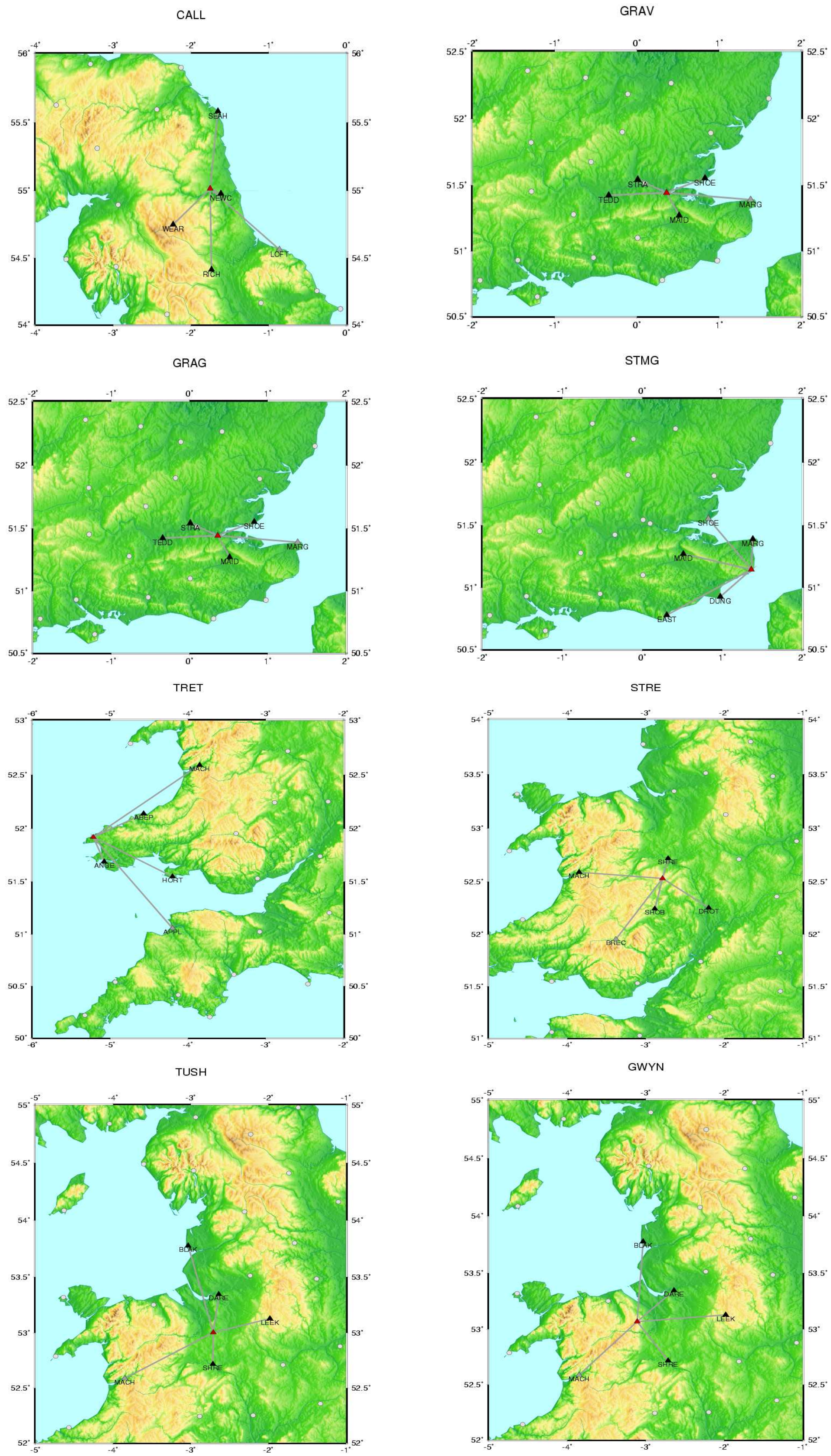

Figure 4. Test site locations and vectors to nearest five OS Net active stations.

Table 2. Test site residuals from four fixed sites in Bernese v5.0 processing.

Network RTK Test site	**Active Station**	**Distance from test site**	**dN (mm)**	**dE (mm)**	**dU (mm)**	**% L1 and L2 ambiguities fixed**
CALLerton	-	-	-	-	-	91
	NEWC	10	-	-	-	
	WEAR	42	-5	3	3	
	SEAH	64	-5	5	8	
	RICH	67	0	9	4	
GRAVsend	-	-	-	-	-	73
	MAID	22	-	-	-	
	STRA	27	4	0	5	
	SHOE	35	-3	2	-9	
	MARG	71	8	-1	-8	
GRAG	**-**	-	-	-	-	71
	MAID	22	-	-	-	
	STRA	27	1	0	-4	
	SHOE	35	-3	-1	-2	
	MARG	71	9	-2	-4	
STMG (St. Margarets)	**-**	-	-	-	-	65
	MARG	28	-	-	-	
	DUNG	36	-1	3	10	
	SHOE	59	-11	2	12	
	MAID	61	-9	2	10	
TRETio	**-**	-	-	-	-	98
	ANGE	26	-	-	-	
	ABEP	52	-2	-1	0	
	HORT	82	-1	-1	0	
	MACH	120	6	-4	2	
Church **STRET**ton	**-**	-	-	-	-	92
	SHRE	22	-	-	-	
	SHOB	32	1	3	2	
	DROT	51	-1	3	8	
	MACH	72	4	7	16	
TUSHington	**-**	-	-	-	-	96
	SHRE	31	-	-	-	
	DARE	39	-2	-3	6	
	LEEK	51	-2	-6	0	
	LICH	69	-2	1	-3	
GWYNfryn	**-**	-	-	-	-	100
	SHRE	47	-	-	-	
	DARE	45	-2	-3	9	
	LEEK	77	0	-4	7	
	LICH	96	-1	0	-1	
Root mean square	**-**	-	**4.6**	**3.5**	**6.9**	-

Using the Bernese-derived precise coordinates of the central antenna (Ncl_rec), the Leica GeoOffice GPS processing software (LGO) was used subsequently to establish the 'truth' coordinates for both the SmartNet and VRS NOW antennas by processing short baselines relative to Ncl_rec. The following parameters were used during this very short baseline processing:

- Elevation cut-off angle 15°
- IGS final precise orbits
- Solution Type - Phase: all fix
- Frequency: L1 and L2
- Tropospheric model: Hopfield*
- Ionospheric model: Automatic*

* *note that both tropospheric and ionospheric errors would cancel completely for these very short baseline lengths (250 mm)*

4.2 Test methodologies

The test methodologies corresponding to the objectives are now described, being carried out with each manufacturer's equipment utilising the SmartNet and VRS NOW network RTK services. At each of the test sites, experiments were undertaken at periods of different satellite geometries and hence differing DOP values to allow analysis of system performance during times of both high and low DOP. The following aspects were assessed for each of the sites occupied:

1. **System accuracies:** At each test site, time series of SmartNet and VRS NOW derived coordinates were compared to the 'truth' values in order to assess overall system accuracies in each coordinate component.

2. **RTK system coordinate repeatabilities:** These were examined by study of the temporal variation of short-term system accuracy (as described above) at each site.

3. **Reference network extents:** System performance at test sites STMG & TRET was analysed in regard to the fact that both sites are located at the geographical extents of the continuously operating reference station network. This analysis is particularly important for those professionals who operate in such geographical locations and for those working in areas that are more sparsely populated with reference stations.

4. **Height effects:** System performance in relation to ability to mitigate tropospheric effects was examined by testing NetRTK solutions at a range of altitudes with respect to network reference stations.

5. **GLONASS aiding:** There currently exists an area around London where the base station infrastructure is both GPS and GLONASS capable. Solutions from both VRS NOW and SmartNet were tested at a site towards the centre of this area firstly using GPS alone and then using GPS + GLONASS.

5. Data analysis

Prior to any statistical analysis of network RTK performance both the VRS NOW and SmartNet solutions obtained at each site were further filtered based on two criteria:

(i) **CQ filter:** Filtering criteria based on instrument-reported coordinate quality (CQ) measures were applied such that solutions where the instrument-reported quality measures in excess of 5 cm in plan i.e. North and East directions and 10 cm in height i.e. Up direction were rejected as outliers. This is reasonable assuming the formal errors reported by the network RTK systems are valid.

(ii) **CQ+DOP filter:** A further DOP threshold was applied following (i) above such that solutions passing the CQ filter but with DOP values greater than or equal to 3 were also rejected. Again this is a reasonable practical quality criterion to impose.

Table 3 presents information on the total number of observations recorded by each network RTK provider's equipment at each test site together with the number and percentage reduction in these following the application of filters (i) and (ii). The overall mean reduction in observations available for further analysis was ~ 8%; however, this figure is biased by problems experienced at GRAV and GRAG by one of the providers (purple). More realistically it can be seen from Table 3 that following the combined application of filters (i) and (ii) the total number of solutions available for further analysis was in excess of 95% in the majority of cases. With regard to those sites exceeding the thresholds for filter (i) the most likely cause of rejection is that of very local effects and may reflect some measure of multipath or other local interference. Some of the problems associated with GRAV and GRAG experienced by one service provider can be explained, in part, by communication issues although other (unspecified) factors may have had an effect. Overall, following the application of (i) and (ii) there remained in excess of 5.8 hours of data for subsequent analysis.

Notwithstanding the application of the above filters the nature of statistical analysis will inevitably identify observations that range outside what the user may expect. The statistical analysis undertaken in this report aims to quantify the significant trends that are important to users and upon which best practice guidance can be soundly based.

Figure 5 shows a typical East, North and Up time series plot for site CALL with outliers removed based on filter (i) criteria. East, North and Up values have been computed by transforming the raw coordinate solutions for each manufacturer into a local planar coordinate system. Individual manufacturer solutions are denoted by the different colours (purple and pink) but no further significance should be read into this aspect. For each piece of equipment two line plots are shown in three panes corresponding to East, North and Up coordinate components. For each coordinate component the complete epoch by epoch time series of solutions is shown (thicker line with more variation). The smoother lines represent 5 minute running average solutions. The running averages allow trends in solutions to be drawn out more easily. Statistical data for these graphs is computed from the complete time series of solutions. The bottom pane on these plots shows the DOP variations for HDOP and VDOP for the respective manufacturer's equipment. Similar plots were also generated for CQ+DOP filter (ii) solutions.

Figure 6, as Figure 5, shows the whole time series [filter (i) output] of reported quality measures for each coordinate component (lighter thicker lines with more variation) together with the variation in actual rms (root mean squared) error computed over 300 epoch (5 minute) sliding windows. Again, individual manufacturer's solutions are simply denoted by different colours. Results are shown for East, North and Up directions but for this analysis a logarithmic scale has been employed. GDOP values are shown in the bottom panel of the plot. Plots showing CQ+DOP filter (ii) output are also provided in Appendix 1. The rms error has been computed for each coordinate component, as:

$$rms = \sqrt{\frac{(obs_1 - truth)^2 + (obs_2 - truth)^2 + ... + (obs_n - truth)^2}{n}}$$

Where:

$obs_{1...n}$ are the network RTK determined coordinate components
$truth$ is the corresponding ‘truth’ coordinate component
n is the number in the sample e.g. 300 epochs

Table 3. Recorded observations by manufacturer at each test site.

	Site	Net RTK Provider	Number of obs	Number of obs rejected	% Obs reduction	% Obs available after filter (i) and (ii)
Total obs in time window	CALL	Purple	20125			
After CQ filter (i)			20073	52	0.3	
After CQ+DOP filter (ii)			19891	182	0.9	98.8
Total obs in time window		Pink	20775			
After CQ filter (i)			20775	0	0.0	
After CQ+DOP filter (ii)			20308	467	2.2	97.8
Total obs in time window	GRAV	Purple	21254			
After CQ filter (i)			8817	12437	58.5	
After CQ+DOP filter (ii)			5533	3284	37.2	26.0
Total obs in time window		Pink	18430			
After CQ filter (i)			18380	50	0.3	
After CQ+DOP filter (ii)			13281	5099	27.7	72.1
Total obs in time window	GRAG	Purple	23305			
After CQ filter (i)			9048	14257	61.2	
After CQ+DOP filter (ii)			6368	2680	29.6	27.3
Total obs in time window		Pink	18555			
After CQ filter (i)			18555	0	0.0	
After CQ+DOP filter (ii)			18398	157	0.8	99.2
Total obs in time window	STMG	Purple	22176			
After CQ filter (i)			19697	2479	11.2	
After CQ+DOP filter (ii)			19019	678	3.4	85.8
Total obs in time window		Pink	20970			
After CQ filter (i)			20970	0	0.0	
After CQ+DOP filter (ii)			20781	189	0.9	99.1
Total obs in time window	TRET	Purple	22035			
After CQ filter (i)			20773	1262	5.7	
After CQ+DOP filter (ii)			20763	10	0.0	94.2
Total obs in time window		Pink	19961			
After CQ filter (i)			19961	0	0.0	
After CQ+DOP filter (ii)			19642	319	1.6	98.4
Total obs in time window	STRE	Purple	22803			
After CQ filter (i)			22668	135	0.6	
After CQ+DOP filter (ii)			22637	31	0.1	99.3
Total obs in time window		Pink	21273			
After CQ filter (i)			21273	0	0.0	
After CQ+DOP filter (ii)			20816	457	2.1	97.9
Total obs in time window	TUSH	Purple	22583			
After CQ filter (i)			22020	563	2.5	
After CQ+DOP filter (ii)			21302	718	3.3	94.3
Total obs in time window		Pink	21392			
After CQ filter (i)			21392	0	0.0	
After CQ+DOP filter (ii)			20350	1042	4.9	95.1
Total obs in time window	GWYN	Purple	23610			
After CQ filter (i)			23193	417	1.8	
After CQ+DOP filter (ii)			21538	1655	7.1	91.2
Total obs in time window		Pink	23029			
After CQ filter (i)			23029	0	0.0	
After CQ+DOP filter (ii)			21574	1455	6.3	93.7

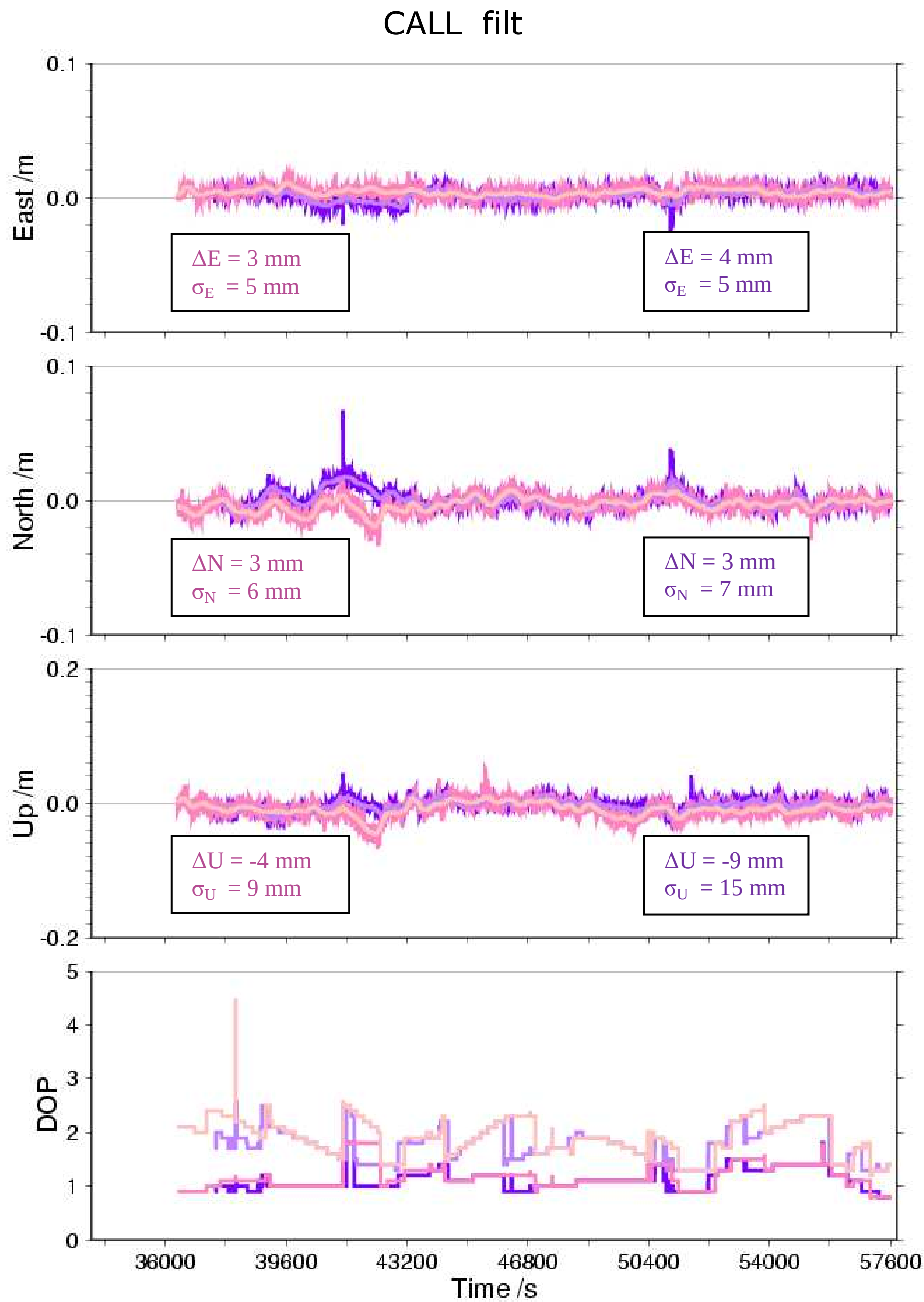

Figure 5. Time series of SmartNet and VRS NOW solutions (epoch by epoch as darker lines, and running average as paler lines) and DOP variations (HDOP as darker lines, VDOP as paler lines) for CALLerton site after application of the CQ filter (i).

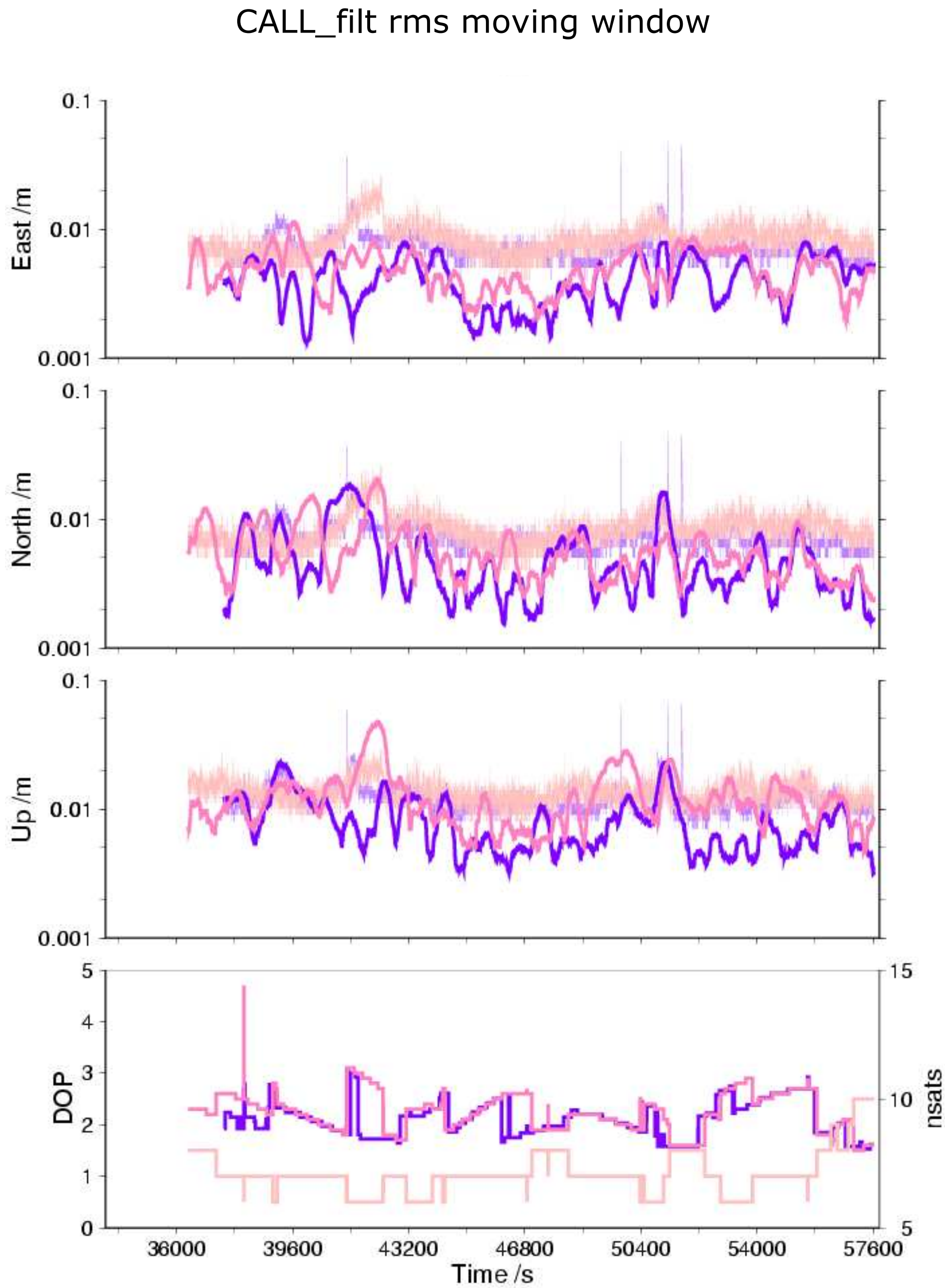

Figure 6. Reported coordinate quality (darker lines) and rms moving window time series (paler lines) of SmartNet and VRS NOW East, North, Up solutions together with GDOP variations (darker lines, left-hand scale) and number of observed satellites (paler lines, right-hand scale) for CALLerton site after application of the CQ filter (i).

Figure 7 shows a typical scatter plot of the plan coordinates for the CALL test site indicating the variation in East and North of VRS NOW and SmartNet solutions. Whilst the raw data is the same as for the East and North panels of Figure 5, the alternate form of the plot enables biases and periods of deviation away from the 'truth' coordinate components to be more easily visualised. The statistics of the individual coordinate components for these plots are naturally the same as those shown for CQ filter (i) type plots.

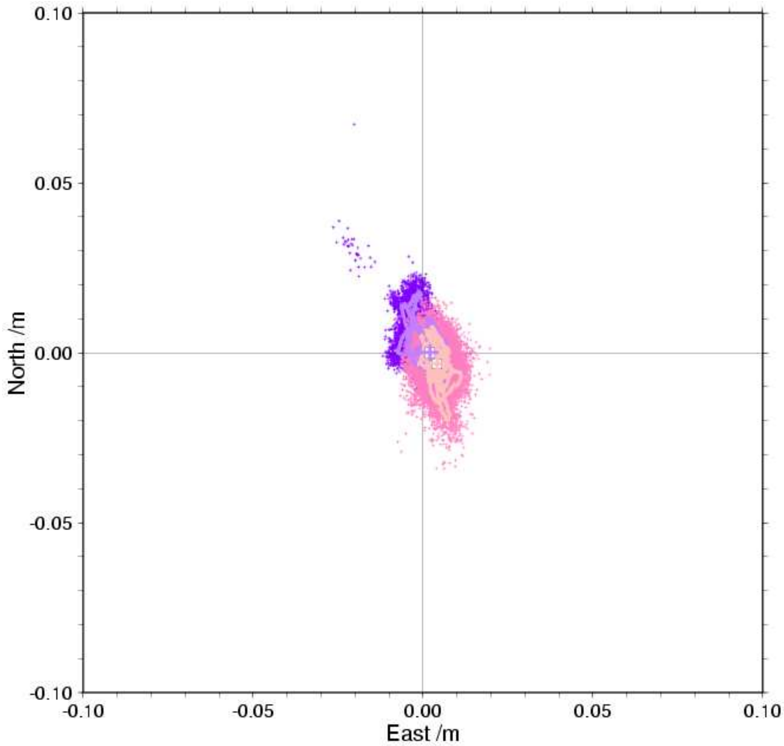

Figure 7. Scatter plot of SmartNet and VRS NOW solutions (darker lines) and moving-window averages (paler lines) for CALLerton site after application of the CQ filter (i).

Table 4 shows the statistics for all sites after application of CQ filter (i) and Table 5 shows the matching statistics after application of CQ+DOP filter (ii). In conjunction with these Tables, histogram plots have been generated. The left hand side of Figure 8 gives the mean and rms values (one sigma) together with histograms for each of the East, North and Up directions and for each manufacturer's equipment. The right hand side of Figure 8 shows cumulative histograms of the absolute differences from the truth coordinates, e.g. for CALL 68% of solutions in the East direction and passing CQ filter (i) fall within 5 mm of the true East component, for the 'purple' equipment. Coordinate quality (CQ) ratio plots have also been generated by determining the actual rms error of a moving 5 minute window and dividing this figure by the network RTK equipment reported quality indicator for the centre epoch of that 5 minute window. Figure 9 presents this ratio plot using a logarithmic scale on the y axis for the East, North and Up coordinate components of CALL following the application of CQ filter (i). Thus where the ratio is less than unity, actual coordinate quality is better than that reported by the equipment, and vice versa.

The corresponding plots to those shown in Figures 5 to 9 for all sites following both filter (i) and (ii) results can be found in Appendix 1.

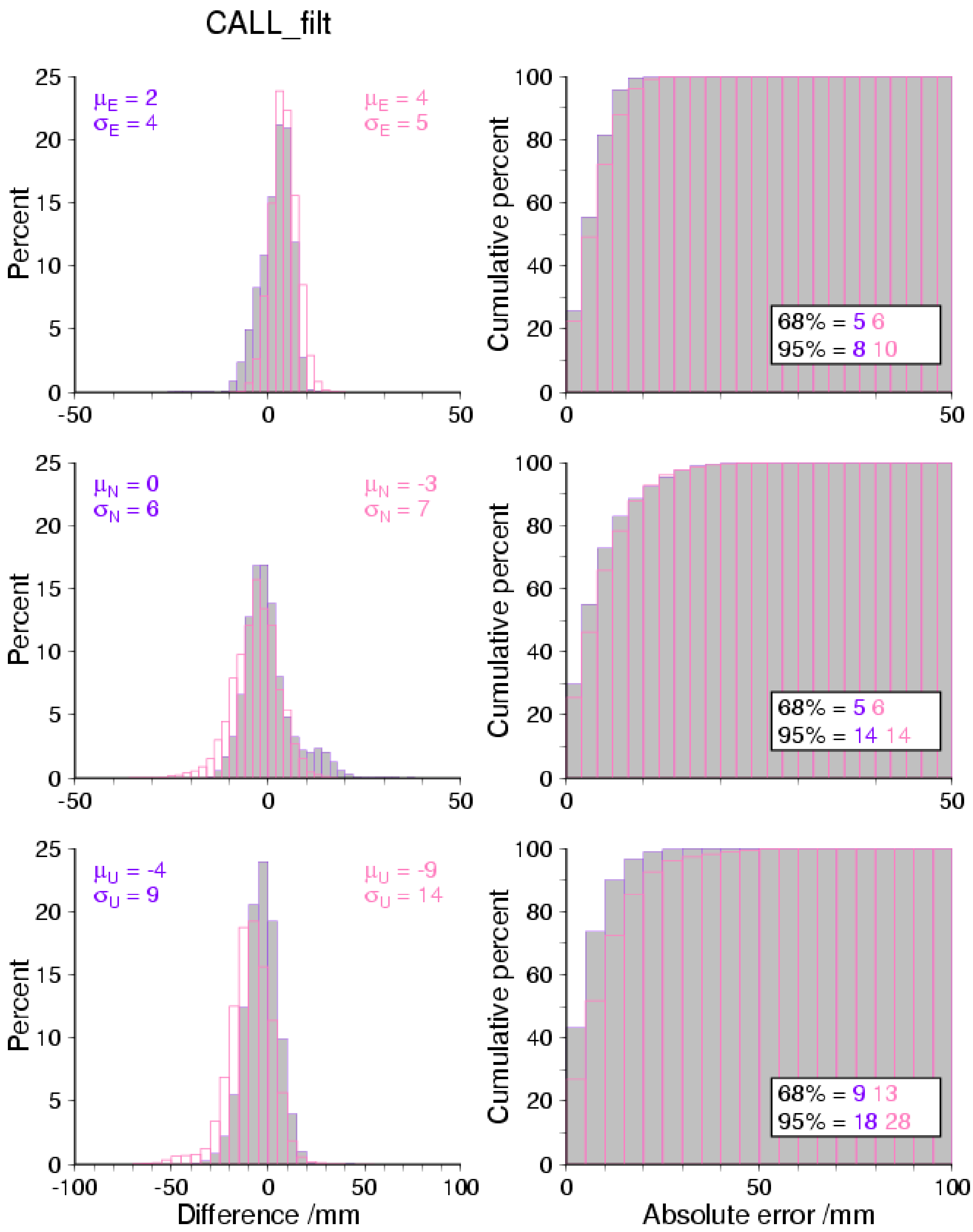

Figure 8. Histogram plots of mean East, North, Up difference and absolute errors in network RTK solutions compared to truth coordinates for the CALLerton site, following the CQ filter (i).

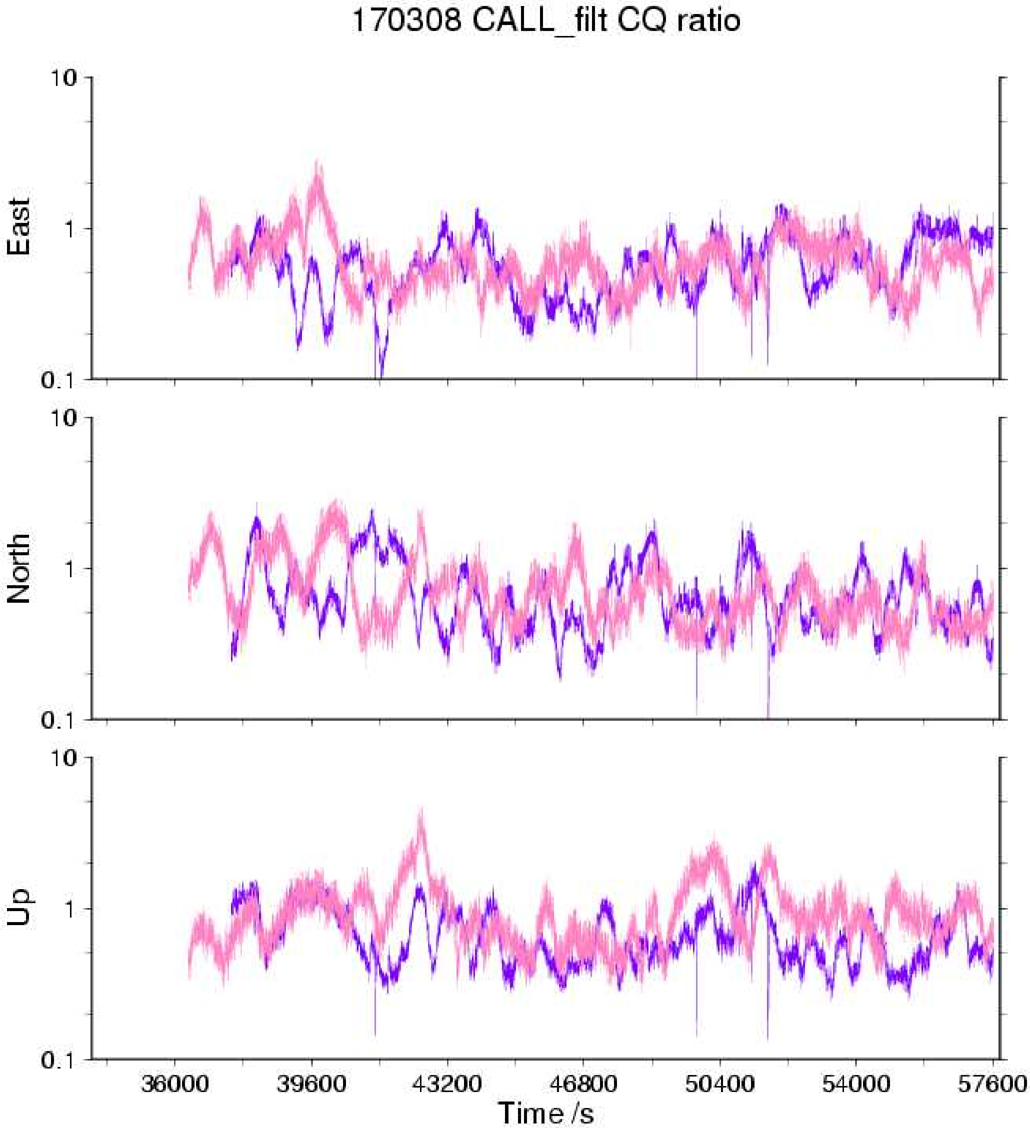

Figure 9. Time series plots of coordinate quality (CQ) ratios for the CALLerton site, following the CQ filter (i).

Table 4. Test statistics for all sites after application of CQ filter (i).

Site Name		CALL			TUSH			GWYN			GRAV		
		North	East	Up	North	East	Up	North	East	Up	North	East	Up
Purple	min (mm)	-15	-26	-38	-127	-125	-110	-48	-56	-107	-29	-27	-75
	max (mm)	67	14	45	62	25	601	52	35	106	62	25	81
	mean (mm)	0	2	-4	13	-4	-13	2	3	21	2	5	-6
	rms (mm)	6	5	9	19	8	24	10	9	30	12	9	23
	Mean CQ	0.709	0.591	0.682	1.456	0.637	1.059	0.822	0.735	1.491	0.958	0.738	1.067
Pink	min (mm)	-34	-8	-69	-33	-42	-81	-128	-73	-167	-52	-34	-132
	max (mm)	17	20	52	37	33	89	54	51	82	86	61	92
	mean (mm)	-3	4	-9	5	-1	-11	5	2	-14	8	6	-10
	rms (mm)	7	5	15	10	8	22	17	13	30	17	14	33
	Mean CQ	0.742	0.614	0.953	0.758	0.592	1.056	0.981	0.805	1.185	1.181	0.939	1.368
Site Name		GRAG			STMG			STRE			TRET		
		North	East	Up	North	East	Up	North	East	Up	North	East	Up
Purple	min (mm)	-62	-41	-2470	-44	-33	-28	-11	-21	-142	-27	-38	-64
	max (mm)	1263	1220	143	22	65	68	85	39	43	48	28	42
	mean (mm)	22	22	-42	-10	9	24	13	7	0	6	-1	-7
	rms (mm)	134	123	261	15	32	30	20	9	24	10	7	19
	Mean CQ	4.380	3.922	4.688	1.205	2.848	1.554	1.308	0.841	1.024	0.880	0.585	0.962
Pink	min (mm)	-55	-43	-129	-23	-55	-62	-21	-14	-64	-28	-31	-70
	max (mm)	65	59	119	44	56	68	32	30	83	34	23	67
	mean (mm)	9	8	-9	7	7	6	9	6	-1	11	1	-9
	rms (mm)	16	14	34	11	28	19	11	8	14	13	7	18
	Mean CQ	1.228	1.124	1.533	0.947	2.314	1.004	0.997	0.753	0.810	1.123	0.573	0.911

Table 5. Test statistics for all sites after application of CQ+DOP filter (ii).

Site Name		CALL			TUSH			GWYN			GRAV		
		North	East	Up	North	East	Up	North	East	Up	North	East	Up
Purple	min (mm)	-15	-26	-38	-127	-61	-110	-48	-56	-107	-23	-27	-75
	max (mm)	67	14	45	62	25	566	52	35	106	62	25	81
	mean (mm)	0	2	-4	13	-4	-14	2	3	21	4	5	-6
	rms (mm)	6	5	9	19	8	24	10	9	30	13	9	24
	Mean CQ	0.727	0.596	0.695	1.424	0.655	1.049	0.842	0.761	1.526	0.960	0.743	1.268
Pink	min (mm)	-34	-8	-69	-33	-42	-81	-128	-73	-167	-47	-31	-109
	max (mm)	17	20	52	37	33	89	54	51	82	62	46	92
	mean (mm)	-3	4	-9	5	-1	-11	5	1	-13	8	6	-9
	rms (mm)	7	5	14	10	8	22	18	14	29	16	13	31
	Mean CQ	0.764	0.622	0.977	0.773	0.600	1.060	0.975	0.823	1.199	1.190	0.974	1.367
Site Name		GRAG			STMG			STRE			TRET		
		North	East	Up	North	East	Up	North	East	Up	North	East	Up
Purple	min (mm)	-62	-31	-129	-44	-33	-18	-11	-21	-142	-27	-38	-64
	max (mm)	84	70	142	16	65	68	85	39	43	48	28	42
	mean (mm)	10	9	-14	-10	8	24	13	7	0	6	-1	-7
	rms (mm)	23	18	38	15	32	30	20	9	24	10	7	19
	Mean CQ	0.669	0.530	0.604	1.268	2.847	1.634	1.308	0.840	1.024	0.880	0.585	0.963
Pink	min (mm)	-55	-43	-129	-23	-55	-62	-21	-14	-64	-28	-31	-70
	max (mm)	65	59	119	44	56	68	32	30	83	34	23	67
	mean (mm)	9	8	-9	7	8	6	9	6	-1	11	1	-9
	rms (mm)	16	14	34	11	28	19	11	9	14	13	7	18
	Mean CQ	1.231	1.124	1.533	0.952	2.302	1.003	0.980	0.759	0.816	1.133	0.577	0.904

Table 6. Effect of time separated averaged window observations compared to non-averaged results for CQ filter (i).

Site	Window Size (sec)	Single window			20 min separation			45 min separation		
		N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
CALL Purple	1	6	5	9	5	4	7	4	3	7
	5	6	4	9	5	4	7	4	3	6
	180	6	4	8	4	3	7	4	3	6
	300	6	4	8	4	3	7	4	3	6
CALL Pink	1	7	5	15	6	5	13	5	5	12
	5	7	5	14	5	5	13	5	5	12
	180	6	5	13	5	4	12	5	4	11
	300	6	5	13	5	4	12	5	4	11
TUSH Purple	1	19	8	24	18	7	20	18	6	21
	5	19	8	24	18	7	20	18	6	21
	180	19	7	22	18	6	19	18	6	19
	300	19	7	21	18	6	19	18	6	19
TUSH Pink	1	10	8	22	8	7	18	8	6	18
	5	10	8	22	8	6	17	8	6	17
	180	9	7	19	7	6	16	7	5	16
	300	8	7	18	7	5	15	7	5	15
GWYN Purple	1	10	9	30	7	7	26	6	7	25
	5	10	9	29	7	7	26	6	6	24
	180	9	9	28	7	7	25	5	6	23
	300	8	8	27	6	6	25	5	6	23
GWYN Pink	1	17	13	30	13	11	23	14	9	23
	5	17	13	29	13	11	22	13	8	22
	180	16	12	26	12	10	20	12	7	20
	300	15	12	25	11	10	20	12	7	19
GRAV Purple	1	12	9	23	11	8	20	12	8	19
	5	12	8	22	11	8	20	12	7	19
	180	12	8	20	11	7	18	12	7	16
	300	12	8	19	11	7	17	12	7	16
GRAV Pink	1	17	14	33	15	11	26	16	13	28
	5	17	14	33	14	11	25	15	12	27
	180	15	12	27	13	10	20	12	11	22
	300	14	11	24	12	9	19	11	10	19
TRET Purple	1	10	7	19	9	5	15	9	5	16
	5	10	7	18	9	5	15	9	5	16
	180	10	6	16	8	4	13	8	4	14
	300	9	6	15	8	4	12	8	4	13
TRET Pink	1	13	7	18	13	6	16	12	6	15
	5	13	7	18	12	6	15	12	5	15
	180	13	6	16	12	5	14	12	5	13
	300	13	6	16	12	5	14	12	4	13

Table 7. Effect of time separated averaged window observations compared with non averaged results for CQ+DOP filter (ii)

Site	Window Size (sec)	Single window			20 min separation			45 min separation		
		N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
CALL Purple	1	6	5	9	5	4	8	4	3	7
	5	6	4	9	5	4	7	4	3	6
	180	6	4	8	4	3	7	3	3	6
	300	6	4	8	4	3	7	3	3	6
CALL Pink	1	7	5	14	6	5	13	5	5	12
	5	7	5	14	6	5	13	5	5	12
	180	6	5	13	5	4	12	5	4	11
	300	6	5	13	5	4	12	5	4	11
TUSH Purple	1	19	8	24	18	7	20	18	6	21
	5	19	8	24	18	7	20	18	6	21
	180	19	8	22	18	6	19	18	6	19
	300	19	7	21	18	6	19	18	6	19
TUSH Pink	1	10	8	22	9	7	18	8	6	18
	5	10	8	22	8	7	17	8	6	17
	180	8	7	19	7	6	16	7	5	16
	300	8	7	18	7	6	15	7	5	15
GWYN Purple	1	10	9	30	8	7	27	7	7	26
	5	10	9	30	7	7	27	7	7	26
	180	9	9	29	7	7	26	6	7	25
	300	8	8	28	6	6	25	5	6	24
GWYN Pink	1	18	14	29	14	11	23	14	9	23
	5	17	13	29	13	11	22	13	9	22
	180	16	12	26	12	10	20	12	8	20
	300	15	12	25	11	10	19	12	7	19
GRAV Purple	1	13	9	24	14	9	23	13	9	22
	5	13	9	24	13	9	22	13	9	22
	180	13	8	22	13	8	21	12	8	19
	300	13	8	22	13	8	20	12	8	19
GRAV Pink	1	16	13	31	15	12	27	15	12	28
	5	16	13	30	15	12	26	14	12	27
	180	15	11	27	14	10	21	14	11	24
	300	15	11	26	14	10	20	14	11	23
TRET Purple	1	10	7	19	9	5	15	9	5	16
	5	10	7	19	9	5	15	9	5	16
	180	10	6	16	8	4	13	8	4	14
	300	9	6	15	8	4	12	8	4	13
TRET Pink	1	13	7	18	13	6	16	13	6	15
	5	13	7	17	12	6	15	12	5	14
	180	13	6	16	12	5	14	12	5	13
	300	13	6	16	12	5	14	12	5	12

6. Commentary

6.1 Network RTK accuracies

One of the key areas of interest this report addresses is typical expected accuracies that should be obtainable with network RTK. After the application of CQ rejection [filter (i)], mean and rms values were computed for all test sites (Table 4). Note that the statistics from this and Table 5 have been computed using all data passing the respective filter criteria. An initial inspection of Tables 4 and 5 indicates that both commercial network RTK systems are operating at similar levels of accuracy overall. In this regard it can be seen that with the application of a simple CQ rejection filter (Table 4), rms accuracies when compared with a 'truth' value range between 6 – 20 mm, 5 – 32 mm, and 9 – 30 mm in the North, East and Up directions respectively. Further inter-comparison between Tables 4 and 5 reveals that the additional application of a DOP limit (3 in this case) does not affect the overall rms statistics at most sites, but improves greatly the performance of the network RTK purple system at GRAG (high multipath), reducing rms values from 134 to 23 mm, 123 to 18 mm and 261 to 38 mm in the North, East and Up directions respectively. These results would suggest that the imposition of a DOP limit of 3 does not adversely affect network RTK performance in the open environment, but in more challenging environments can dramatically improve system reliability.

For surveyors and engineers working in real-time, the luxury of comparative analysis of instantaneous results against 'truth' values is not available. Therefore the CQ values provided via manufacturers’ equipment are vital for ensuring quality. An examination of the CQ plots in Appendix 1 suggests that for the majority of the time, both network RTK systems are providing solutions that have an actual coordinate quality better than that which is reported i.e. CQ ratio values are less than unity, e.g. Figure 9. Naturally there is variation around this, but from a user’s perspective this should engender confidence in the systems. However, for more challenging environments e.g. GRAG, the network RTK pink equipment (following the application of CQ+DOP filter (ii)) predominantly reports over-optimistic CQ values. In contrast, at this site the network RTK purple equipment reports cautious CQ values where filtered solutions are available.

6.2 Repeatabilities

The above figures would appear to suggest that overall the commercial network RTK services are currently achieving accuracies at around the 10 – 20 mm level in plan and 15 – 35 mm level in height (one sigma). However, it should be kept in mind that these statistics are derived from the complete time span of filtered data. Clearly, surveyors/engineers take significantly smaller samples than this. Thus the graphs showing epoch-by-epoch scatter plots for CQ filtered points e.g. Figure 7 give a more visual insight into instantaneous network RTK performance. An examination of these 2D plan plots in Appendix 1 reveals that for a relatively open aspect site such as

CALL, epoch-to-epoch 2D performance does indeed reflect the statistics above. However, for other sites such as TRET, there are excursions away from the 'true' plan coordinate at the 30 mm level that persist for several minutes at a time. For GRAV (high multipath GPS only solutions) excursions are at the 40 – 50 mm level. Even at STRE, another open aspect site (but with larger elevation differences), the network RTK purple equipment suffers a significant and prolonged 2D excursion at the 50 mm level. Short term repeatability, observed over seconds to minutes rather than tens of minutes to hours, may therefore give a misleading impression of accuracy, especially in problematic environments.

The above trends seen for CALL, TRET, GRAV and STRE are further exemplified through examination of the histogram plots in Appendix 1. Generally, these plots show that solutions from both network RTK providers are normally distributed with some small biases although other trends are evident. For example, at TUSH the network RTK purple equipment shows a bimodal distribution for solutions in the North component. However, for station GRAG both pink and purple show similar biases in the East, North and Up directions. More detailed analysis of these distributions is beyond the scope of this report, but overall it can be concluded that the 95% confidence level may be more than twice the rms.

6.3 Working at the network extents

Two sites, STMG and TRET were chosen to be at the extremities of the OS Net active station infrastructure. STMG has active stations only to the west while TRET has active stations only to the east. The geometric conditions represented by these two sites are perhaps a little beyond average but surveyors/engineers working in the coastal zone or indeed Scotland may well encounter similar conditions. For STMG after the application of CQ+DOP filter (ii), the rms errors for the network RTK purple are 15, 32 and 30 mm North, East, and Up compared with 11, 28 and 19 mm East, North and Up respectively for the pink equipment. Comparable figures for TRET are 10, 7 and 19 mm for purple and 13, 7 and 18 mm for the pink equipment. Again, these statistics suggest very good performance overall but examining the 2D plots and histograms for these sites reveals epoch to epoch excursions of up to 30 mm for TRET and significantly larger for STMG together with significant biases in the histograms. Indeed, the results for STMG are rather unusual in that both pink and purple equipment reveal very large excursions at the decimetre level in the East/West direction for quite long time periods. The reason for this cannot be determined from the single data set observed and further experimentation beyond the scope of this report would be required.

Despite Ordnance Survey densification of the active station network it is still possible for the user to be in excess of 50 km (mean distance) from the nearest four active stations in parts of Scotland, Wales and the South West of England. As a visual aid for those working in such areas, Figure 10 shows the mean distance to the nearest four OS Net active stations. Under such conditions surveyors/engineers may wish to consider greater use of the averaging techniques outlined below.

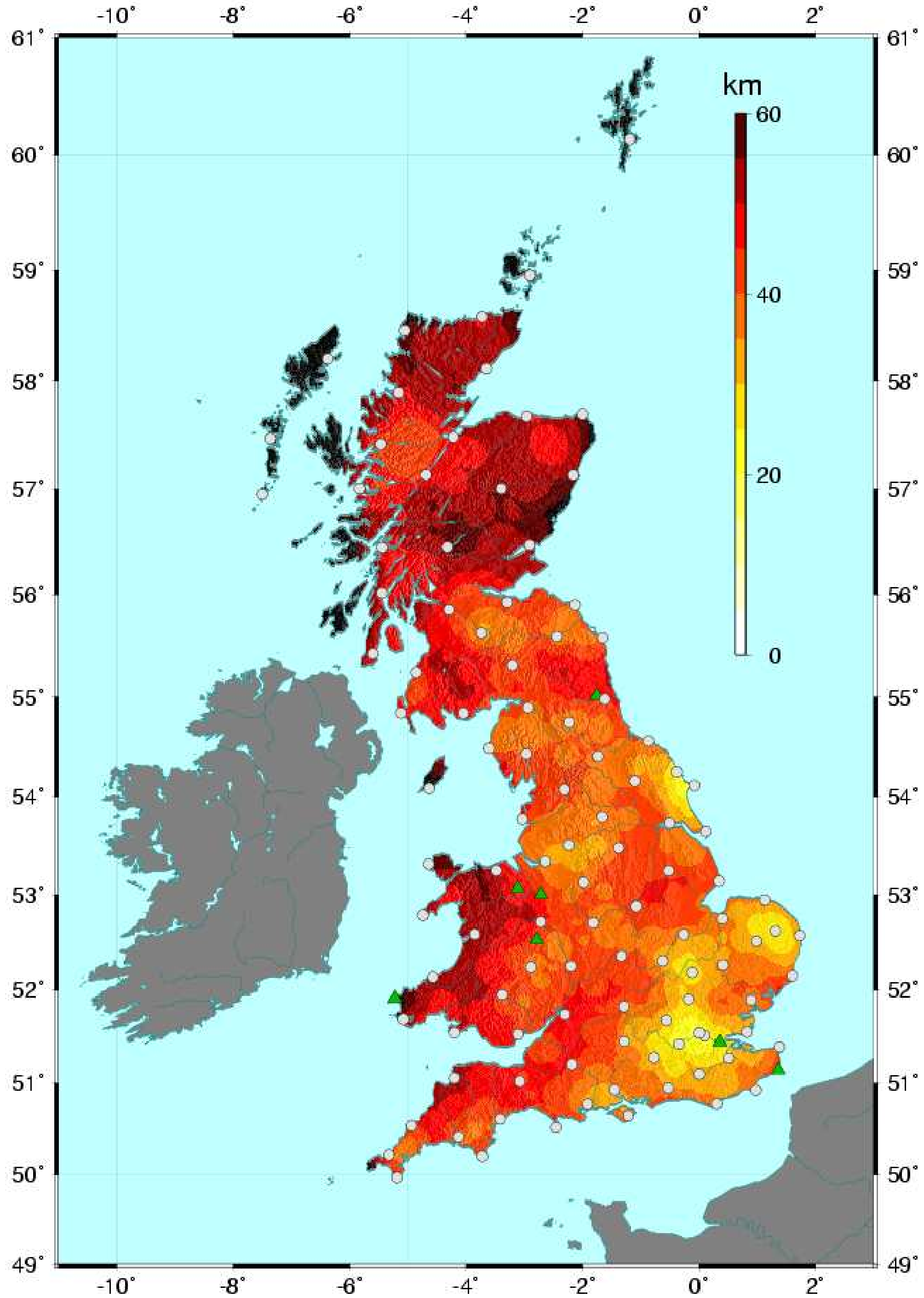

Figure 10. Mean distance from nearest four OS Net active stations (open circles). Green triangles denote test sites used in this work.

6.4 Ocean tide loading effects

The periodic redistribution of water due to the ocean tides loads the Earth's surface, resulting in time-varying *ocean tide loading* (OTL) displacement. The total displacement comprises many periodic terms, but around Great Britain, the dominant terms have semi-diurnal periods of 12 hours 25 minutes (M2) and 12 hours (S2). Lesser effects are also observed with other semi-diurnal and diurnal periods (close to 12 and 24 hours respectively). The complicated Great Britain coastline and shallow seas result in large variabilities in OTL displacement, from up to around ±60 mm over 6 hours in height and ±20 mm in plan near the tip of the South-West Peninsula, to about a third of these ranges throughout much of inland Great Britain east of a line roughly joining Southampton to Aberystwyth. The effect is also large in South-West Wales and the Western Isles. Penna et al. (2008) provide a map of the magnitude of spatial variability of the dominant M2 OTL height displacement across North-West Europe. Instantaneous differences in OTL displacement between a rover and base station can cause errors in the measured coordinates.

The relative baseline technique employed in RTK positioning means that a large proportion of the OTL effects is differenced away, although since the effect is not explicitly modelled in the Trimble VRS Now and Leica SmartNet systems, residual errors will remain. Therefore station TRET in South-West Wales and subject to a large OTL displacement (M2 height amplitude 28 mm), was chosen to assess the importance of unmitigated OTL effects. The nearest Ordnance Survey active station (ANGE 27 km away) has an M2 height amplitude of 32 mm, and over the 6 hour session considered the relative OTL height displacement between TRET and ANGE was ±5 mm. Similarly, between TRET and ABEP (51 km distant) it was ±10 mm and between TRET and MACH (120 km distant) it was ±20 mm. Therefore in the RTK network mode, residual OTL errors in the TRET height estimates would be expected at the 5 – 10 mm level. From inspection of Table 5, the rms height errors over the 6 hour session for TRET are 19 and 18 mm, which are substantially degraded from the control CALL errors of 9 and 14 mm. However, these should be compared with the STRE errors of 14 and 24 mm, which has similar baseline lengths and elevation differences to TRET, yet an M2 OTL height displacement amplitude of only 12 mm. Therefore whilst OTL displacement models undoubtedly should be included in commercial RTK system analyses, more extensive testing is needed, involving more sites and longer observation sessions, to isolate the exact contribution of unmodelled OTL displacement.

Because the dominant periods of OTL are close to 12 hours, in the areas where OTL may be problematic it is possible to estimate a short-term upper bound Σ on the errors at a representative point within a survey area by

$$\Sigma = \sqrt{\tfrac{1}{2}H_1^2 + H_2^2 + \tfrac{1}{2}H_3^2 - H_1H_2 - H_2H_3}$$

where H_1, H_2 and H_3 are the height components determined from three independent averaged windows (see below) separated by 3 – 3¼ hours. More practically, the effect of OTL can be almost completely removed by taking the mean of two averaged window sets of coordinates collected with 6 – 6½ hour separation. This can be seen as follows.

At a given epoch (1), the height of a point is described by

$$H_1 = \overline{H} + A\cos\theta$$

where $\overline{H}$ is the true (long-term mean) height of the point, A is the maximum amplitude of the semi-diurnal OTL displacement there, and θ is the local phase of the tide, which advances through one complete cycle (2π) during the period of the tide (just over 12 hours considering the combined effects of M2 and S2). Just over 3 hours later, the tide will have advanced in phase by a quarter of a cycle (π/2), so the height will be given by

$$H_2 = \overline{H} + A\cos\left(\theta + \tfrac{\pi}{2}\right) = \overline{H} + A\sin\theta$$

and after another similar interval, the tide will have advanced by half a cycle in total, giving

$$H_3 = \overline{H} + A\cos\left(\theta + \pi\right) = \overline{H} - A\cos\theta$$

Taking the first and third measurements, the true height is clearly given by

$$\overline{H} = \tfrac{1}{2}\left(H_1 + H_3\right)$$

biased only by the smaller diurnal OTL error which will not be cancelled out over the same interval.

Taking the first measurement, subtracting the true height and squaring, we get

$$\left(H_1 - \overline{H}\right)^2 = A^2\cos^2\theta$$

and similarly for the second measurement,

$$\left(H_2 - \overline{H}\right)^2 = A^2\sin^2\theta$$

Adding these together and substituting for $\overline{H}$ yields an estimate of the amplitude A of the semi-diurnal OTL displacement at that point.

$$A = \sqrt{\tfrac{1}{2}{H_1}^2 + {H_2}^2 + \tfrac{1}{2}{H_3}^2 - H_1H_2 - H_2H_3}$$

Because the interaction of the tidal constituents leads to modulation of A (spring and neap tides), this estimate is only valid on the day of observation, although it may reasonably be adopted on adjacent days. It will also tend to be an overestimate, because of the random errors present in observations H_1 H_2 and H_3. Individual network RTK measurements made in the vicinity will be biased by OTL by an amount smaller than $\pm A$, so the bound on OTL error Σ given above is best described as a short-term upper bound. If the value of A is sufficiently small (within survey tolerance), there is no need to carry out the averaging of 6 – 6½ hour separated coordinate sets as described above.

The OTL-related errors associated with any other coordinate component i.e. East, North, can be similarly determined and mitigated, although it should be remembered that these are typically only around a third of the magnitude of the vertical error in the locality.

6.5 Windowing and repeating observations

Current advice from both commercial network RTK providers is that some form of epoch to epoch averaging is recommended where the most precise surveying is required. Two key questions therefore present themselves:

(i) What is the optimal reasonable averaging window period, given time constraints that exist in most survey tasks?

(ii) Does taking the average of two such windows, separated by a time period to allow for constellation geometry change and possible change in atmospheric conditions, improve solutions further?

To answer these questions statistics have been generated for 1, 5, 180 and 300 second samples using only a single moving window average and then for a double-window average using the average of two such windows separated by 20 or 45 minutes. Tables 6 and 7 present these figures for CQ filter (i) only and CQ+DOP filter (ii) results respectively. As current practice generally recommends the application of a DOP filter when using network RTK, only results from Table 7 are considered here where a DOP value of 3 has been applied. Thus in regard to question (i) above the rms errors based on a single 1 second window range from 6, 8, 9 mm to 19, 14, 31 mm in the North, East and Up directions respectively. Little improvement is seen for a window of 5 seconds duration. However, for a 3 minute window some small improvement can be seen particularly in the Up direction, although further averaging over a single window e.g. 5 minutes does not appear to offer much additional improvement on the determined coordinates. With regard to question (ii), results from the mean of two windows separated by 20 minutes show more substantial reductions in the rms values compared to a single window approach. For example, employing this approach at TUSH based on 5 second windows improves coordinate rms values in the Up direction by 4 mm for both network RTK pink and purple equipment. Similar improvements are also noted for GRAV where multipath was more challenging. In this case, employing two 3 minute windows separated by 20 minutes offers improvement in the rms value of the Up coordinate but does not in general give significantly improved results, nor does the use of a 45 minute separation appear to offer any real improvement over that of 20 minutes. The reason for the improvement delivered by this double window averaging approach is that the separation period is driving down short period system biases. However, beyond 45 minutes no significant advantage is derived from this technique.

Based on the results obtained single window averaging yields some improvement in coordinate determination but taking the mean of coordinates derived from time separated windowing (e.g. 20 minutes) offers better results. It should be noted however that the results obtained by the user may not demonstrate such significant improvements in that the second window will require the equipment to be reset over the station with the consequent introduction of centring errors not present in our test scenarios. That said, in the field the potential for compensating errors in re-centring may well mask any biases. Further testing would be required to determine such effects but this is currently beyond the scope of this report.

6.6 Height effects

One of the challenges when using any GNSS technique is the mitigation of tropospheric effects. Traditionally, for static processing and single base station RTK surveying up to distances of around 10 km, this has been addressed by the use of differencing together with models of the 'dry' atmosphere, e.g. Saastamoinen (1972). Key assumptions in the employment of such models are that the base and rover stations are at similar altitudes and that the baseline distances are relatively short. Clearly, these conditions cannot always be satisfied when using network RTK and while tropospheric models remain important, manufacturers must deal with residual tropospheric delays arising from different atmospheric conditions at the rover and reference station locations. To investigate this, sites TUSH and GWYN were chosen. Table 1 shows that TUSH has a mean height difference of only 16 m from the nearest four OS Net active stations, whereas for GWYN this value is ~250 m. The range of baseline distances from OS Net active stations to both GWYN and TUSH is similar. After application of CQ+DOP filter (ii), Table 5 shows that the rms values overall are slightly worse for GWYN in comparison to TUSH, suggesting that despite the large height separation at GWYN both network RTK systems are able to deal with residual tropospheric error to a large extent. However, where these height differences increase (e.g. Snowdonia, the Lake District and Scottish Highlands) as shown in Figure 11, the mitigation of residual tropospheric effects cannot be guaranteed. Under these circumstances the adoption of windowing techniques should again be considered. It should also be noted that it is possible for the user to be significantly below the nearby OS Net active stations.

6.7 Other satellite constellations (GLONASS aiding)

Sites GRAV and GRAG differ only in that GRAG was operated in GLONASS-enabled mode. A comparison of the CQ+DOP-filtered results (Table 5) suggests that, if anything, the inclusion of GLONASS has led to a small worsening in position quality. However, this should not be over-interpreted as one manufacturer's system suffered severe communication problems during the tests at GRAG, reducing the total available data for subsequent analysis. It can be concluded that additional satellite constellation signals improve network RTK system availability. However, since the testing phase of this work, further OS Net active stations offer GLONASS signals and it is recommended this section of the work be reassessed in the future.

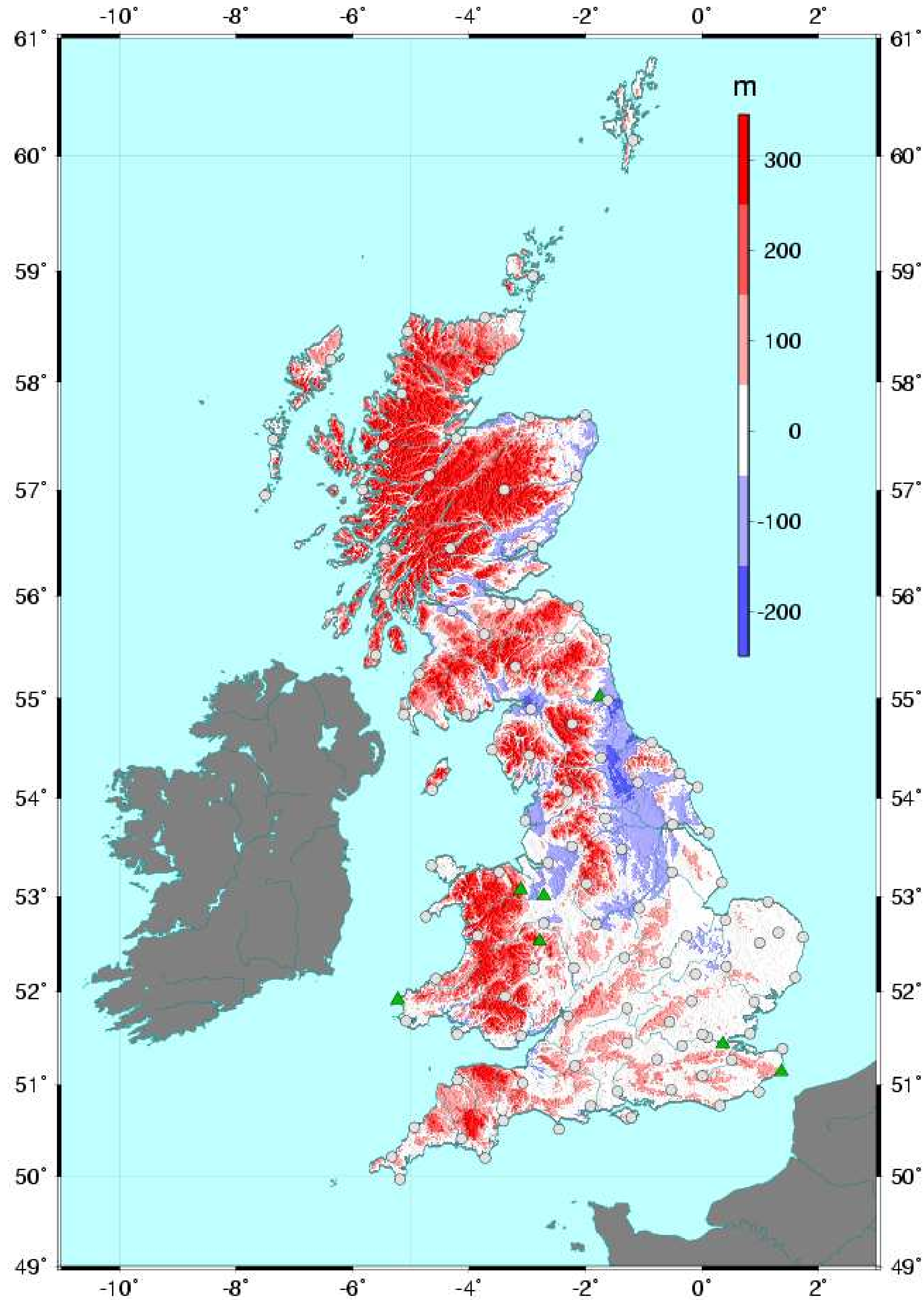

Figure 11. Mean height difference from nearest four OS Net active stations (open circles). Green triangles denote test sites used in this work.

7. Recommendations for best practice

The primary goal of this report is to provide underpinning quantitative analysis of network RTK provision in Great Britain upon which best practice guidance for users of the various systems can be soundly based. A total of seven test sites were chosen to provide a range of representative situations that users of network RTK might face. Selection criteria included factors such as the distances and elevation differences to nearby OS Net active stations, the aspect (open or urban), proximity to edges of the network, and susceptibility to ocean tide loading effects. At each site approximately 6 hours of data were collected from each of the two current (2008) commercial providers of network RTK solutions in Great Britain using proprietary equipment and firmware configurations.

The following sections present the fundamental text for the proposed best practice document. However, previous guidance notes such as the *RICS Guidelines for the Use of GPS in Surveying and Mapping* (RICS, 2003) and *Virtually Right? – Networked GPS* (RICS, 2007) have already addressed many of the more fundamental aspects of GPS use and still provide a useful body of knowledge which practitioners are encouraged to use.

In preparing the best practice text below the intention is to complement and extend current guidance and whilst the body text addresses best practice for network RTK surveying in Great Britain it does not address, but assumes the user adopts, general best practice for GPS RTK surveying. Additionally, it is worthy of comment that the use of local base station RTK remains a viable option for land and engineering surveying in Great Britain, although its attendant overheads of cost, security and efficiency make it less attractive in many situations.

7.1 Accuracy

Accuracy is a measure of the difference between a particular measured coordinate and its true value, often quoted as the root mean square error (rms). If the measurement is unbiased and has normally distributed errors, then for each coordinate component roughly 68% of individual solutions will have errors smaller than the rms, and 95% will have errors smaller than twice the rms. However, systematic errors (biases) will reduce these percentages.

Typically, commercial network RTK solutions within Great Britain provide instantaneous results (i.e. single epoch coordinate solutions) that achieve rms accuracies around 10 - 20 mm in plan and 15 - 30 mm in height, with relatively small biases.

7.2 Equipment configuration

Users of commercial network RTK should ensure that their rover firmware is configured according to manufacturer guidelines. Significant variations from recommended settings may lead to unacceptable variations in determined coordinates.

Geometric Dilution of Precision (GDOP) is a measure of the worsening of a GNSS solution caused by the geometric arrangement of visible satellites. Often a maximum GDOP of 5 is imposed. Reducing the GDOP limit to 3 will increase the robustness of determined coordinates under challenging conditions (e.g. urban canyons) but does not reduce productivity in open/benign environments where GDOP values between 2 and 3 predominate. The imposition of such a filter on average provides the user with over 95% of possible coordinate solutions.

7.3 Quality indicators

Users of network RTK should ensure their rover unit is set to display all available coordinate quality indicators for their position fix and pay close attention to them. In most situations these indicators reflect well the actual performance of your system. Coordinate solutions where the reported quality is worse than 100 mm generally result from problems with satellite lock or ambiguity resolution, and should always be discarded. In the most challenging environments (e.g. restricted satellite visibility, large distances or height differences to surrounding OS Net active stations, or high multipath), reported coordinate quality may be over-optimistic by a factor of 3 – 5 especially in the height component. This can be mitigated as below.

7.4 Improving solution robustness

For topographic survey, the use of a 5 second window average will reduce the effect of individual coordinate solution variations. For precise work, especially where the height component is important e.g. control station establishment, the process of double window averaging should be undertaken. Users should observe an averaged window of around 3 minutes followed by another averaged window of the same length separated from the first by a suitable time period e.g. 20 minutes. On average, a time separation of 20 minutes will yield a 10 – 20% improvement in coordinate accuracy and a 45 minute separation will yield improved accuracies at the 15 – 30% level compared to a single epoch solution. Window separations of greater than 45 minutes do not typically provide appreciable further improvement to the determined coordinates, except for the mitigation of ocean tide loading effects (see Section 7.8).

7.5 Additional satellite constellations

When surveying in challenging satellite visibility environments (e.g. urban canyons), the use of satellites from other global navigation satellite system constellations (e.g. GLONASS) can improve overall satellite visibility and hence allow surveying to proceed with less downtime, but may not necessarily lead to an improvement in accuracy. Where satellite availability is significantly diminished (e.g. under a tree or close to an overhang), it is recommended that surveyors/engineers adopt standard terrestrial survey techniques to radiate from a nearby unobstructed point and should not attempt to use network RTK.

7.6 Surveying at the limits of the network

Limited testing of network RTK performance at the network extents (e.g. some parts of the coastal zone) shows greater frequency of excursion from the expected system performance. To aid planning, Figure 10 shows the mean distance to the nearest four OS Net active stations. Users of network RTK who work frequently in areas where this mean distance is large, or where they are outside the polygon formed by the nearest OS Net active stations, should consider making greater use of single window averaging for normal topographic survey and double window averaging for control station establishment.

7.7 Height Effects

For the majority of England and Wales, the errors caused by the tropospheric effects and height variations between OS Net active stations and your network RTK rover position are generally well modelled by network RTK providers. However, where these height differences increase (e.g. Snowdonia, the Lake District and Scottish Highlands), it is recommended that the procedures as for surveying at the limits of the network be adopted to reduce heighting error. To aid planning, height difference from the nearest four OS Net active stations is shown in Figure 11. Note that it is also possible to be significantly below the nearby OS Net active stations.

7.8 Ocean Tide Loading

Ocean tide loading (OTL) is the time-varying displacement of the Earth's surface due to the weight of the ocean tides, and can reach ±60 mm in height and ±20 mm in plan near the tip of the South-West Peninsula and Western Isles. In mainland Britain it decreases to slightly less than half of this magnitude east of a line roughly joining Southampton to Aberystwyth. Instantaneous differences in OTL between a rover and base station can cause errors in the measured coordinates.

Network RTK reduces OTL error to current system noise levels throughout most of mainland Britain. In areas where OTL remains a concern, its effect can be almost completely removed by taking the mean of two sets of coordinates collected with 6 to 6½ hour separation.

To assess the potential OTL error in a locality on a given day, an upper bound $\sum$ on the height error due to OTL can be estimated by

$$\Sigma = \sqrt{\tfrac{1}{2}H_1^2 + H_2^2 + \tfrac{1}{2}H_3^2 - H_1H_2 - H_2H_3}$$

where H_1 H_2 and H_3 are the height components determined from windows separated by 3 – 3¼ hours. If $\sum$ is less than the survey tolerance, the above averaging procedure may be omitted.

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Glossary

Ambiguity	Initial bias in a carrier phase observation of an arbitrary number of cycles. When a GNSS receiver first locks onto a signal the measurement is biased by an integer number of cycles because the receiver does not know the exact number of carrier wave cycles between the antenna and the satellite.
CQ	Coordinate Quality. In the context of network RTK this is a measure of the quality of a position fix, as reported by the receiver (usually in metres). Note it is not that same as DOP.
DOP	Dilution of Precision is a dimensionless number accounting for the contribution of relative satellite geometry to the errors in position determination.
Elevation Mask	Angle above the local horizon in degrees, below which no satellite signals will be recorded. Also referred to as elevation cut-off angle.
Epoch	A particular instant in time for which data values are recorded.
ETRF89	European Terrestrial Reference Frame 1989.
Galileo	A planned European global navigation satellite system, equivalent and complementary to GPS and GLONASS.
GDOP	Geometric Dilution of Precision. Dimensionless value reflecting the effect of the combined errors of latitude, longitude, altitude and time on the accuracy of a three-dimensional position fix.
GLONASS	An alternative and complementary global satellite navigation system to GPS developed by the former Soviet Union.
GNSS	Global Navigation Satellite System. Collective term used to refer to the various navigation satellite constellations including GPS, GLONASS, Galileo etc.
GPS	Global Positioning System. Constellation of nominally 24 navigation satellites continuously orbiting the Earth and transmitting microwave signals suitable for the determination of three dimensional positions. The system was originally developed by the U. S. Military.

IGS	International GNSS service, formerly the International GPS service. Voluntary organisation of worldwide agencies that combine GPS and GLONASS data to produce precise GPS and GLONASS orbit products.
Ionospheric free	GNSS observable free from ionospheric effects. These can be modelled in basic software or mitigated by data processing.
L1/L2 frequencies	Radio carrier frequencies transmitted by GPS satellites. L1 carries the Coarse Acquisition Code (C/A-code), P-code and the navigation message (1575.42 MHz). L2 carries the P-code only (1227.6 MHz).
MAC	Master-Auxiliary Concept. A network RTK algorithm used by the Leica SmartNET system.
OS Net®	Ordnance Survey OS Net®. The network of continuously operating GNSS receivers installed and operated by Ordnance Survey throughout Great Britain.
OTL	Ocean Tide Loading. Time varying displacement of the Earth's surface arising from the periodic redistribution of water due to the ocean tides.
PDOP	Position Dilution of Precision. Dimensionless value expressing the relationship between the error in user position and that in satellite range. Geometrically, for four satellites the PDOP is proportional to the inverse of the volume of the pyramid formed by unit vectors connecting the antenna to the four satellites.
RMS	root mean square (rms).
RTK	Real Time Kinematic.
SmartNET	Commercial network RTK service provided throughout Great Britain by Leica Geosystems.
Tropospheric delay	Delay affecting GNSS signals caused by water vapour present in the lower atmosphere.
VRS	Virtual Reference Station. A synthesised set of GNSS observations generated for a given location from the real GNSS observations collected at nearby static receivers.
VRS NOW	Commercial network RTK service provided throughout Great Britain by Trimble.

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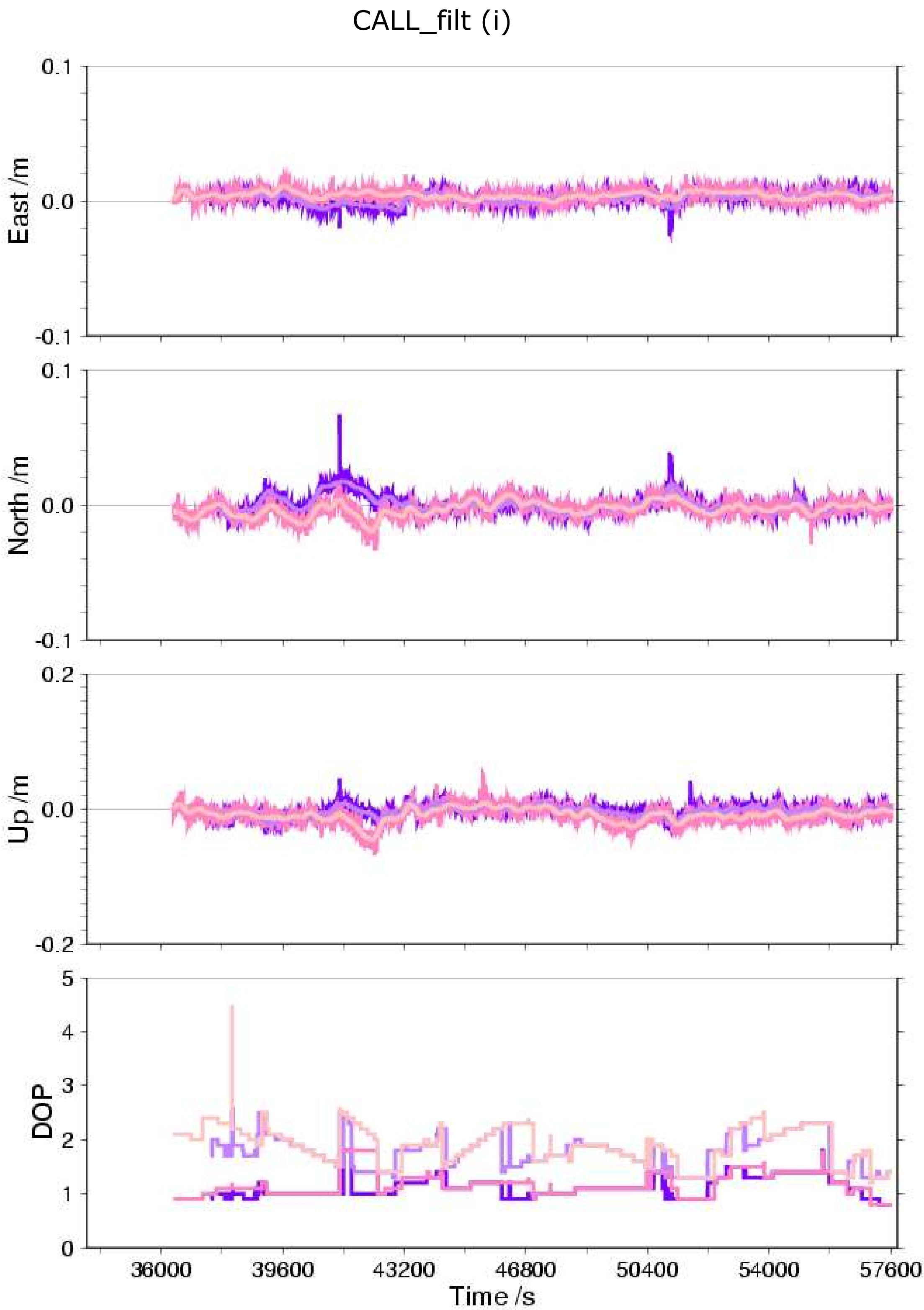
Appendix 1

CALLerton

L = 10 – 67 km, σ_L = 51km
Δh = 53 m, $\sigma_{\Delta h}$ = 144 m



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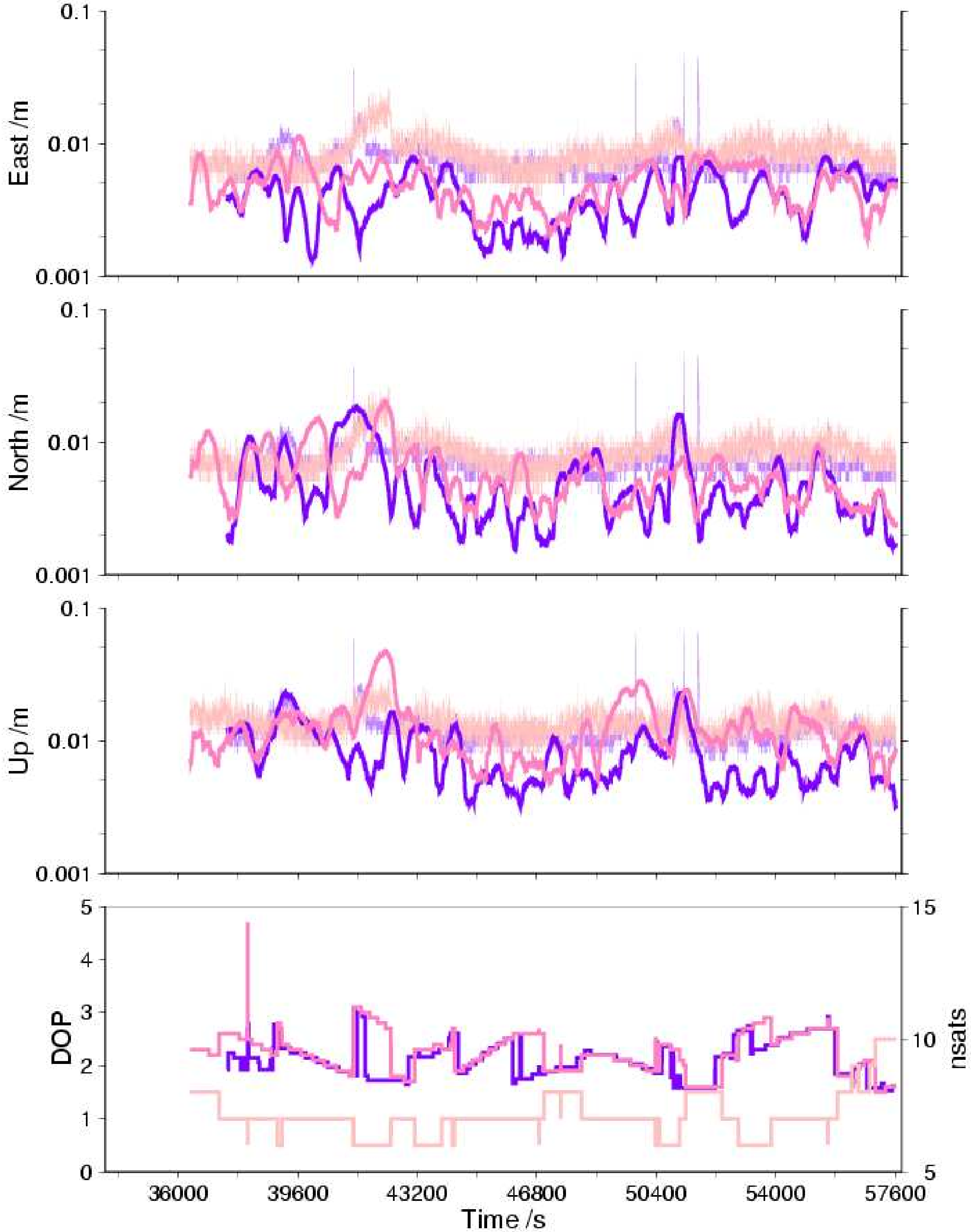

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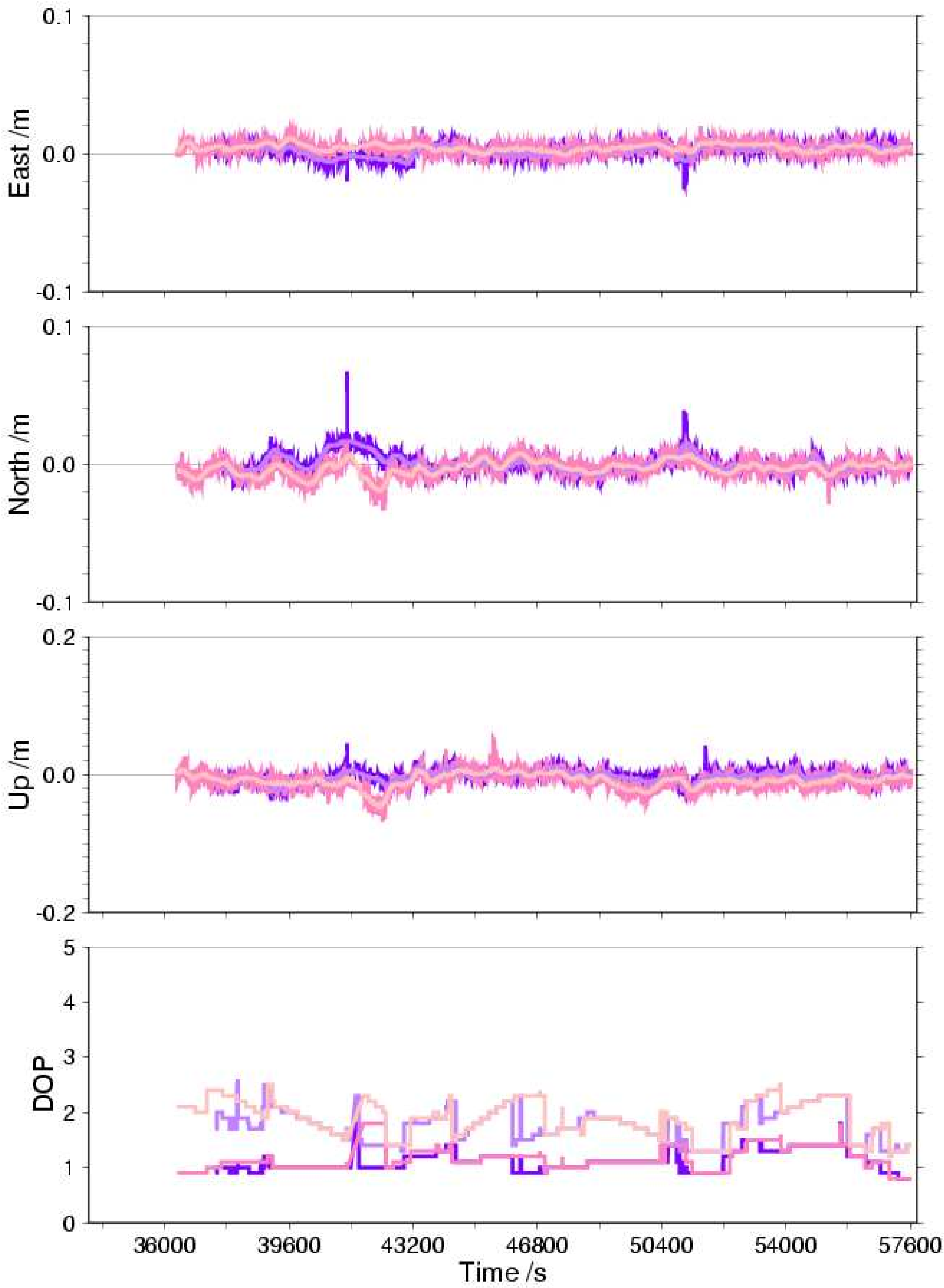

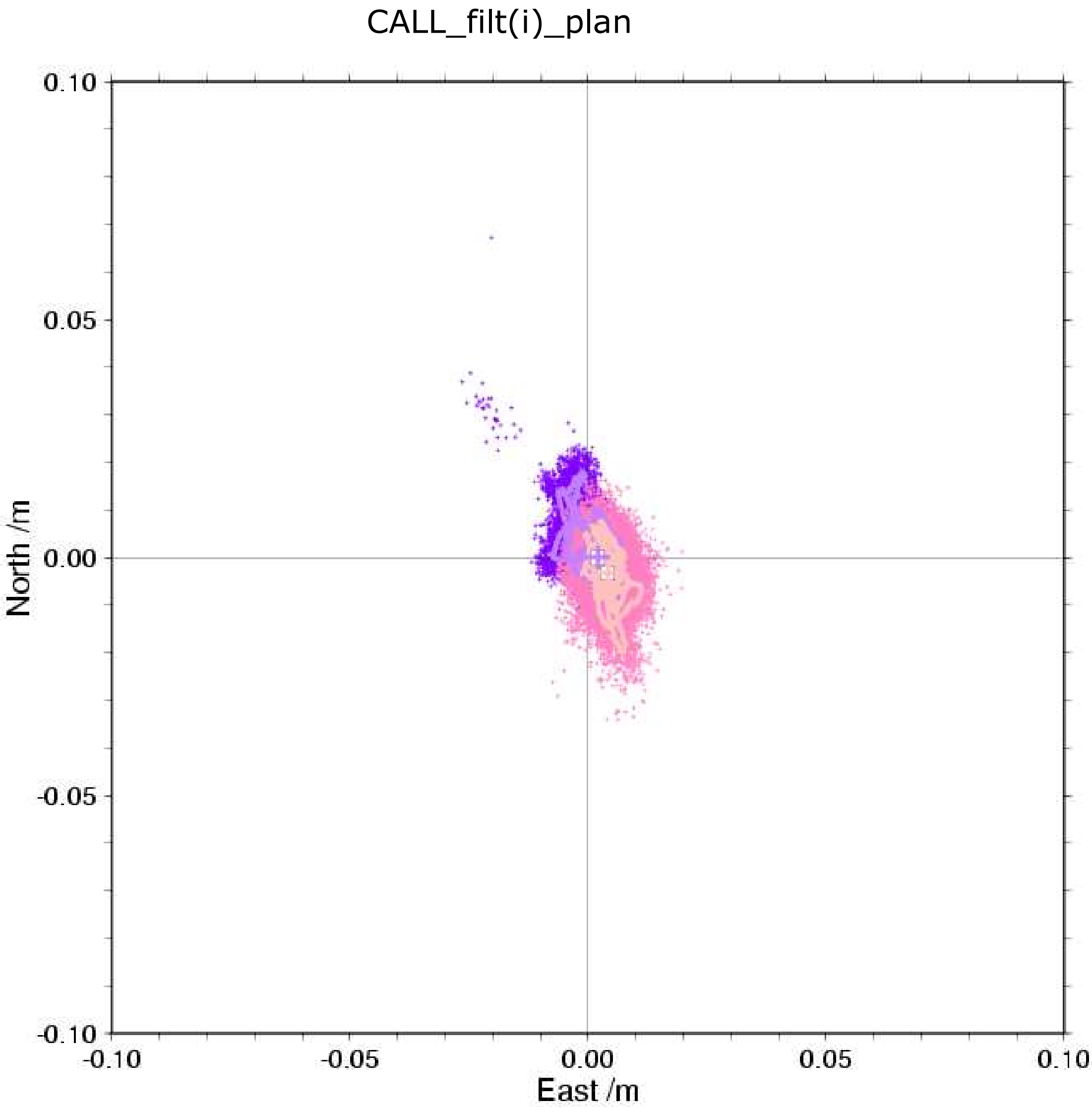
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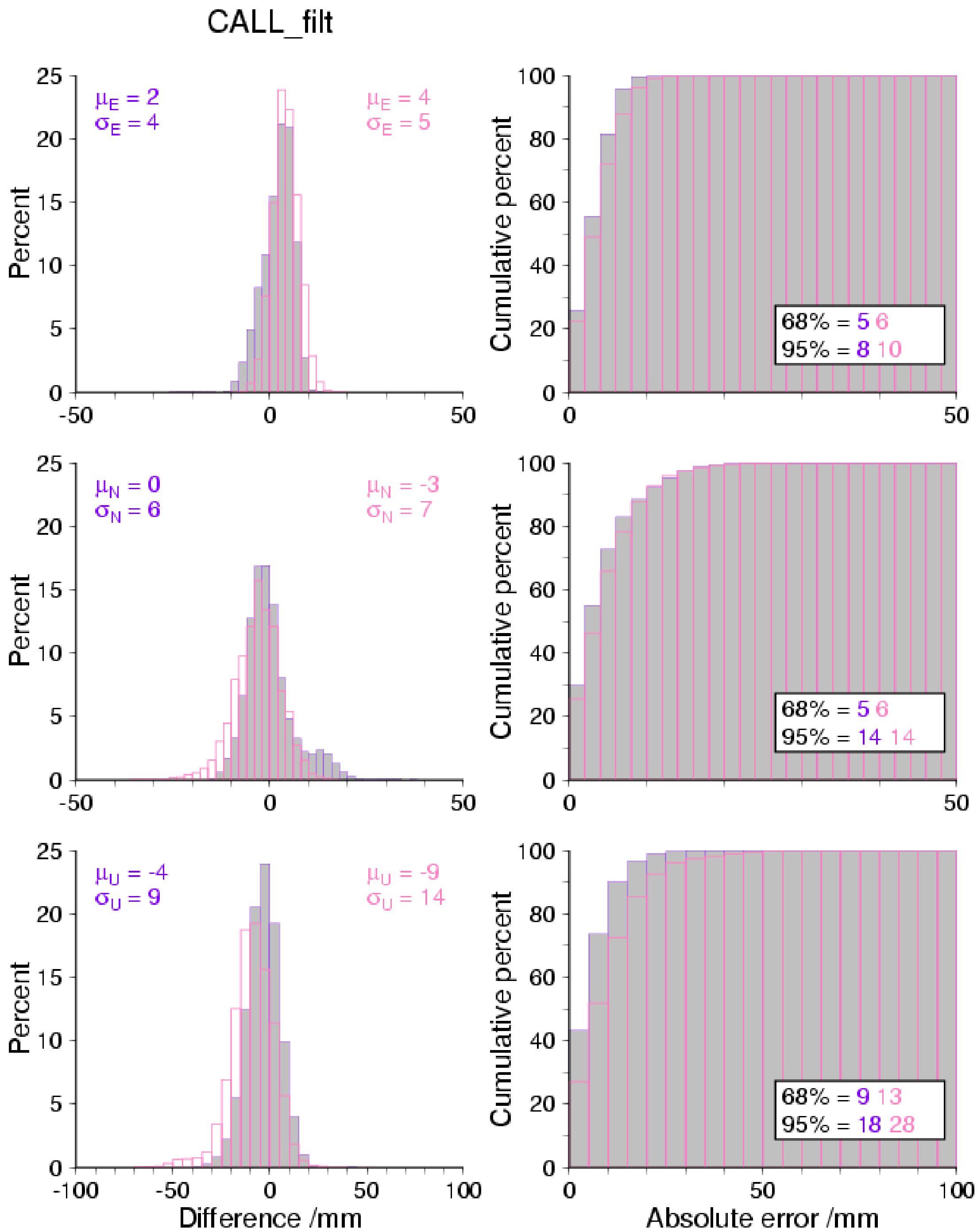
0.00
-0.05
-0.10
North /m
-0.10
-0.05
0.00
0.05
0.10
East /m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Percent
Cumulative percent
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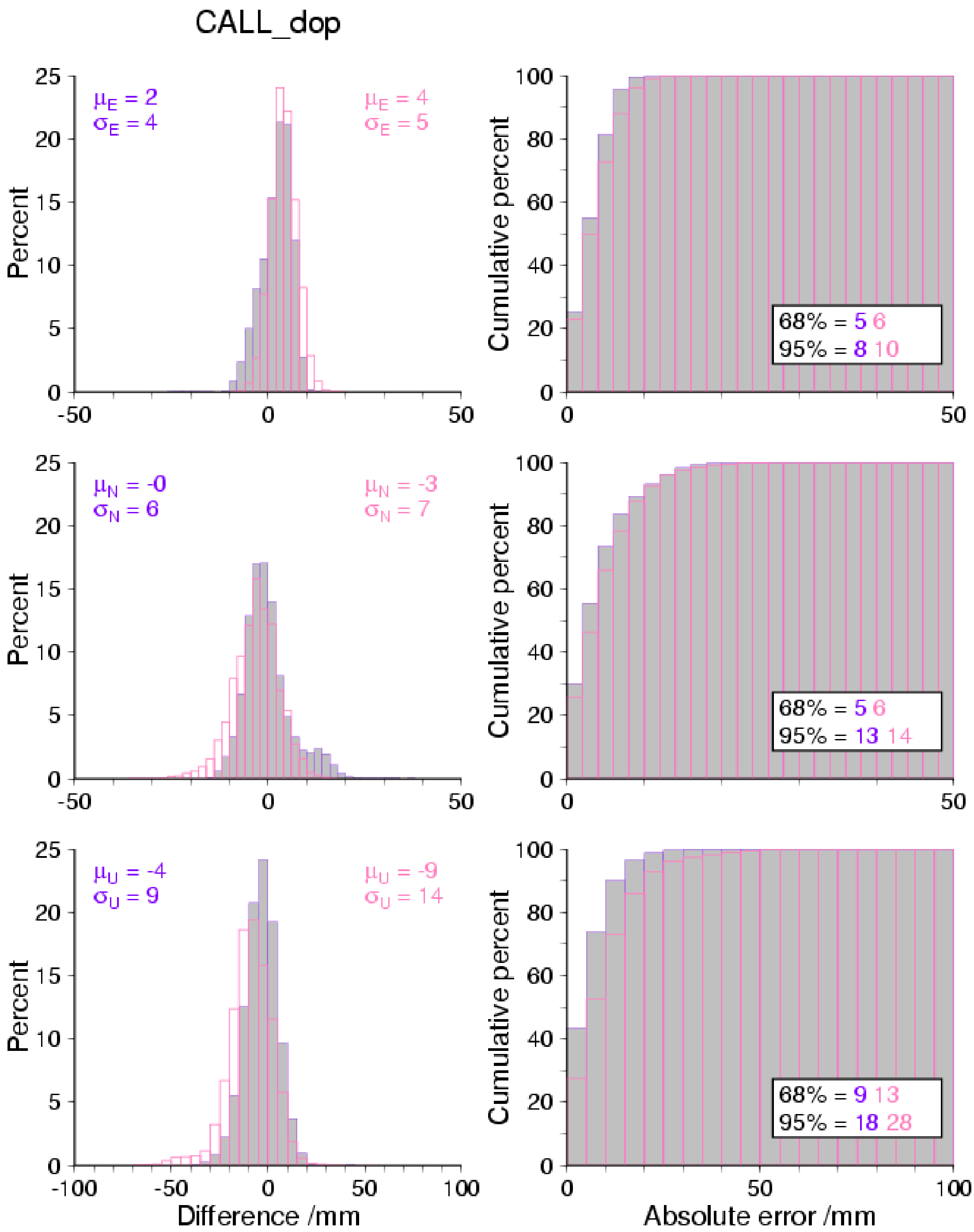
σE = 4
μE = 4
σE = 5
68% = 5 6
95% = 8 10
μN = 0
σN = 6
μN = -3
σN = 7
68% = 5 6
95% = 14 14
μU = -4
σU = 9
μU = -9
σU = 14
68% = 9 13
95% = 18 28
Difference /mm
Absolute error /mm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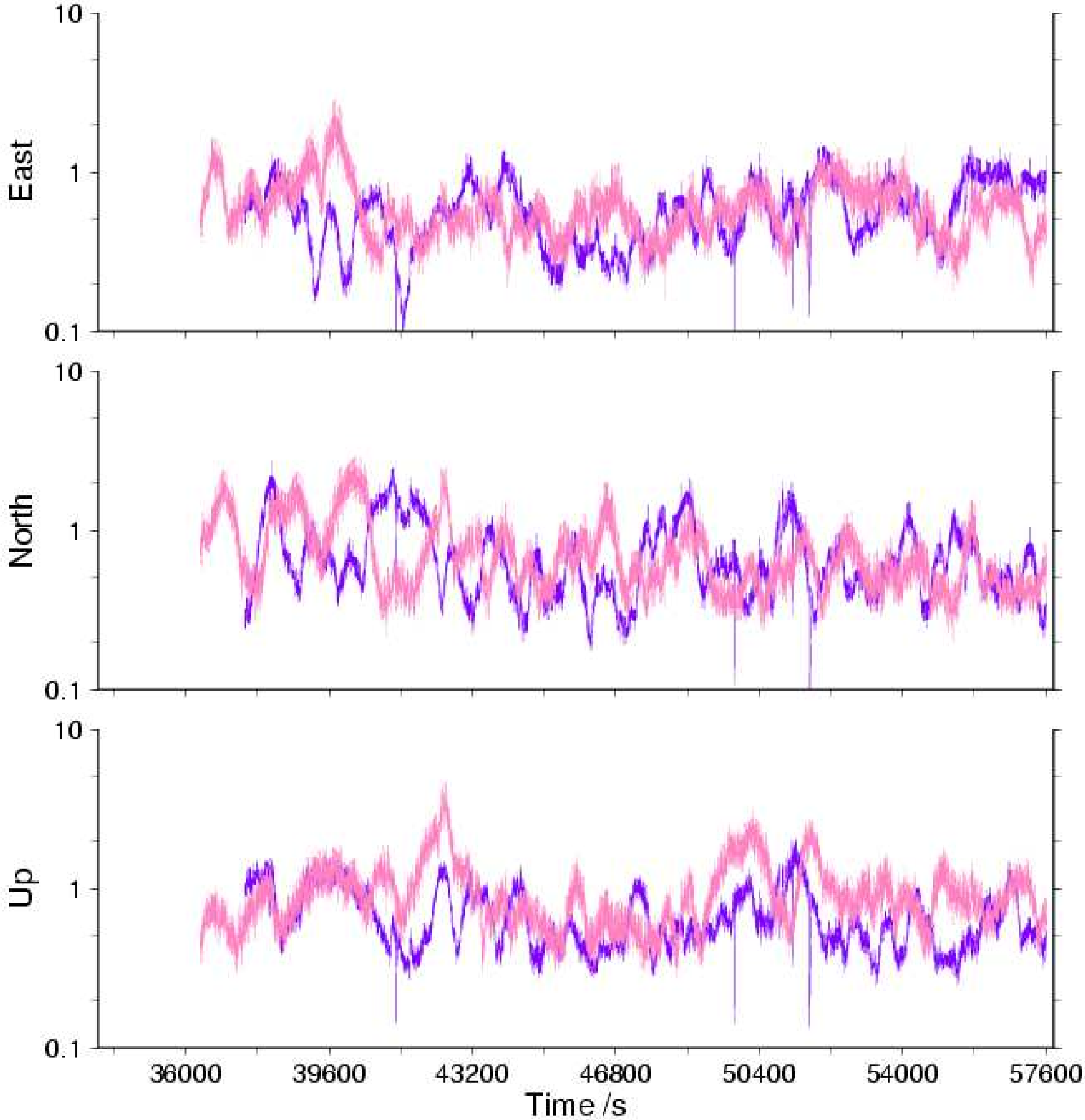
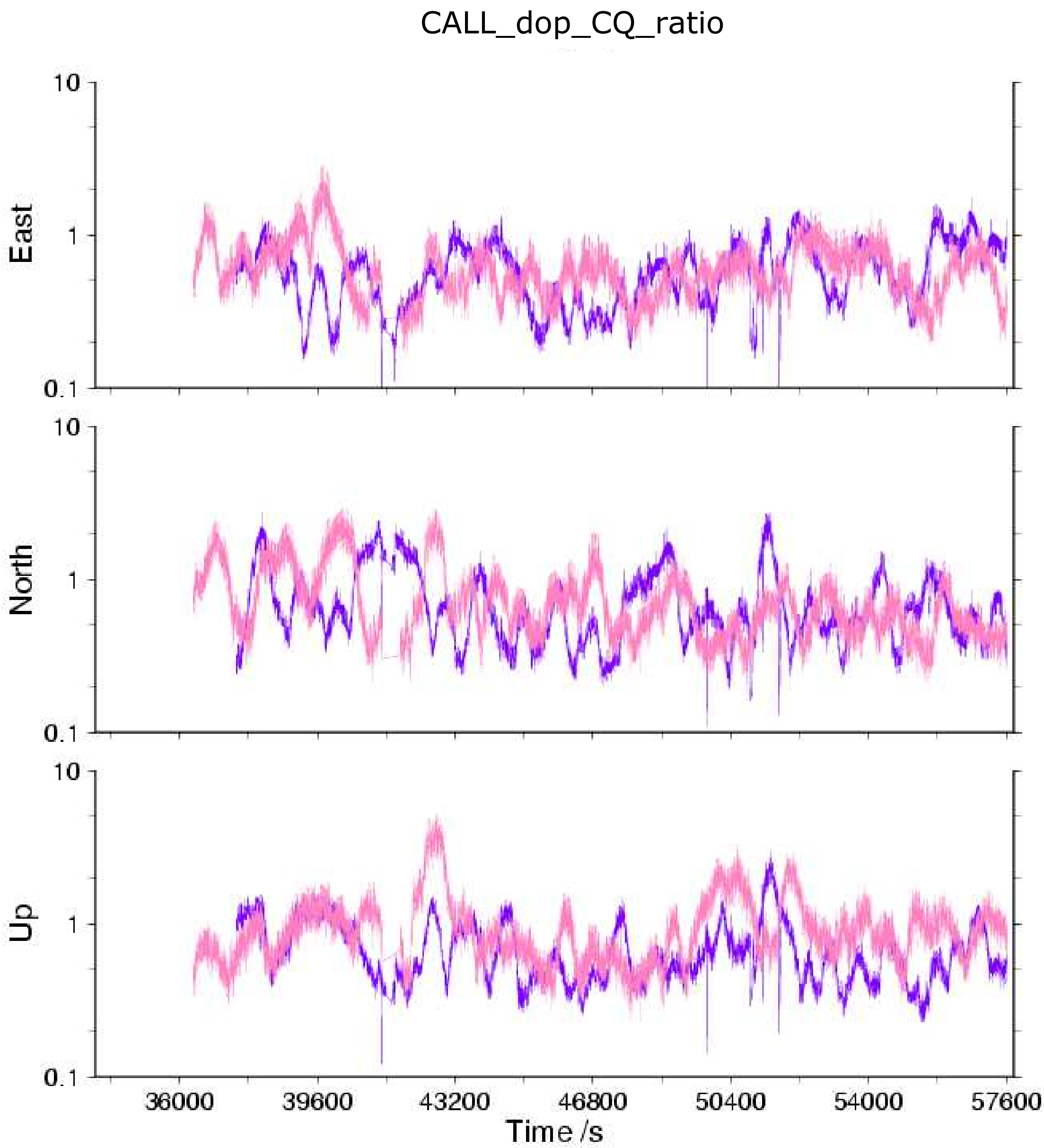
σE = 4
μE = 4
σE = 5
68% = 5 6
95% = 8 10
μN = -0
σN = 6
μN = -3
σN = 7
68% = 5 6
95% = 13 14
μU = -4
σU = 9
μU = -9
σU = 14
68% = 9 13
95% = 18 28
Percent
Cumulative percent
Difference /mm
Absolute error /mm

CALL_filt (i)_CQ_ratio

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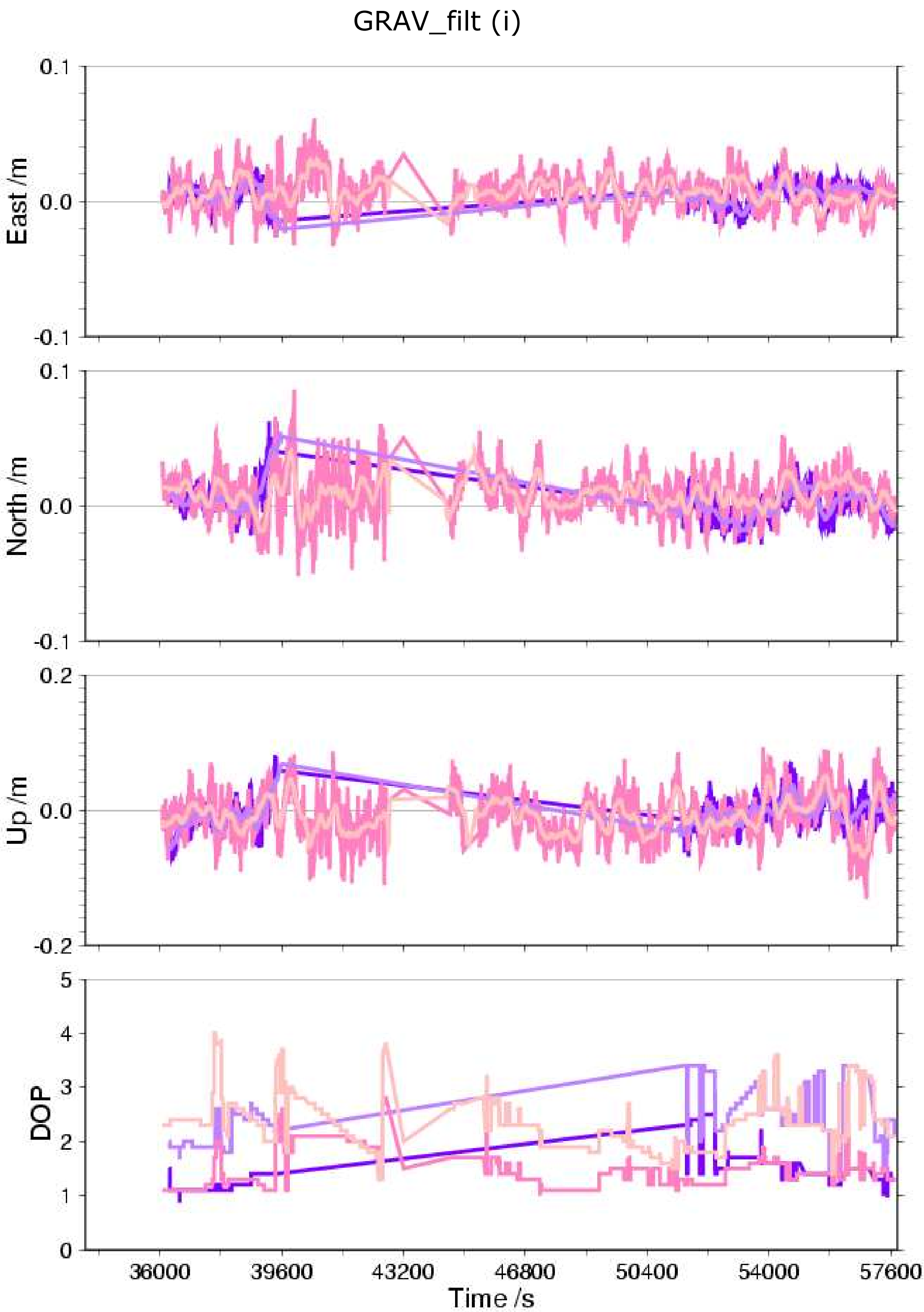
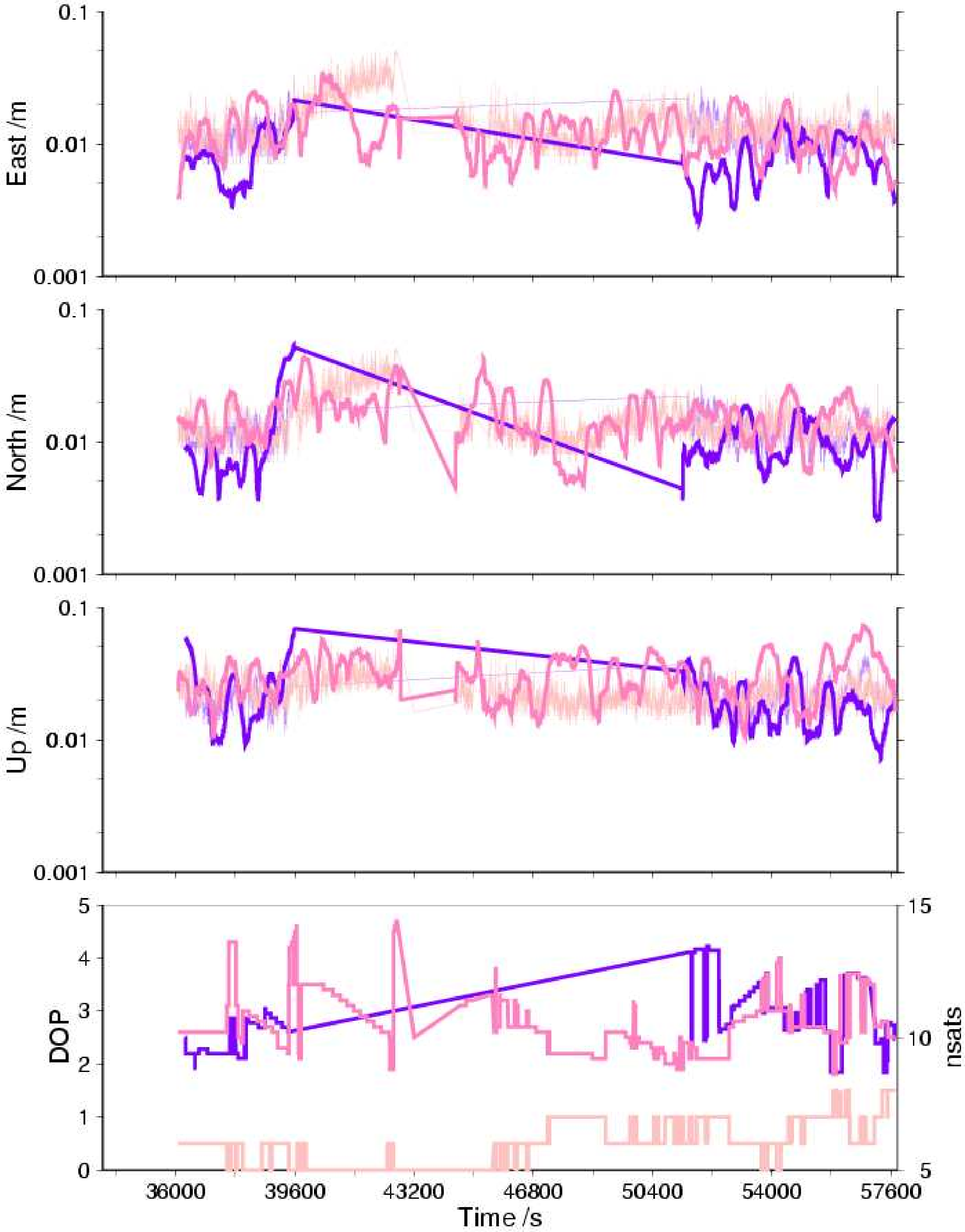
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

GRAVesend (GPS only)

L = 22 – 50 km, σ_L = 35 km
Δh = 21 m, $\sigma_{\Delta h}$ = 26 m



GRAV_filt (i) rms_moving window



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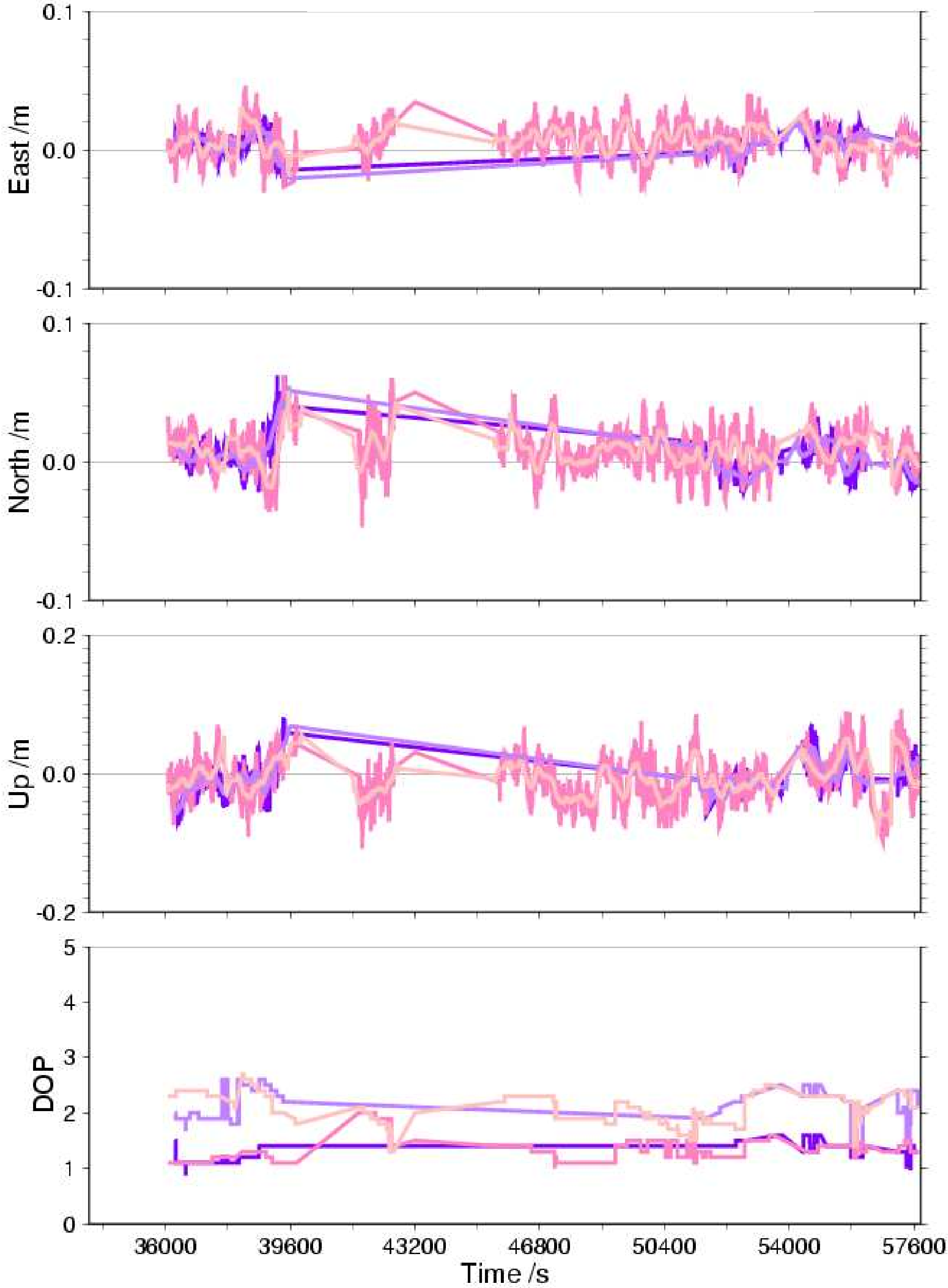

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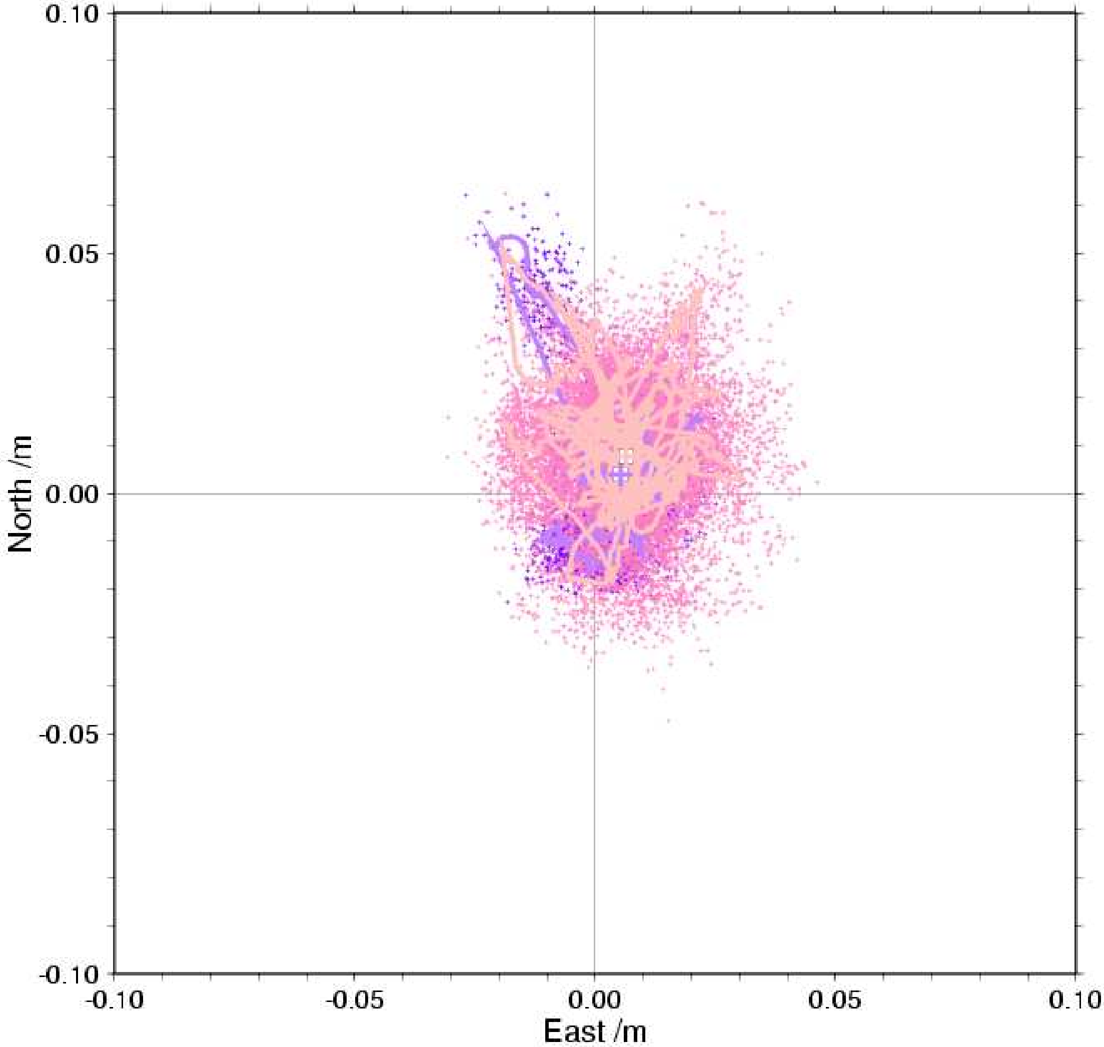

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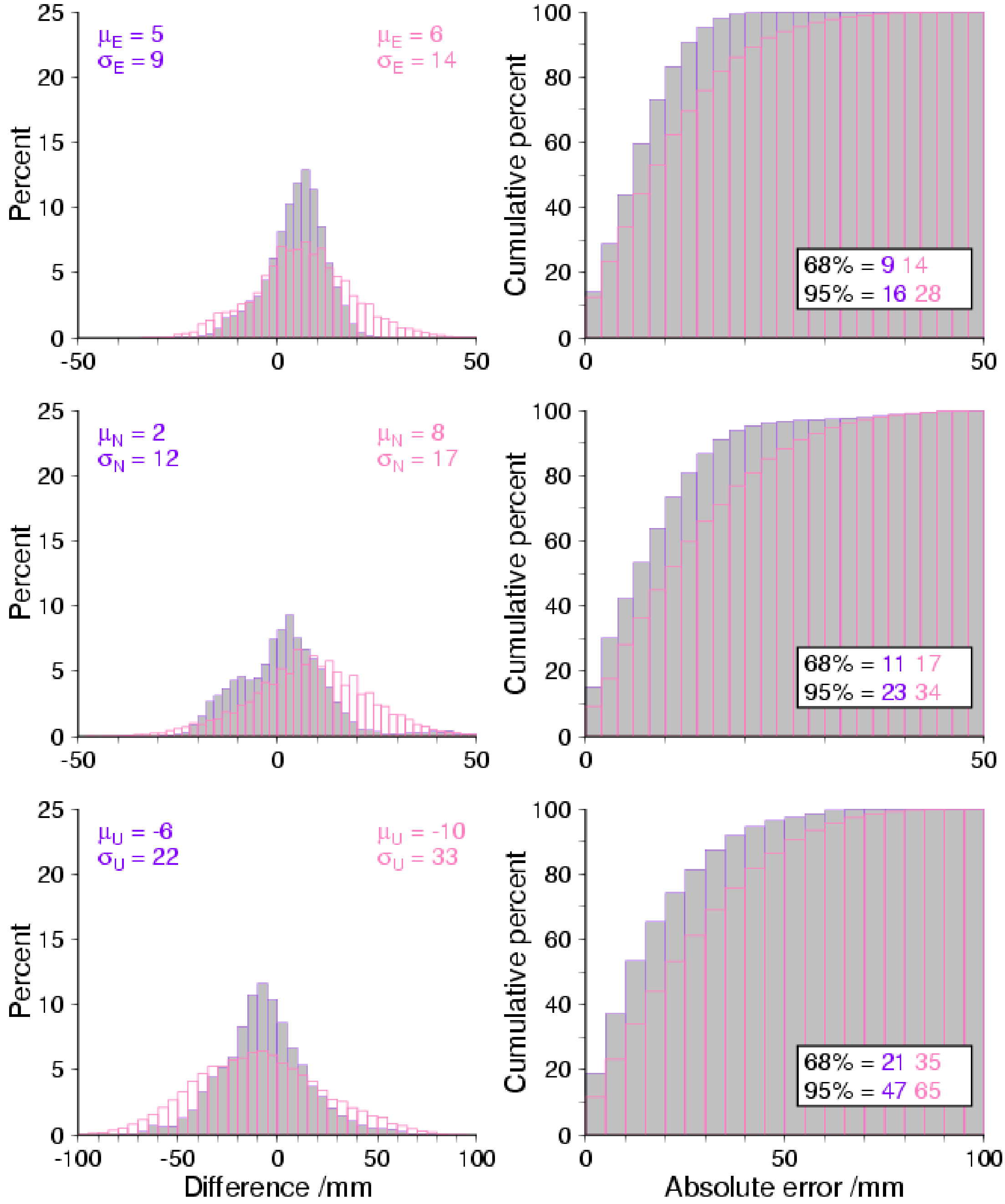

$\mu_E = 5$
$\sigma_E = 9$
$\mu_E = 6$
$\sigma_E = 14$
Percent
Cumulative percent
68% = 9 14
95% = 16 28
$\mu_N = 2$
$\sigma_N = 12$
$\mu_N = 8$
$\sigma_N = 17$
68% = 11 17
95% = 23 34
$\mu_U = -6$
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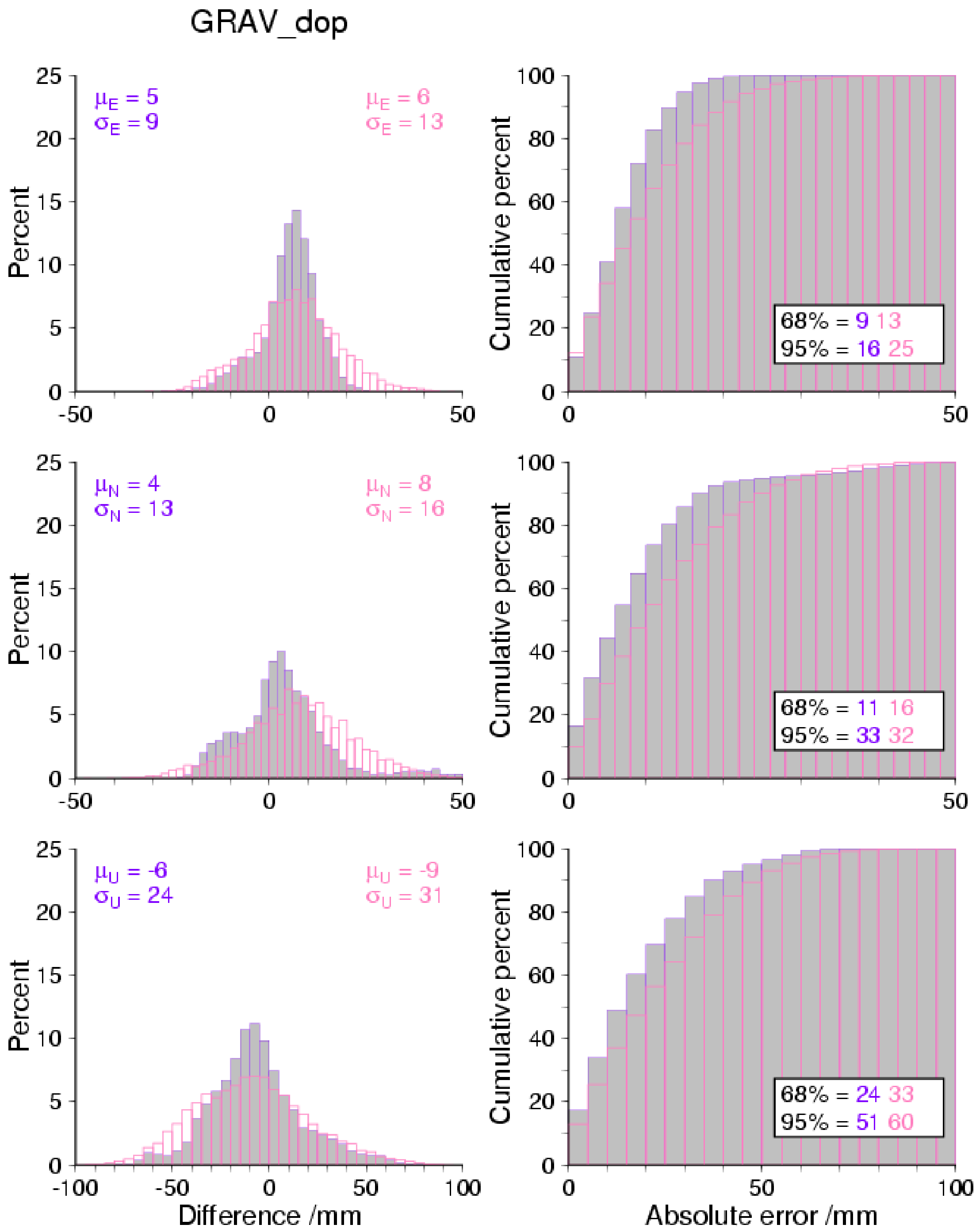
$\mu_U = -10$
$\sigma_U = 33$
68% = 21 35
95% = 47 65
Difference /mm
Absolute error /mm


GRAV_dop
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σE = 9
μE = 6
σE = 13
68% = 9 13
95% = 16 25
μN = 4
σN = 13
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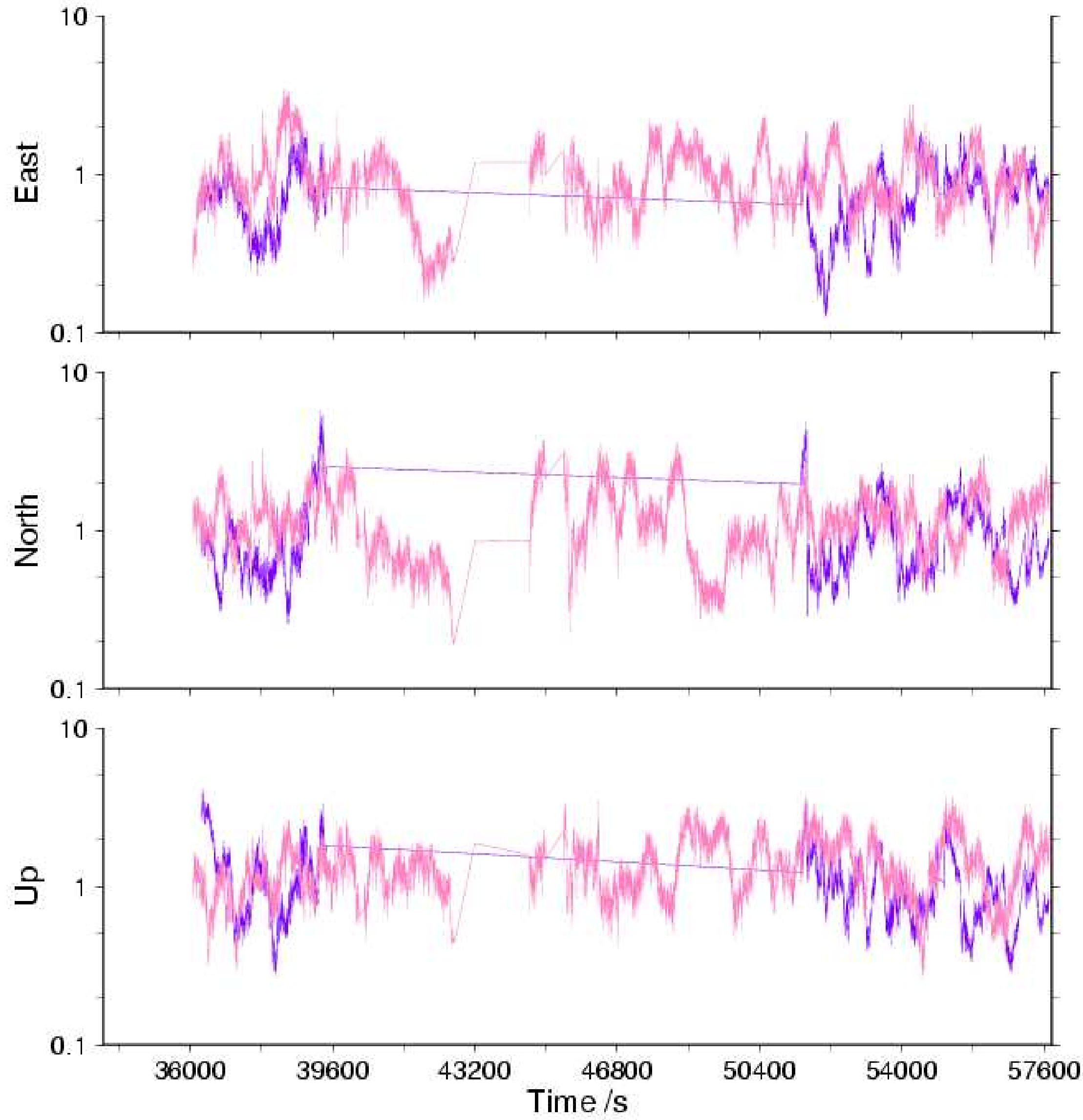
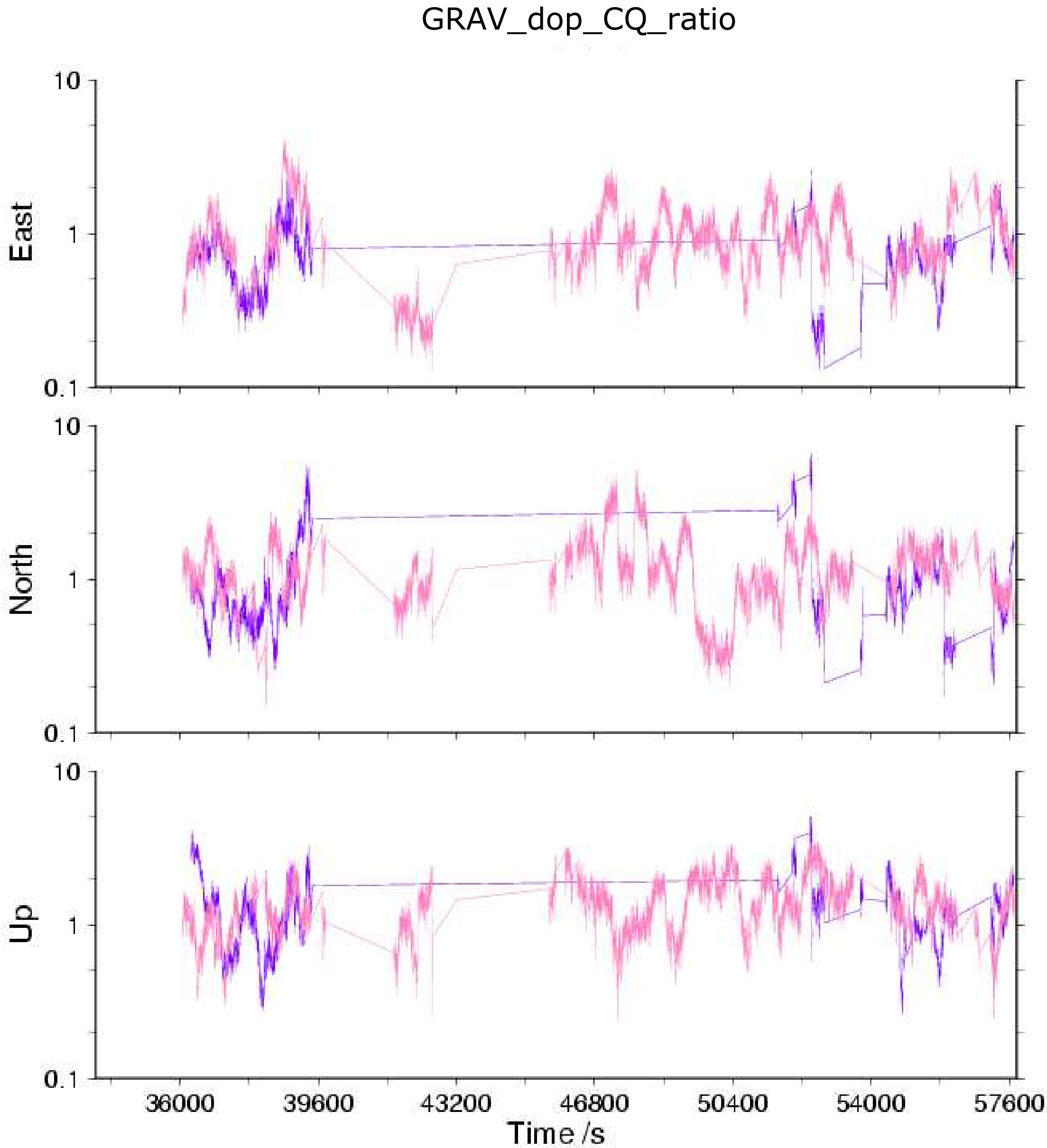
σN = 16
68% = 11 16
95% = 33 32
μU = -6
σU = 24
μU = -9
σU = 31
68% = 24 33
95% = 51 60
Percent
Cumulative percent
Difference /mm
Absolute error /mm

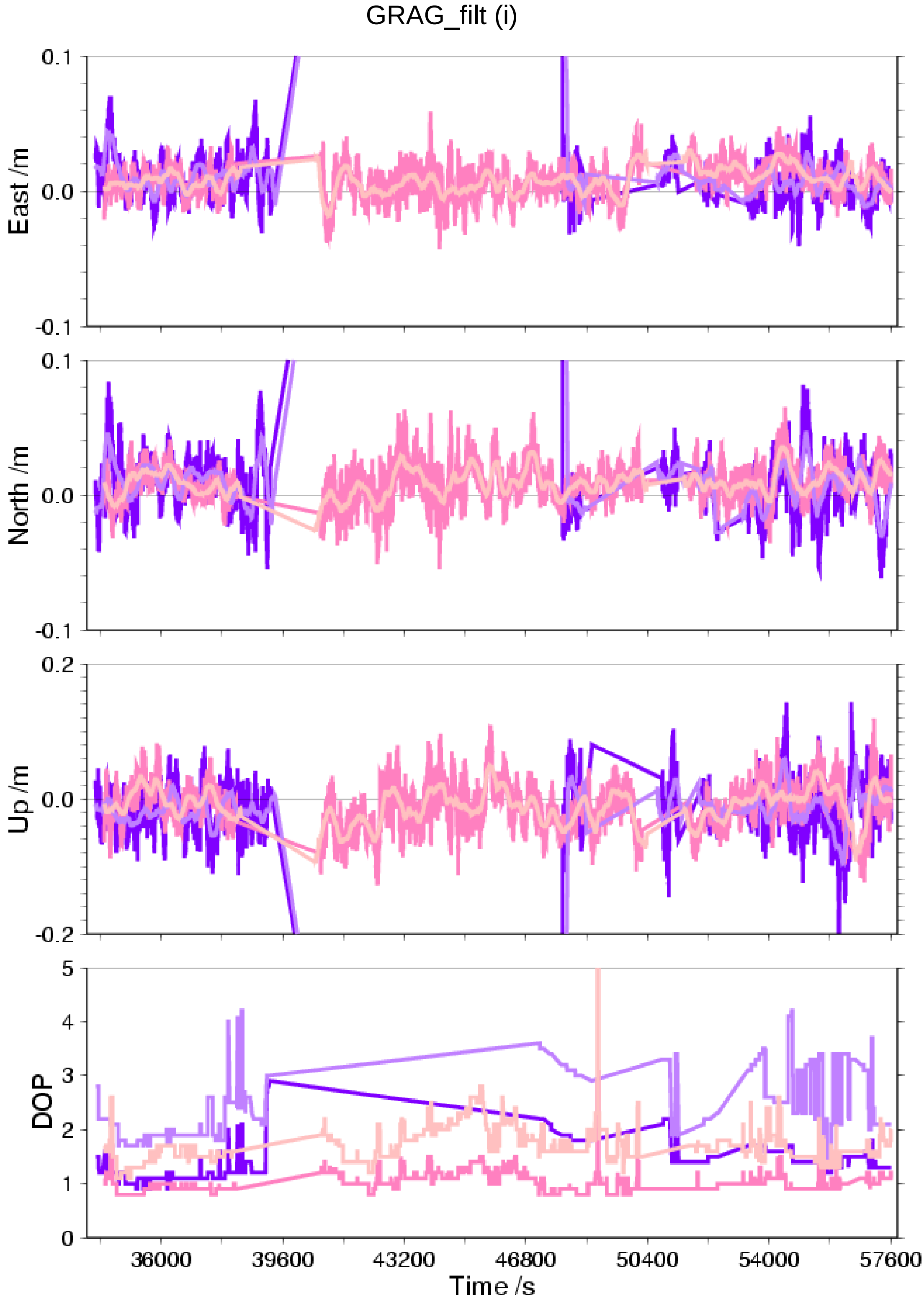
GRAV_filt_CQ_ratio



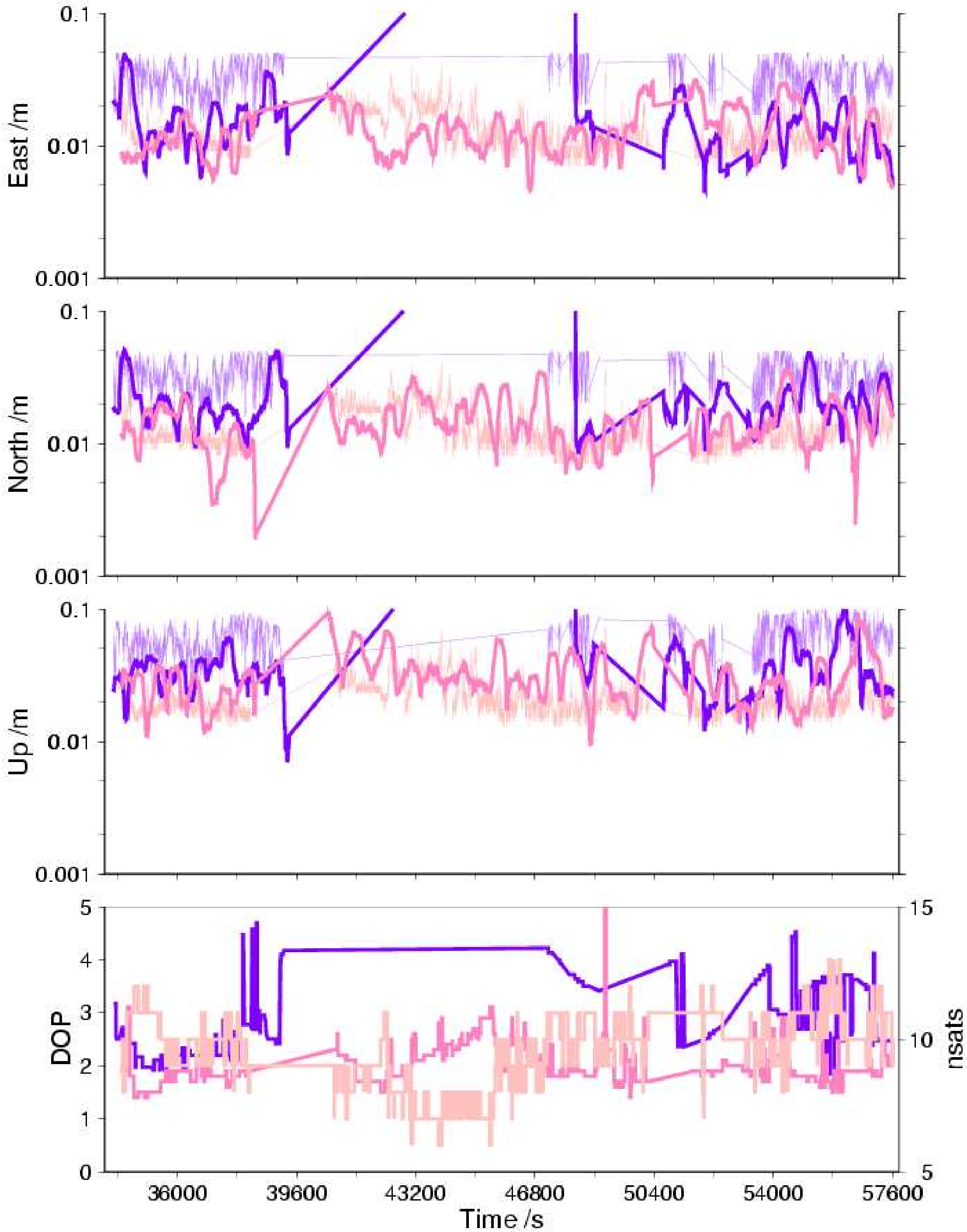

GRAV_dop_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

GRAG (Gravesend GPS/GLONASS)

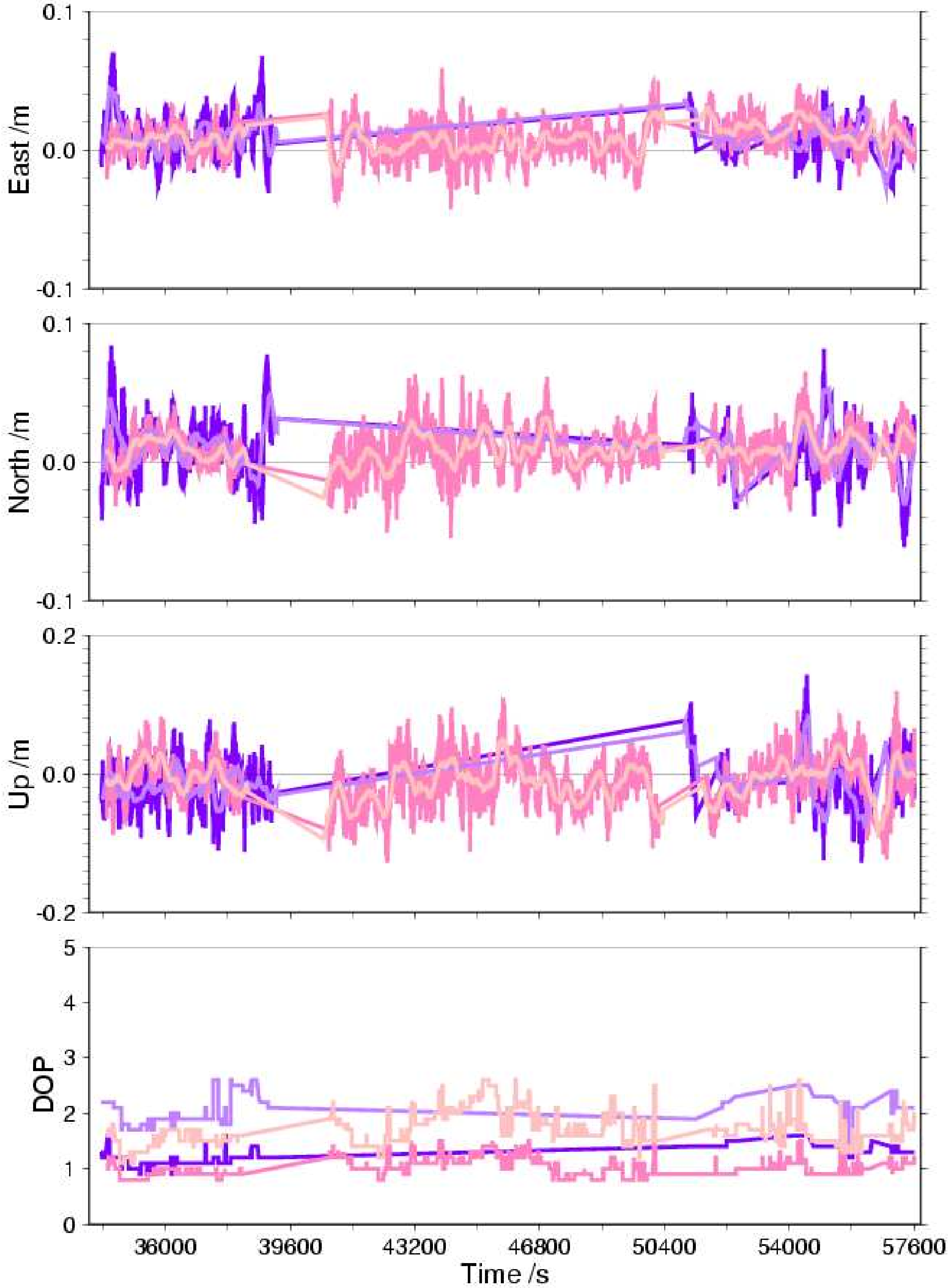
L = 22 – 50 km, σ_L = 35 km
Δh = 21 m, $\sigma_{\Delta h}$ = 26 m



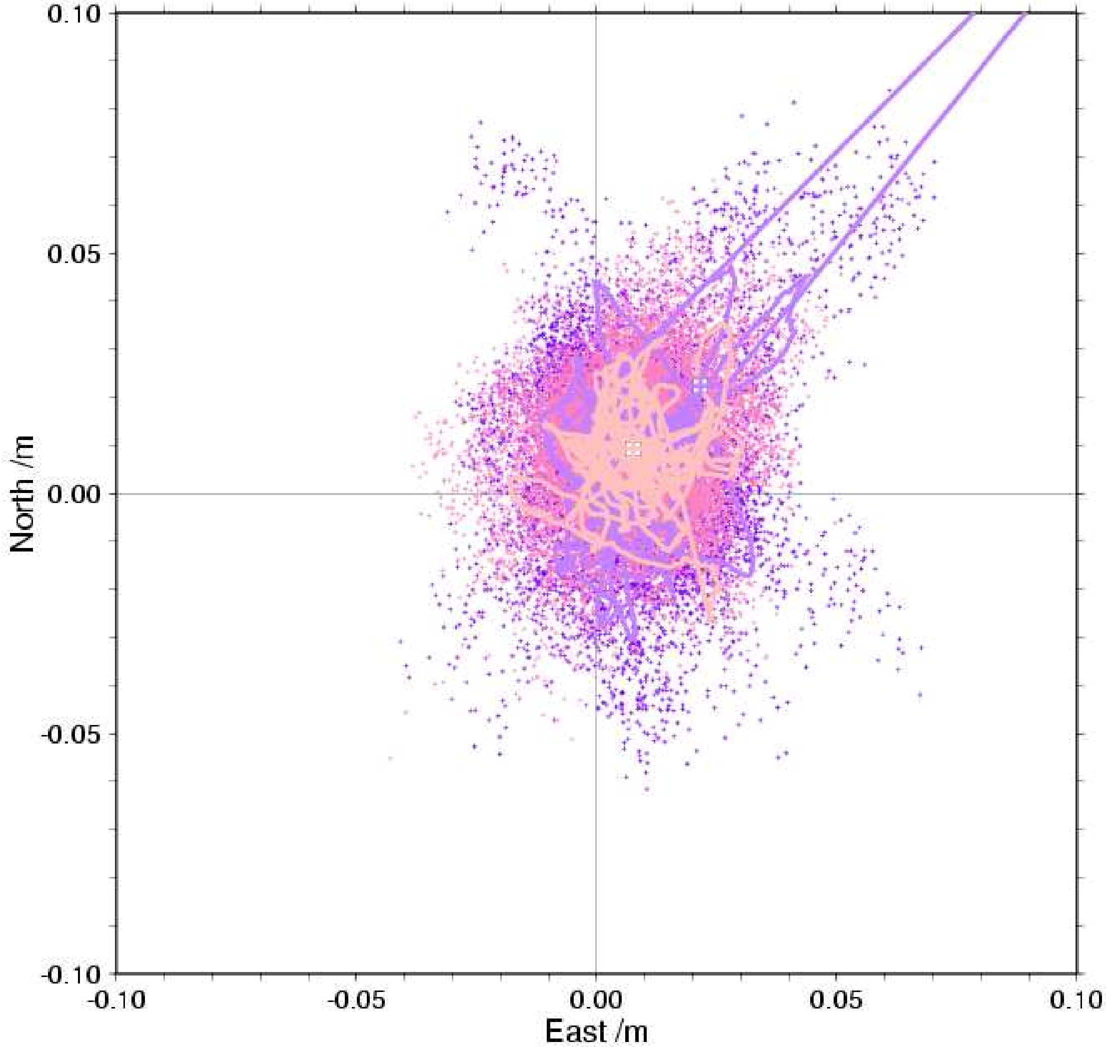
GRAG_filt (i) rms_ moving window

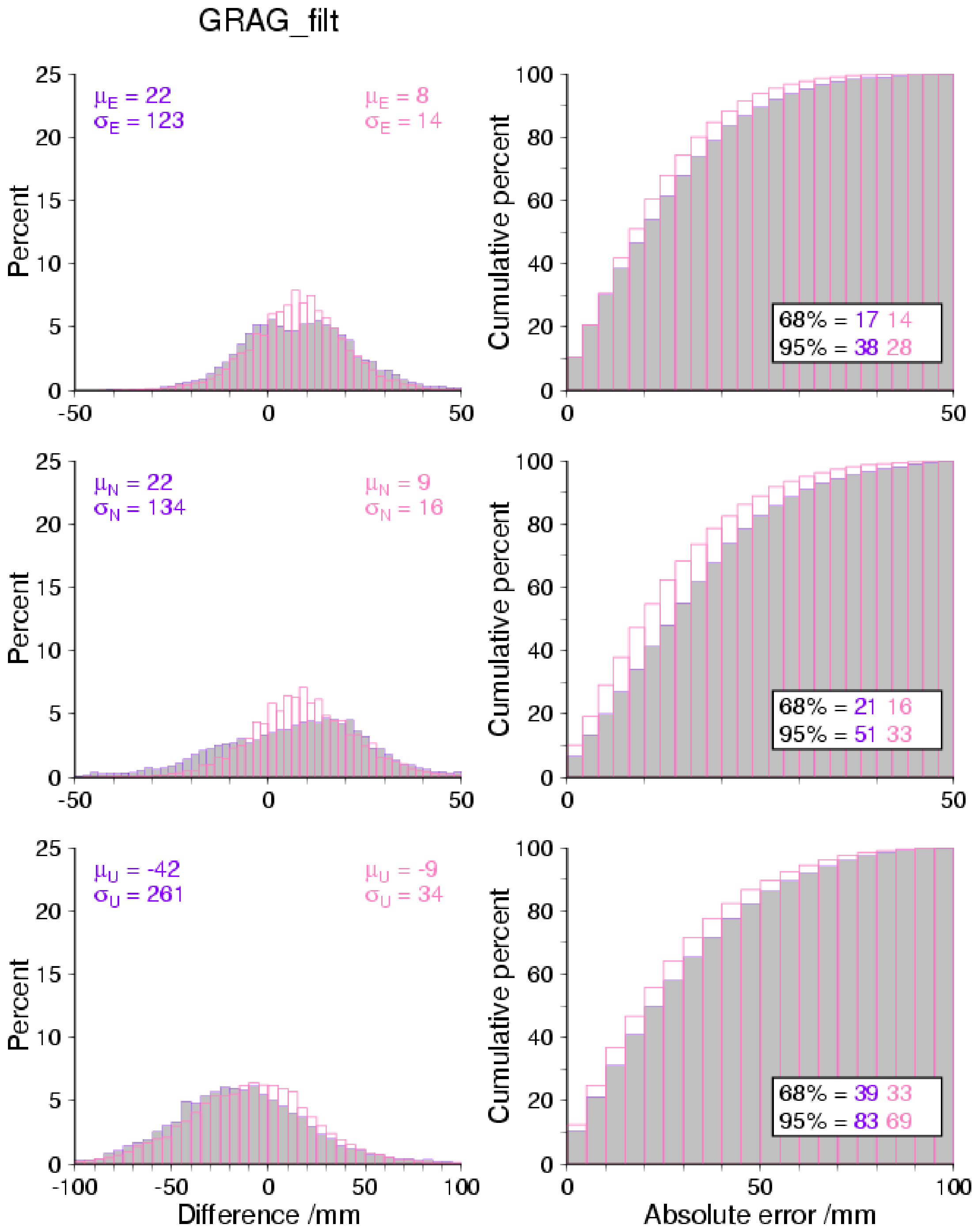


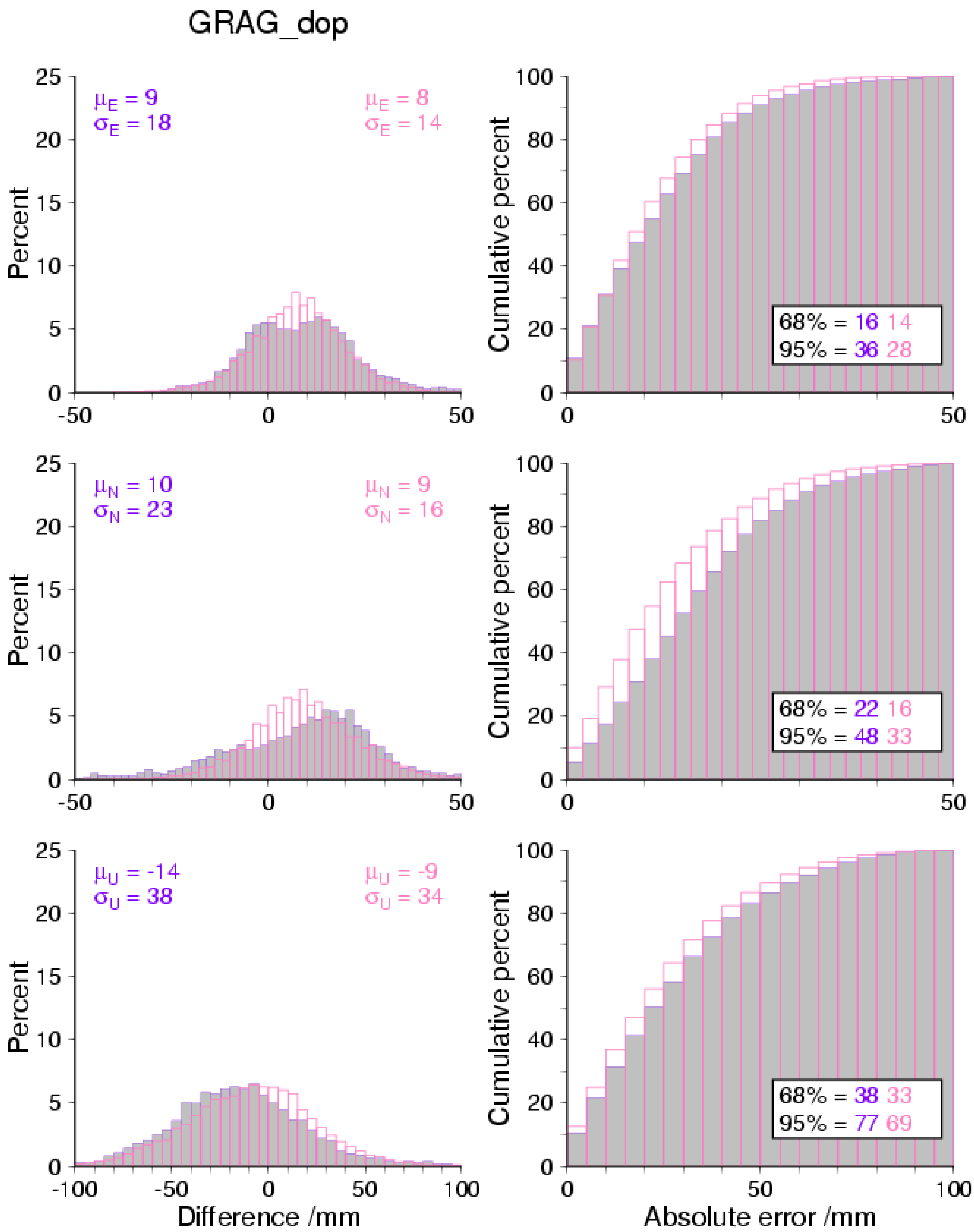
GRAG_DOP_filt (ii)

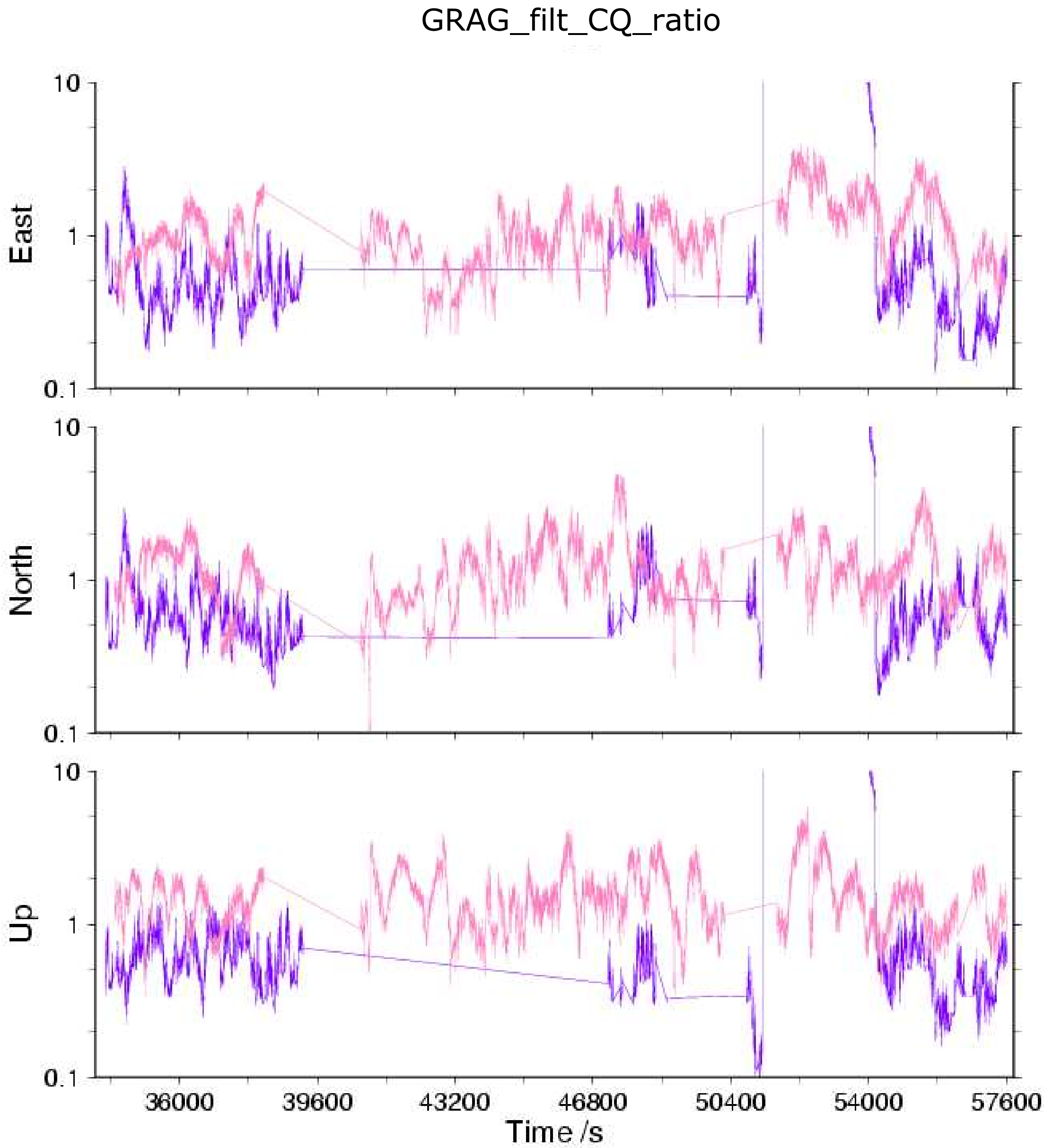


GRAG_filt (i)_plan



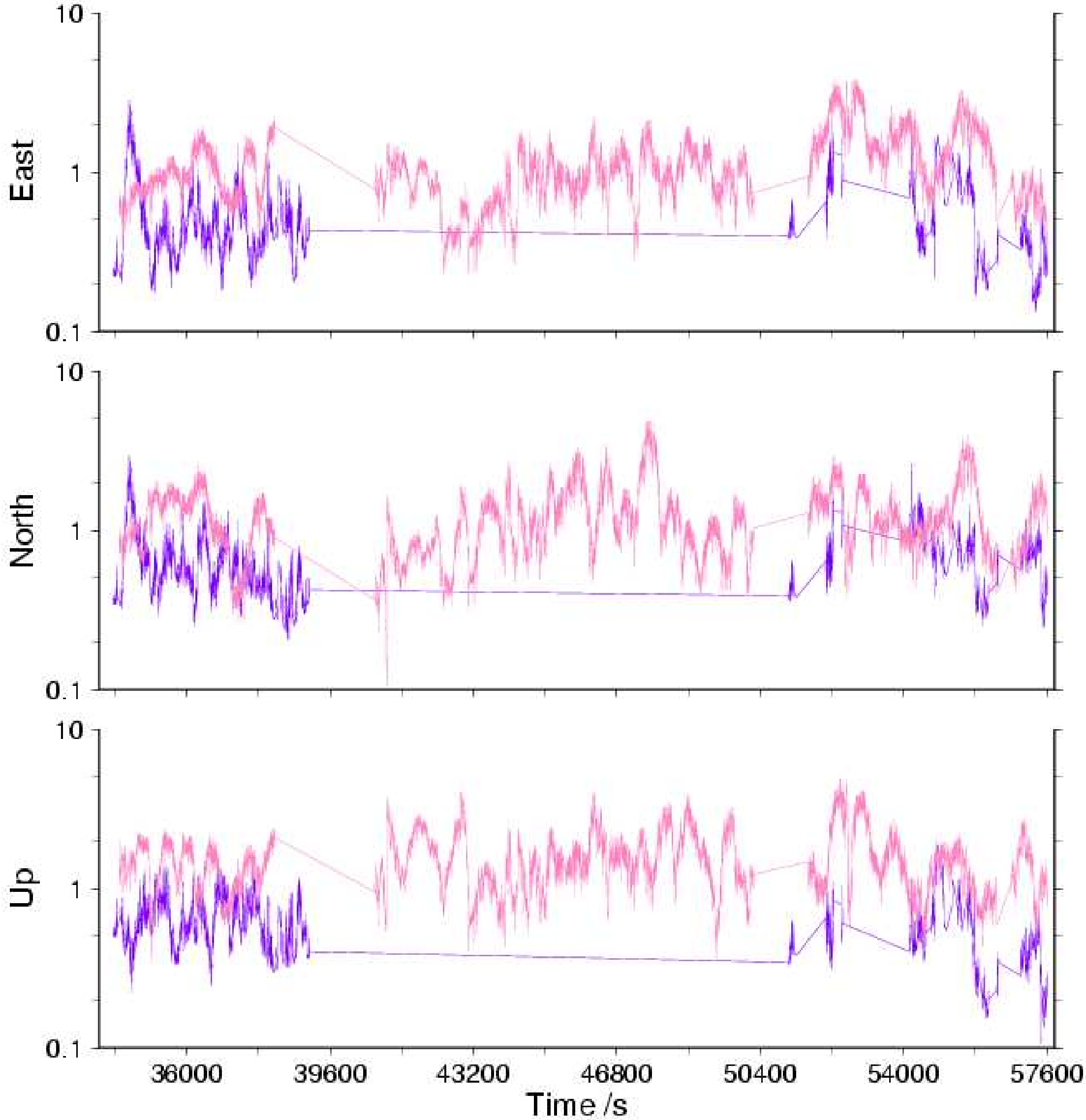

GRAG_filt
μE = 22
σE = 123
μE = 8
σE = 14
Percent
Cumulative percent
68% = 17 14
95% = 38 28
μN = 22
σN = 134
μN = 9
σN = 16
68% = 21 16
95% = 51 33
μU = -42
σU = 261
μU = -9
σU = 34
68% = 39 33
95% = 83 69
Difference /mm
Absolute error /mm


GRAG_dop
μ_E = 9
σ_E = 18
μ_E = 8
σ_E = 14
68% = 16 14
95% = 36 28
μ_N = 10
σ_N = 23
μ_N = 9
σ_N = 16
68% = 22 16
95% = 48 33
μ_U = -14
σ_U = 38
μ_U = -9
σ_U = 34
68% = 38 33
95% = 77 69
Percent
Cumulative percent
Difference /mm
Absolute error /mm



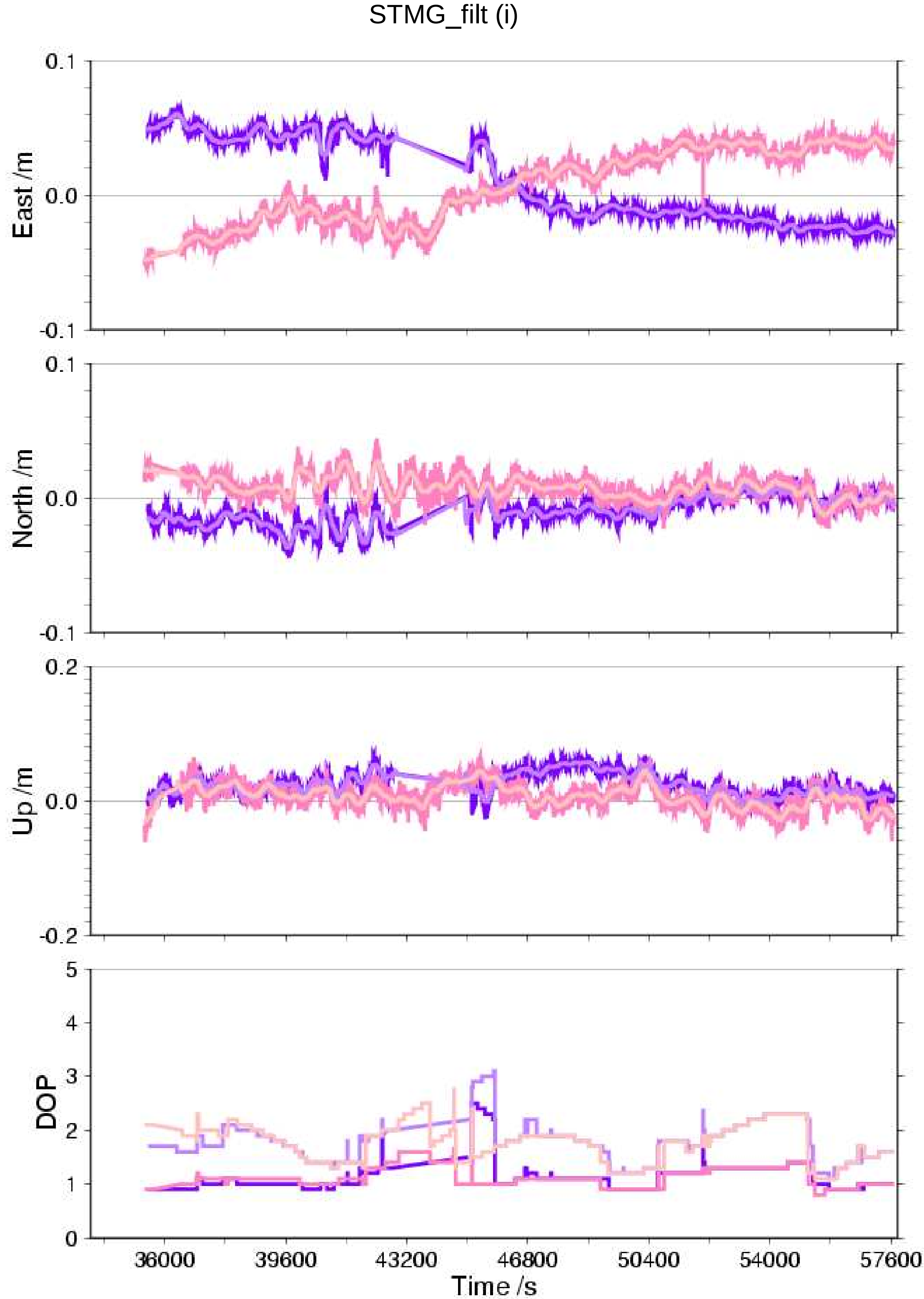
GRAG_filt_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

GRAG_dop_CQ_ratio

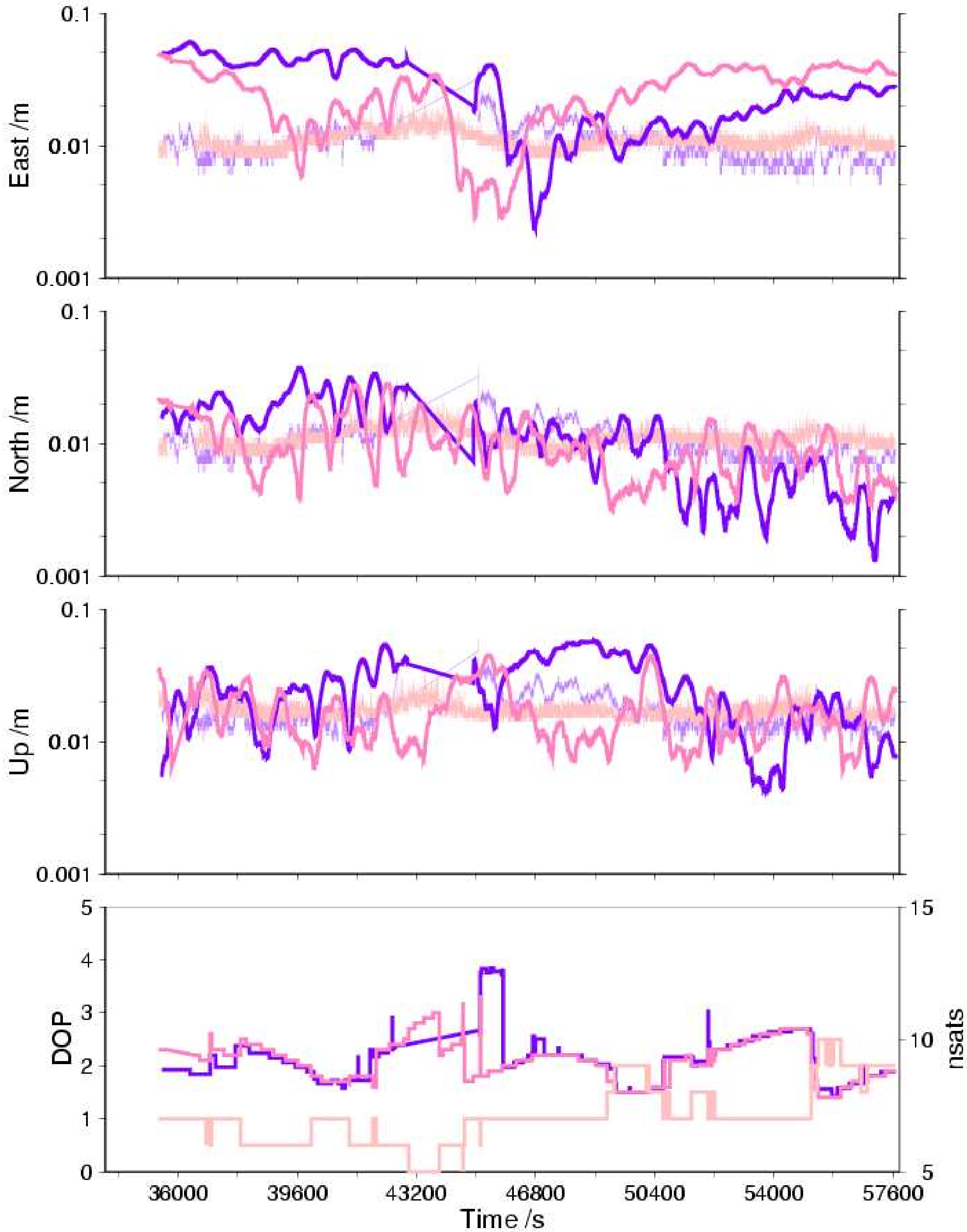


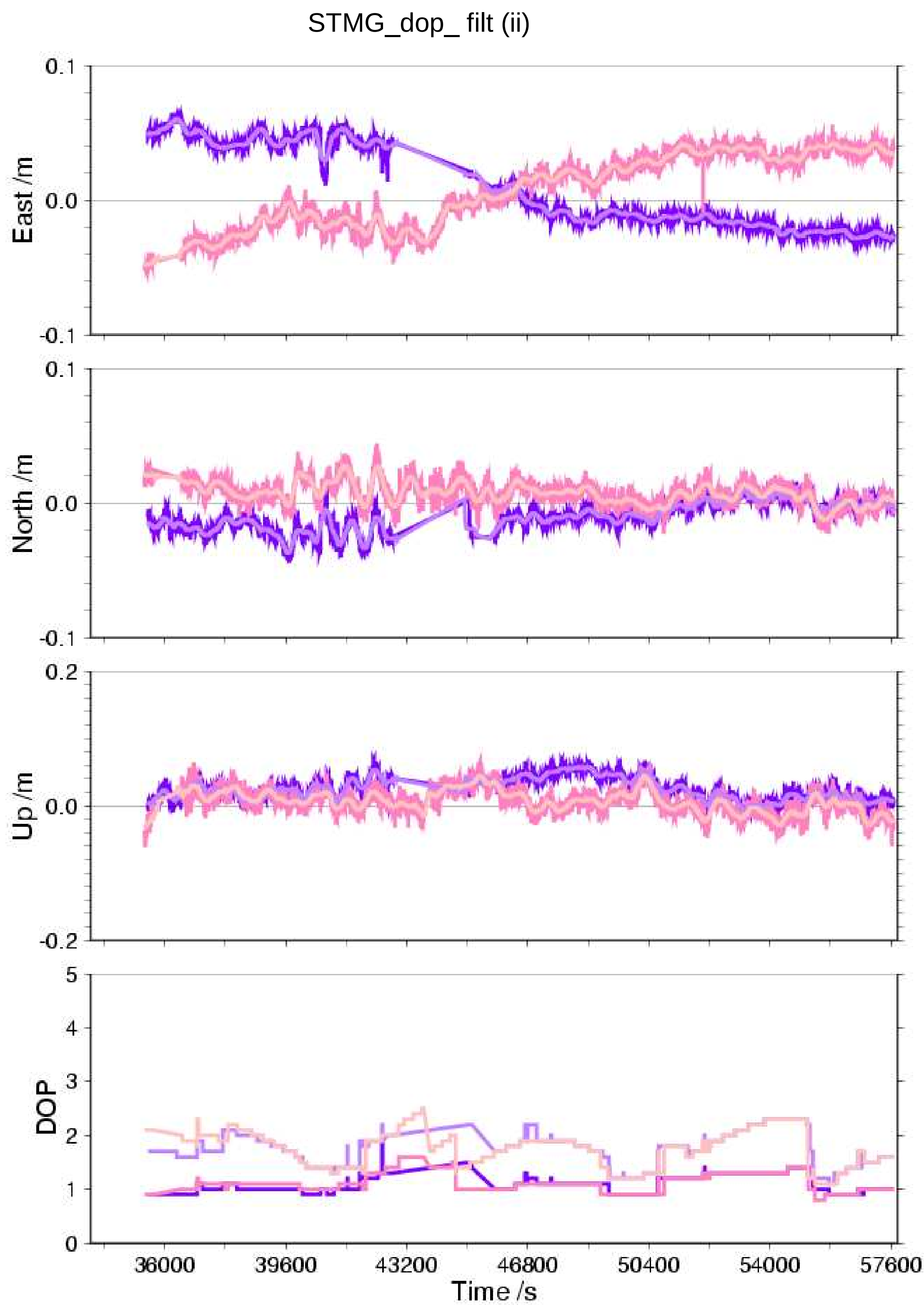
STMG (St. Margarets)

L = 28 – 61 km, σ_L = 48km
Δh = -81 m, $\sigma_{\Delta h}$ = 82 m



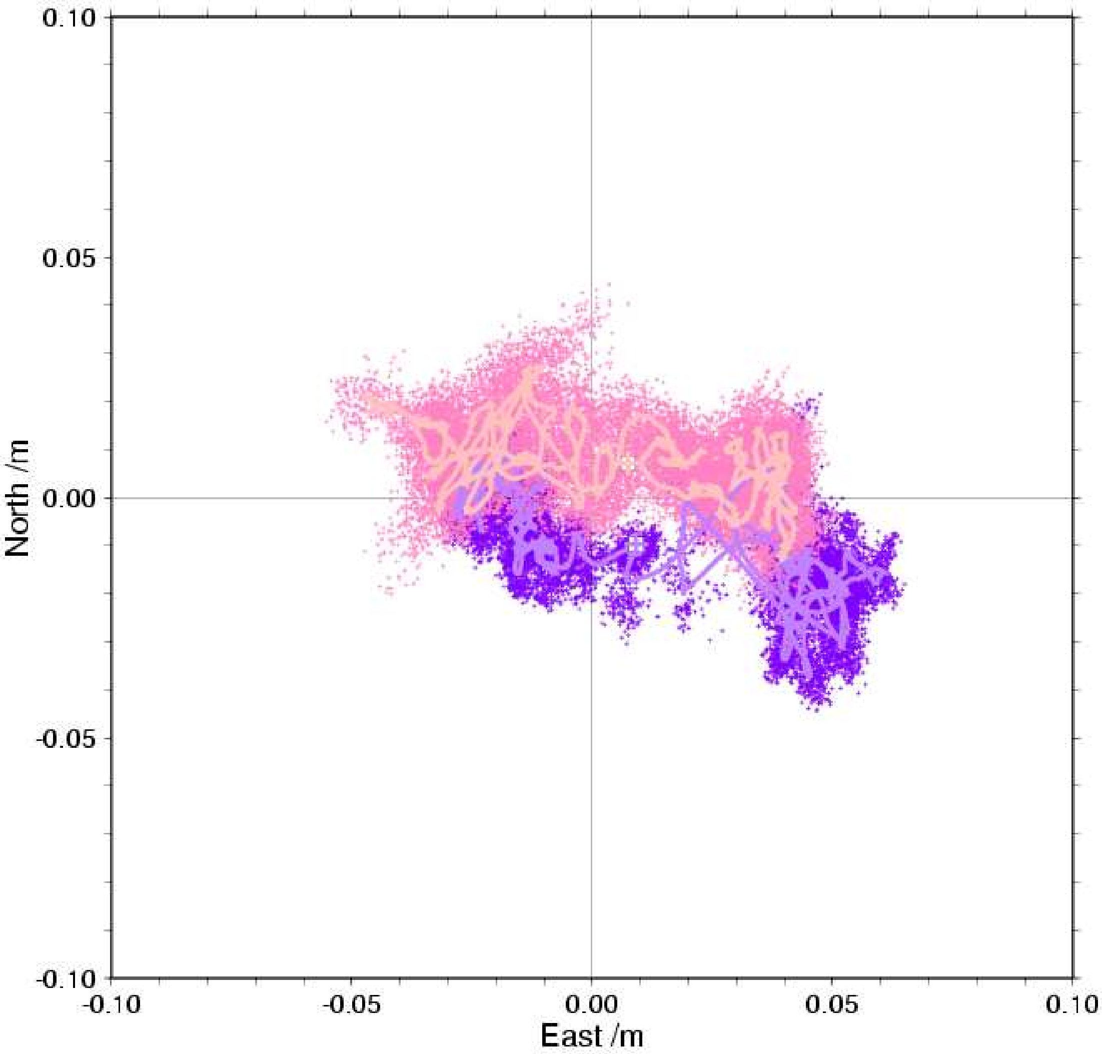
STMG_filt (i) rms_ moving window



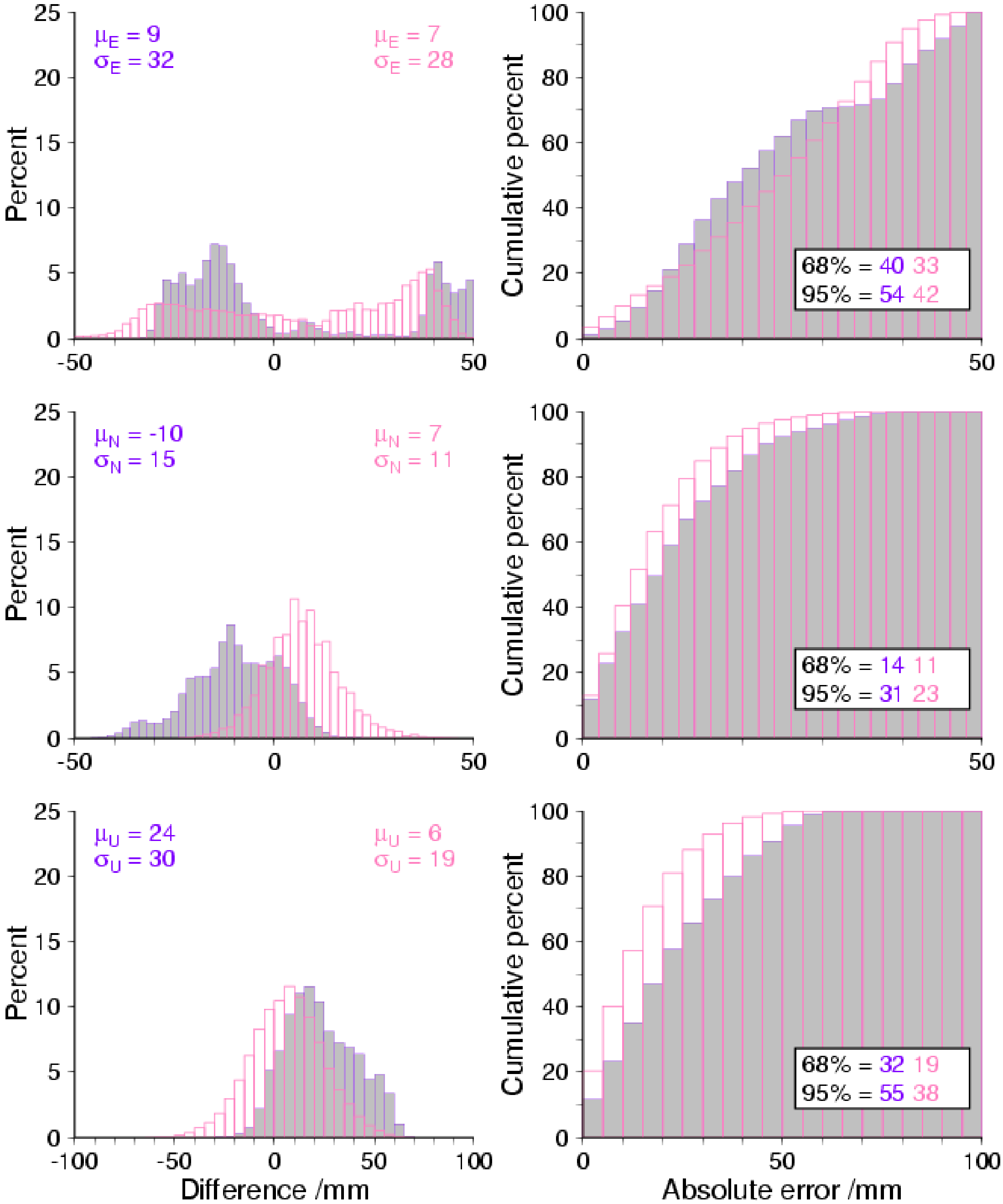


STMG_dop_ filt (ii)
East /m
North /m
Up /m
DOP
Time /s
0.1
0.0
-0.1
0.2
-0.2
0
1
2
3
4
5
36000
39600
43200
46800
50400
54000
57600

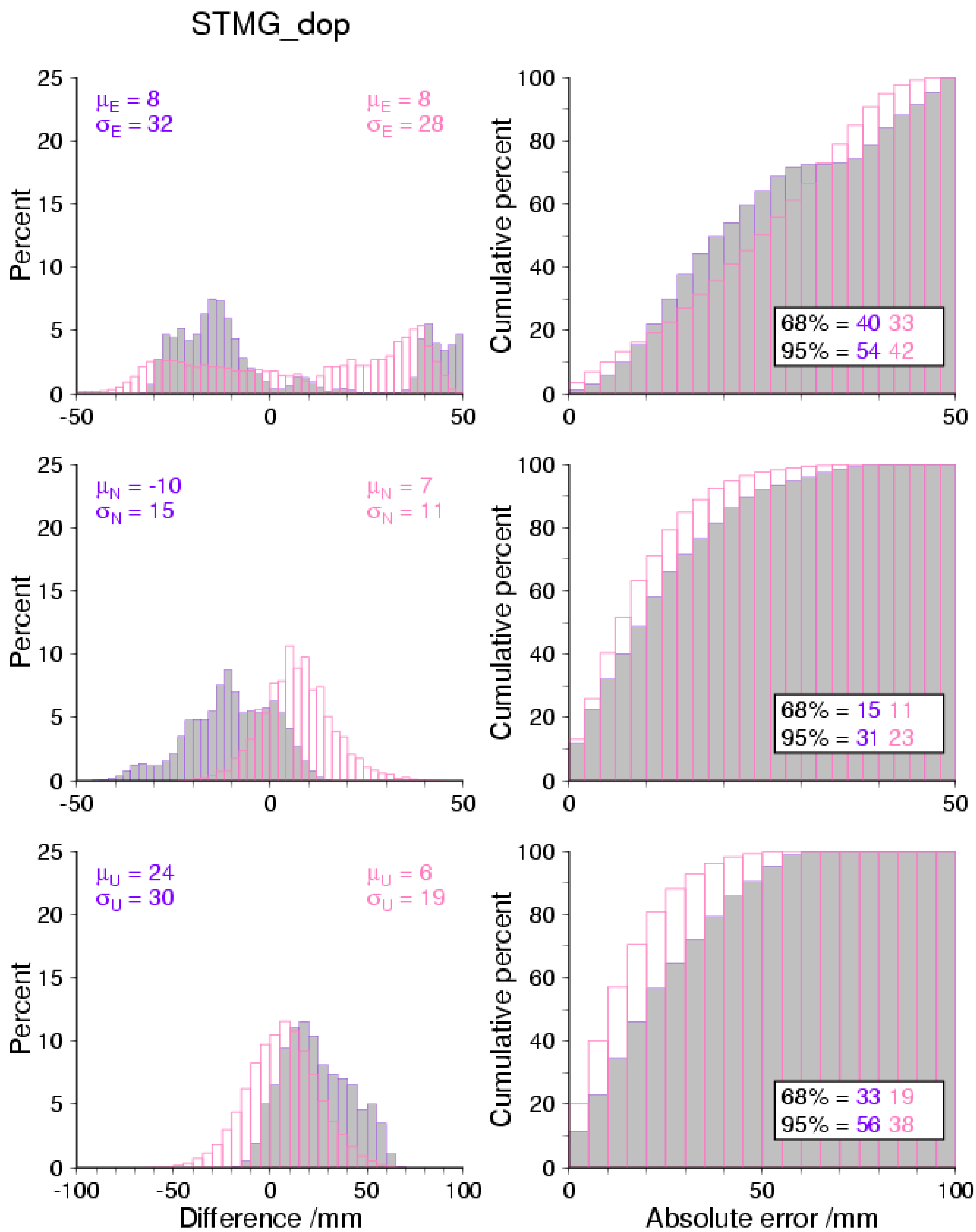
STMG_filt (i)_plan



STMG_filt

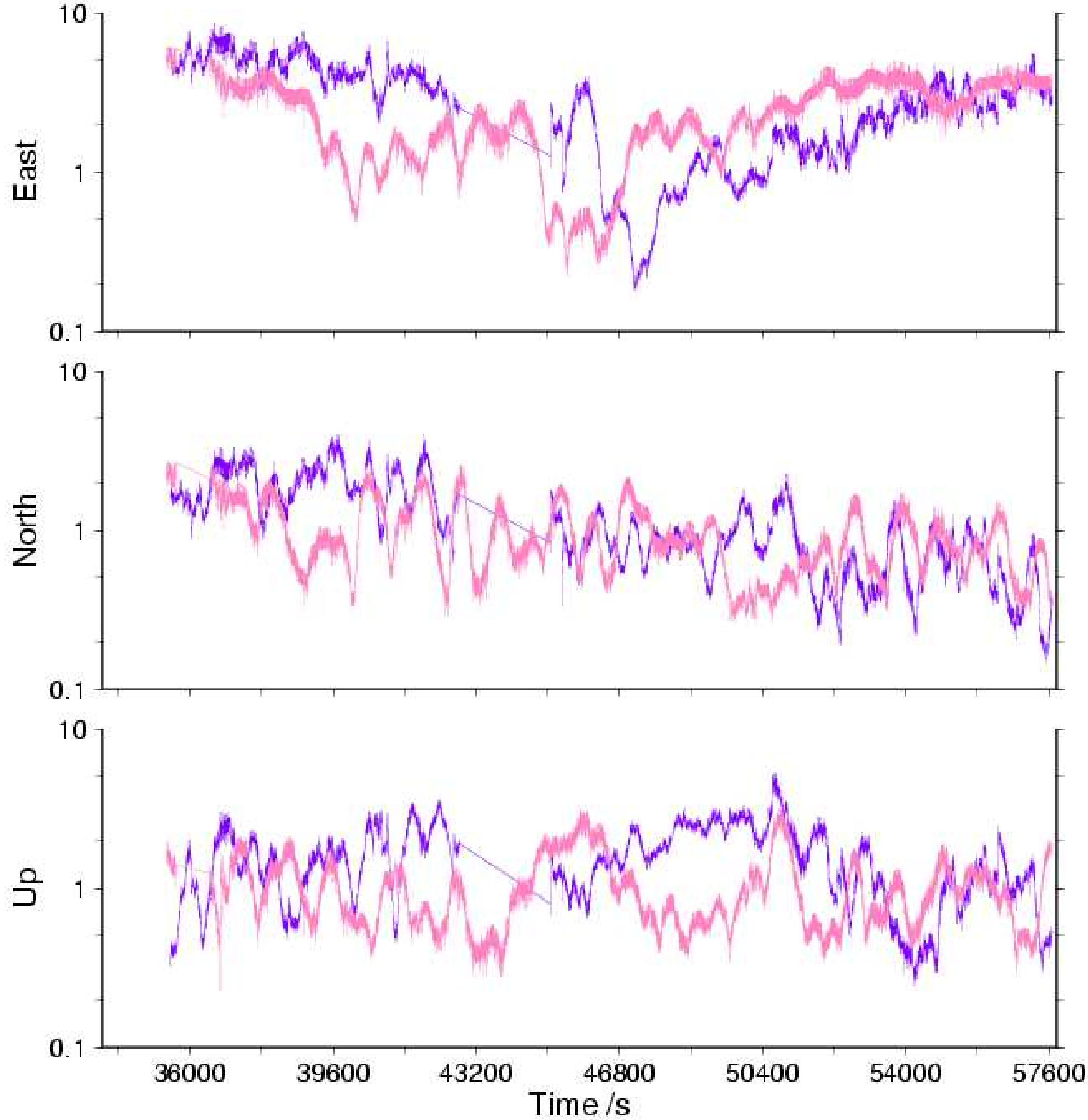


μ_E = 9
σ_E = 32
μ_E = 7
σ_E = 28
μ_N = -10
σ_N = 15
μ_N = 7
σ_N = 11
μ_U = 24
σ_U = 30
μ_U = 6
σ_U = 19
Percent
Difference /mm
68% = 40 33
95% = 54 42
68% = 14 11
95% = 31 23
68% = 32 19
95% = 55 38
Cumulative percent
Absolute error /mm

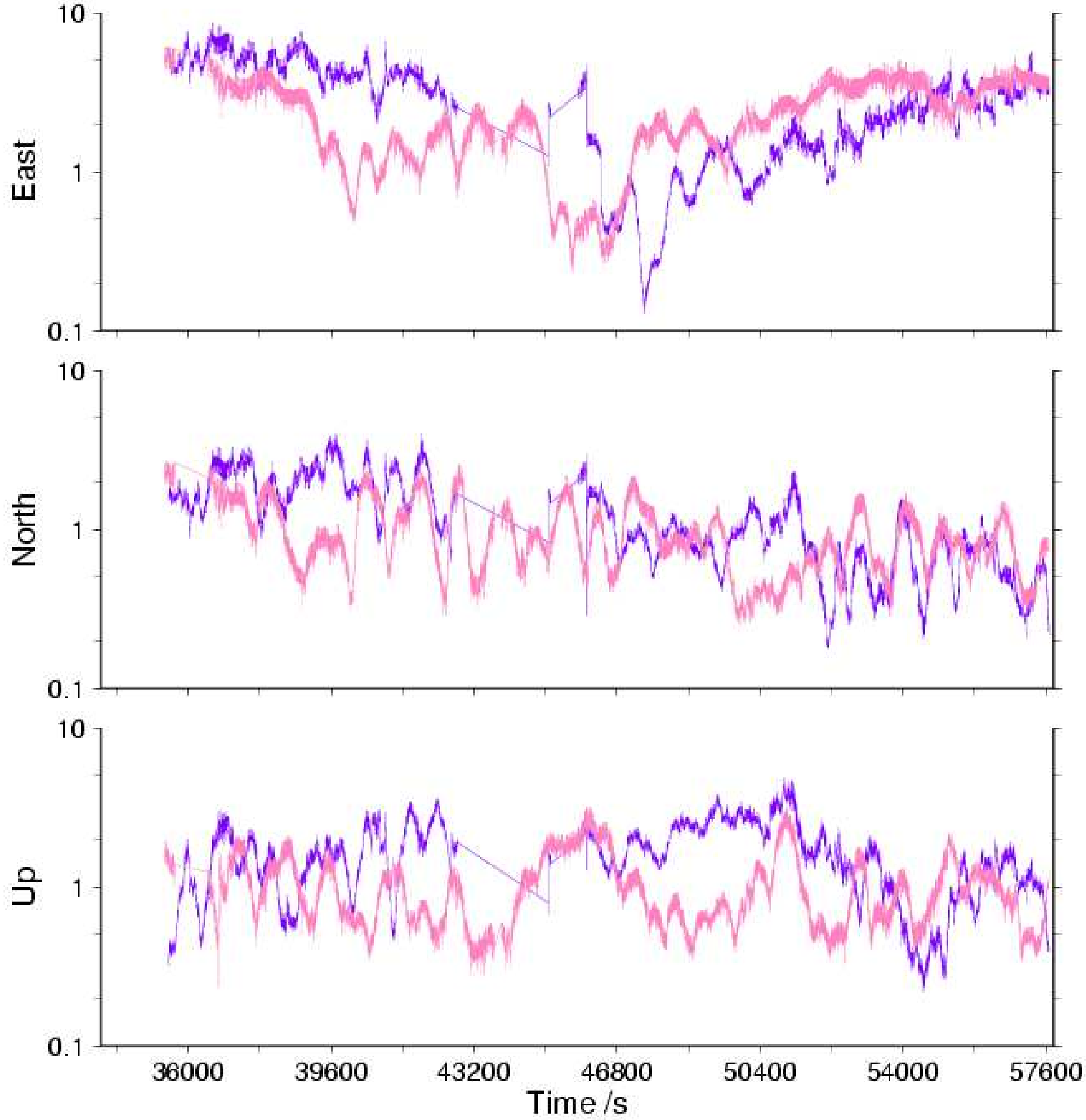


STMG_dop
μE = 8
σE = 32
μE = 8
σE = 28
Percent
Cumulative percent
68% = 40 33
95% = 54 42
μN = -10
σN = 15
μN = 7
σN = 11
68% = 15 11
95% = 31 23
μU = 24
σU = 30
μU = 6
σU = 19
68% = 33 19
95% = 56 38
Difference /mm
Absolute error /mm

STMG_filt_CQ_ratio

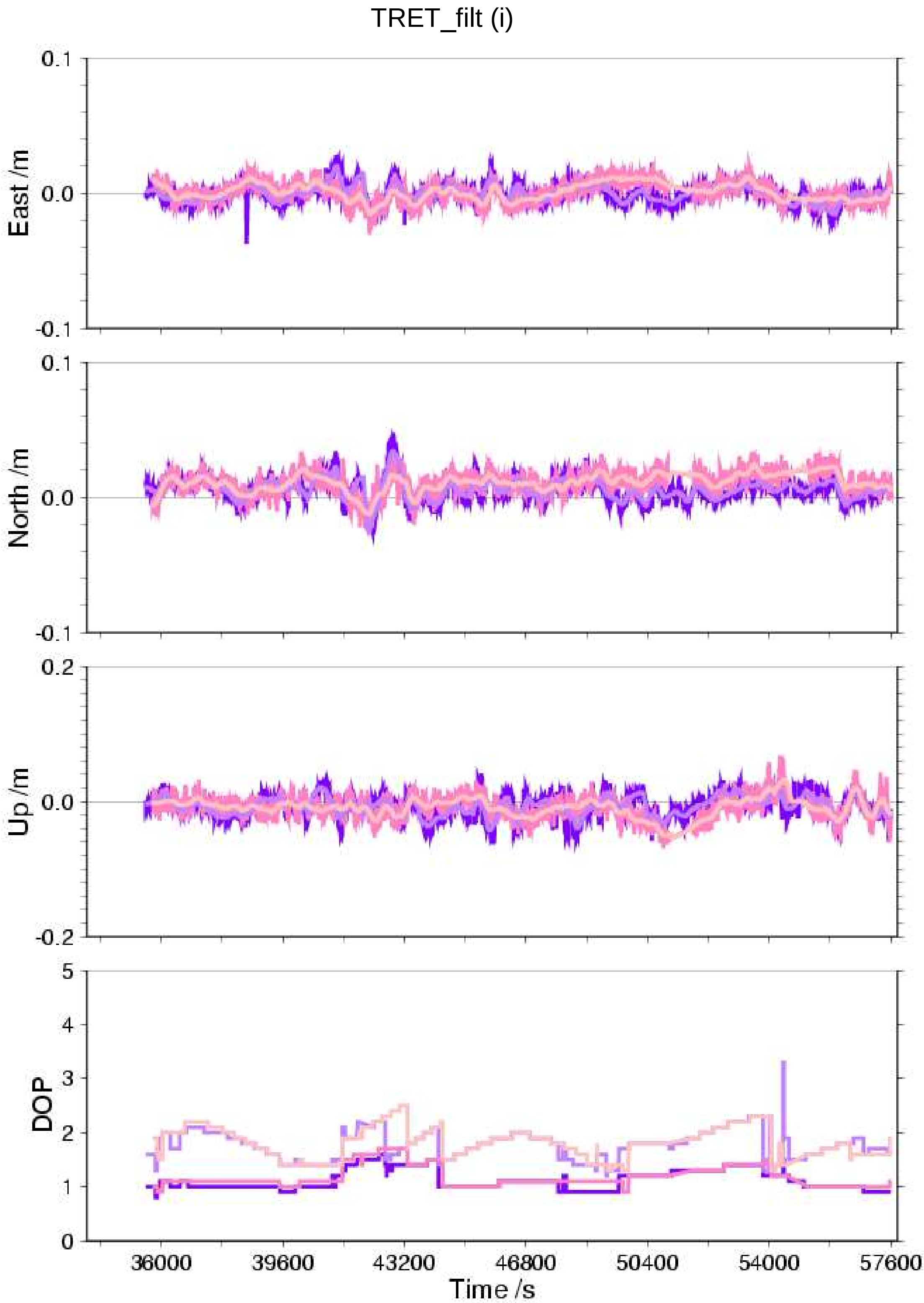


STMG_dop_CQ_ratio

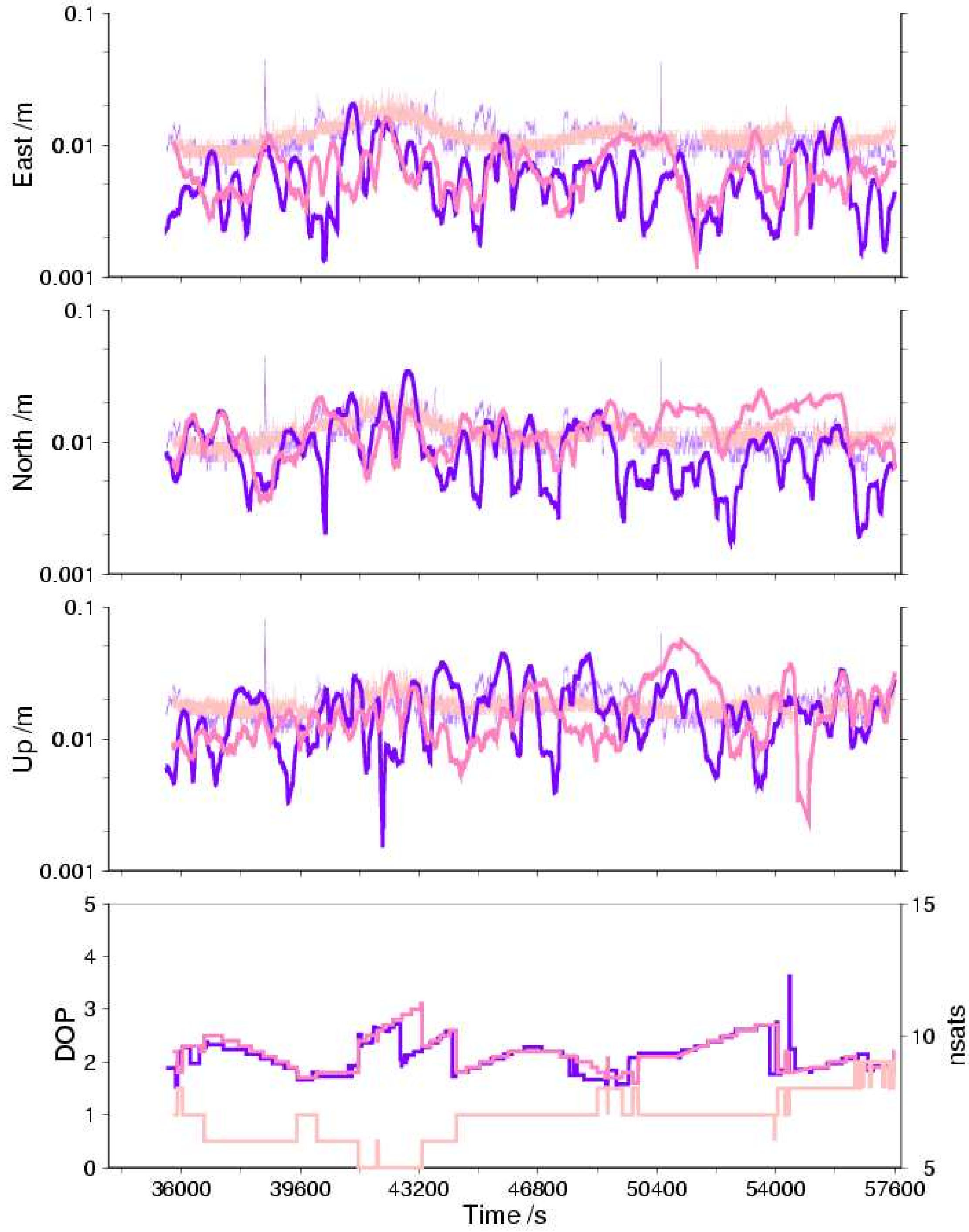


TRETio

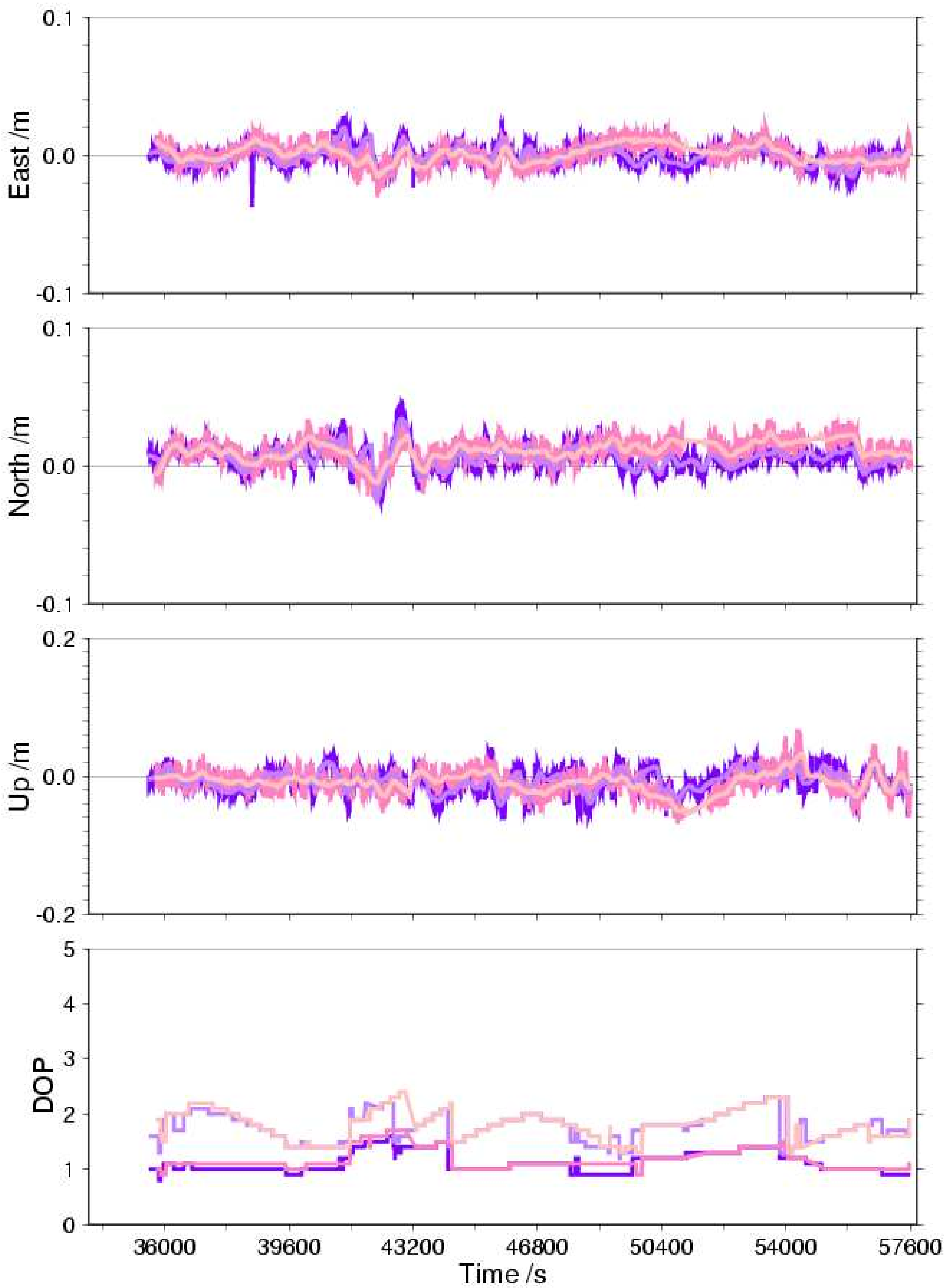
L = 27 – 119 km, σ_L = 70 km
Δh = -56 m, $\sigma_{\Delta h}$ = 72 m

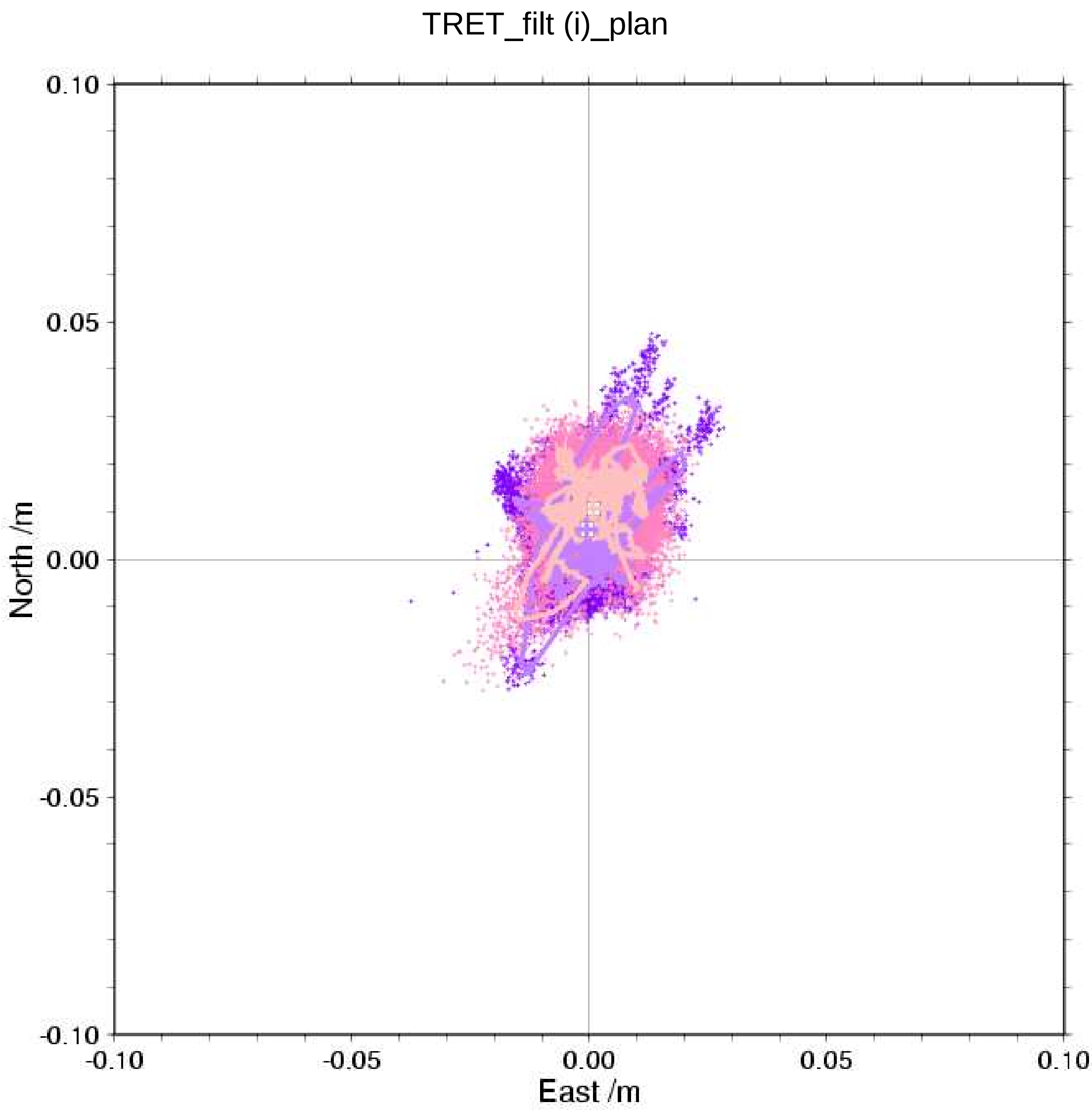


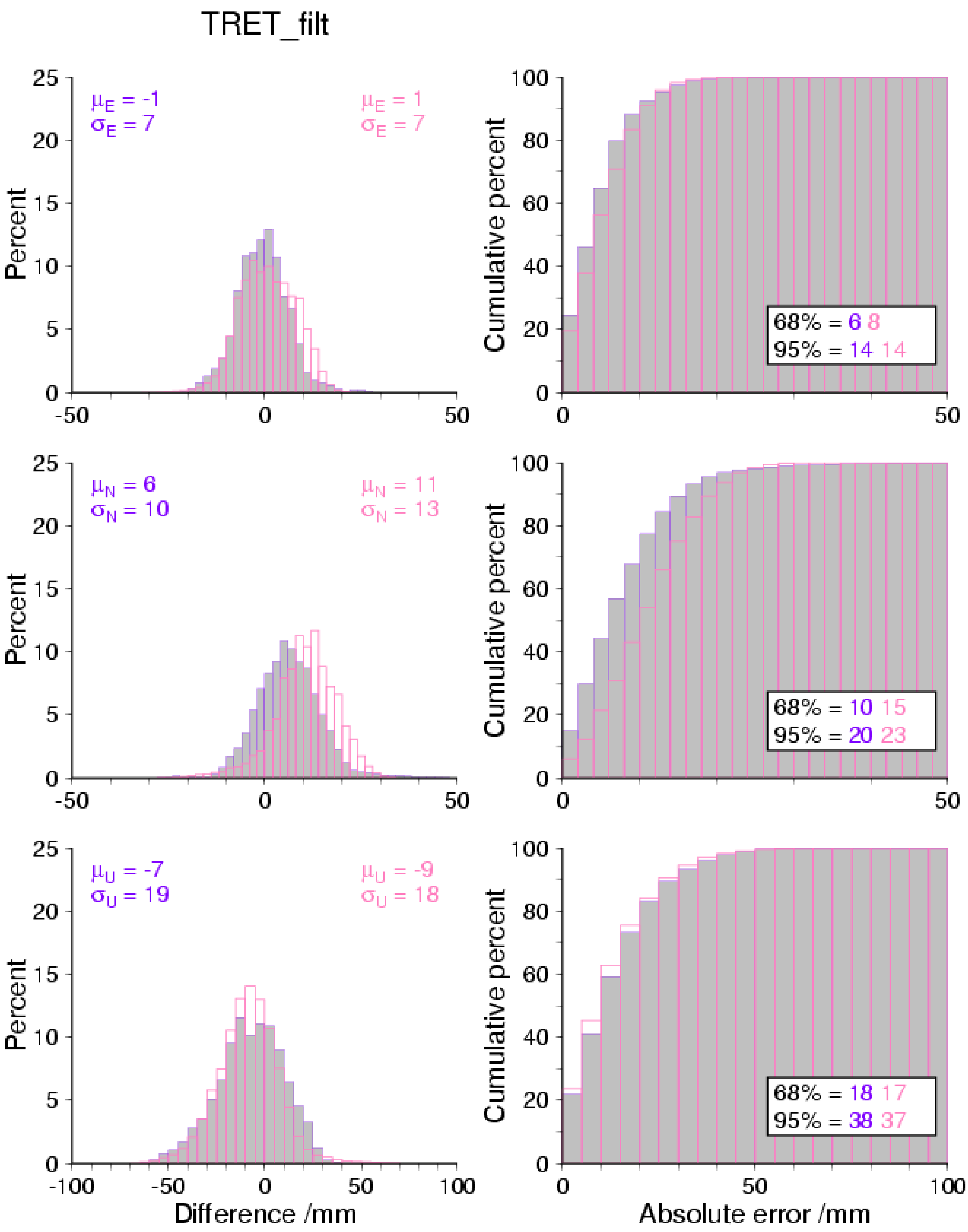
TRET_filt (i) rms_moving window



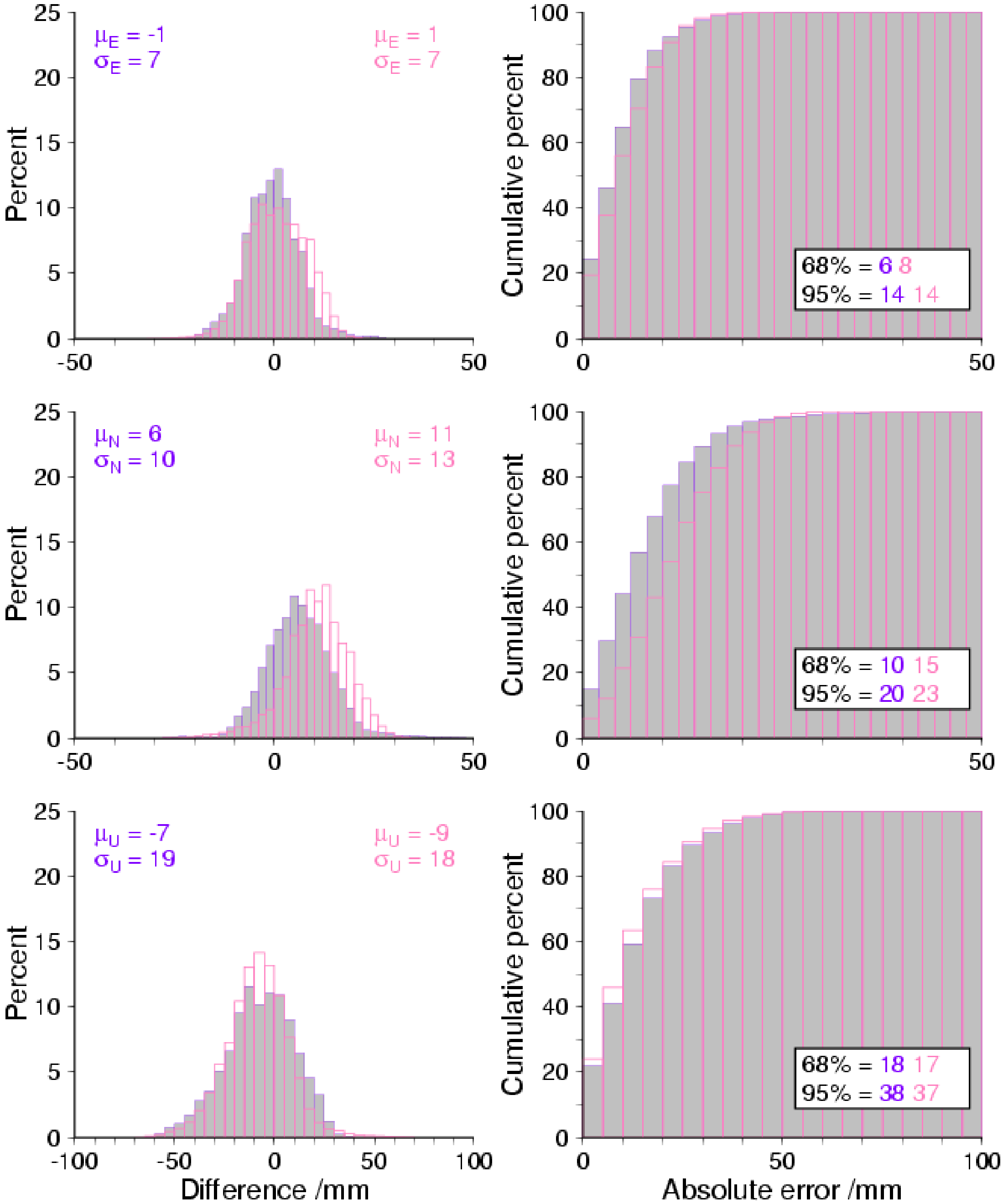
TRET_dop_ filt (ii)



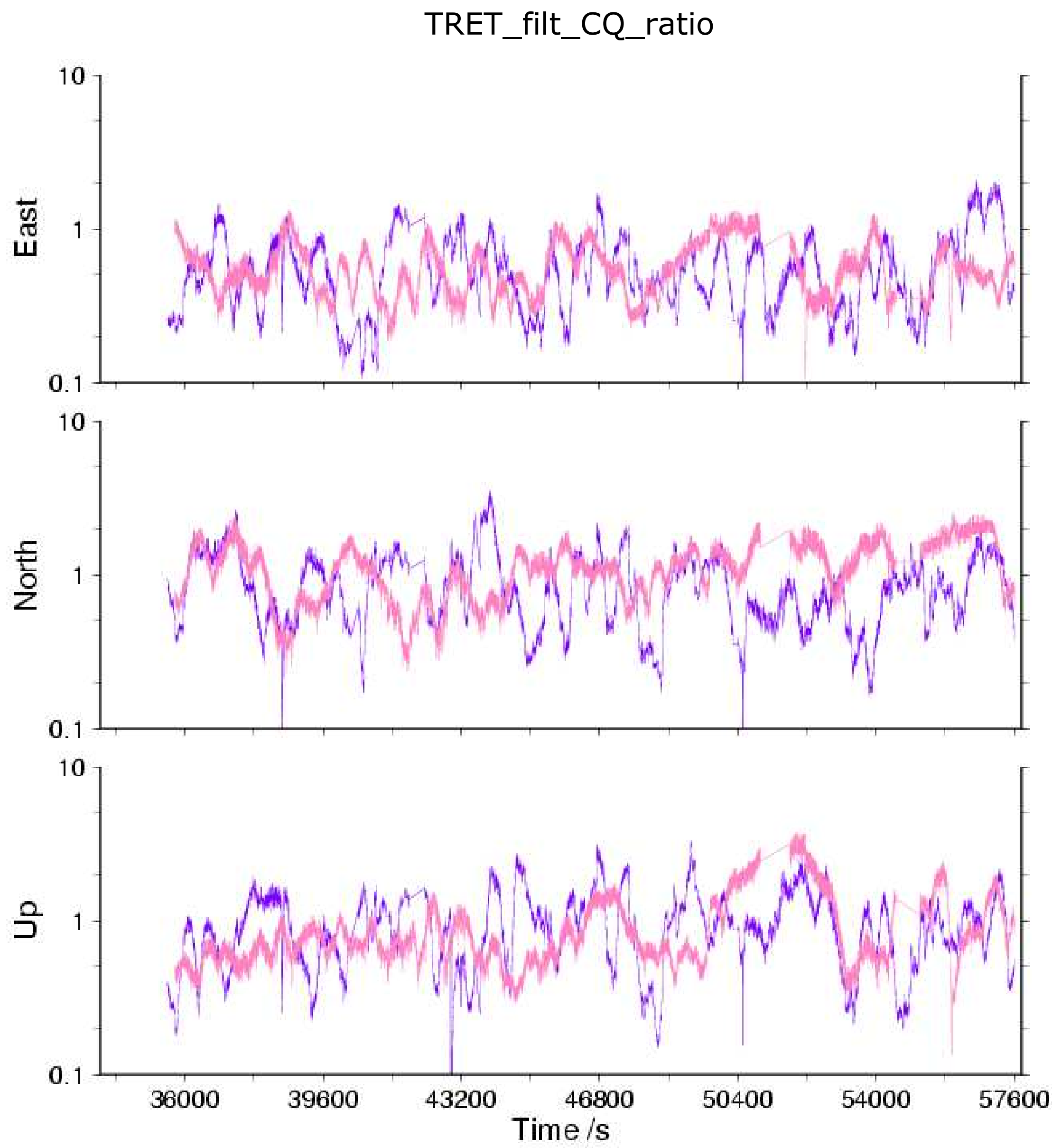

TRET_filt (i)_plan
0.10
0.05
0.00
-0.05
-0.10
North /m
-0.10
-0.05
0.00
0.05
0.10
East /m

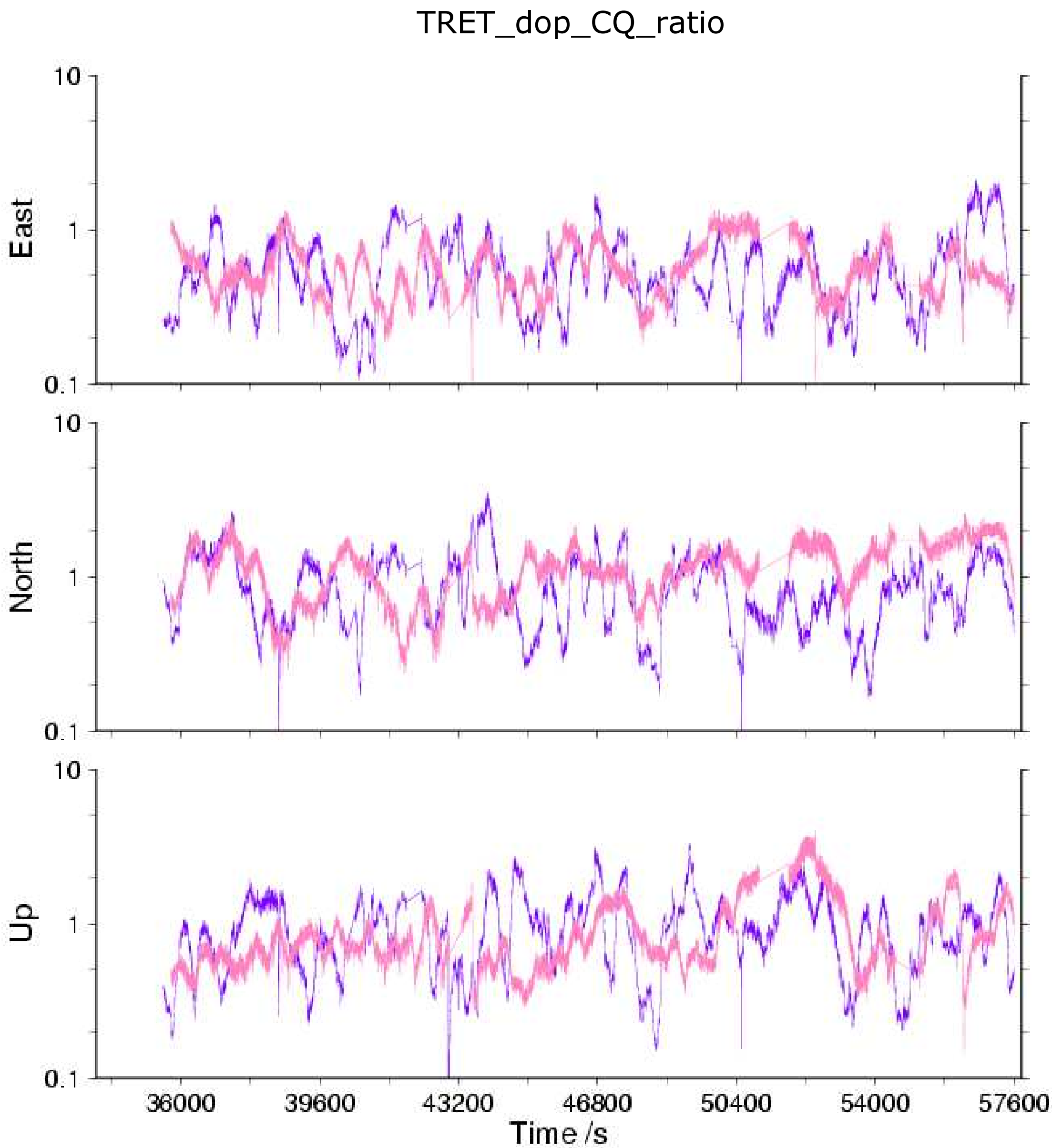

TRET_filt
μE = -1
σE = 7
μE = 1
σE = 7
Percent
68% = 6 8
95% = 14 14
Cumulative percent
μN = 6
σN = 10
μE = 11
σN = 13
68% = 10 15
95% = 20 23
μU = -7
σU = 19
μU = -9
σU = 18
68% = 18 17
95% = 38 37
Difference /mm
Absolute error /mm

TRET_dop



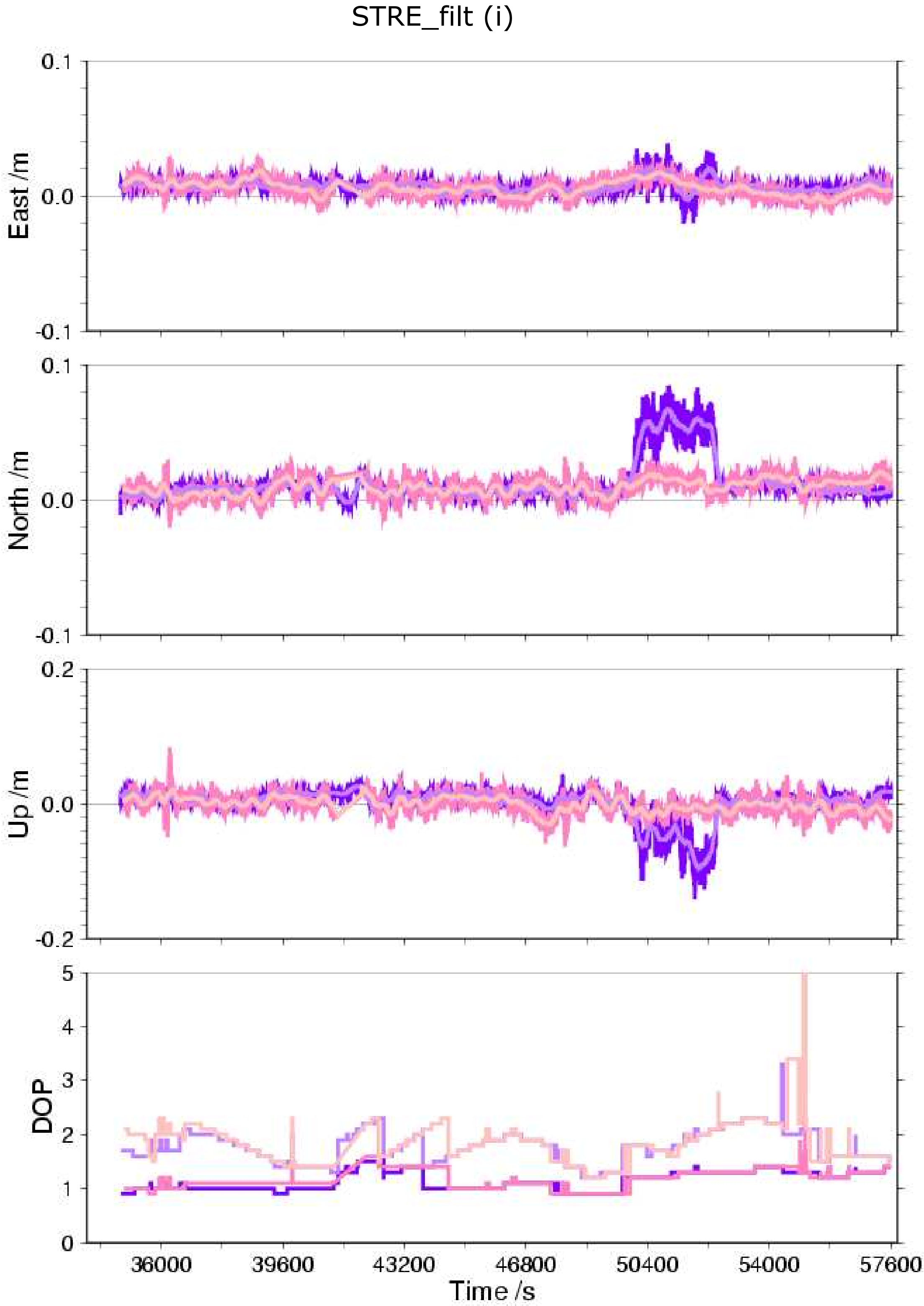
μ_E = -1
σ_E = 7
μ_E = 1
σ_E = 7
Percent
Cumulative percent
68% = 6 8
95% = 14 14
μ_N = 6
σ_N = 10
μ_N = 11
σ_N = 13
68% = 10 15
95% = 20 23
μ_U = -7
σ_U = 19
μ_U = -9
σ_U = 18
68% = 18 17
95% = 38 37
Difference /mm
Absolute error /mm


TRET_filt_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

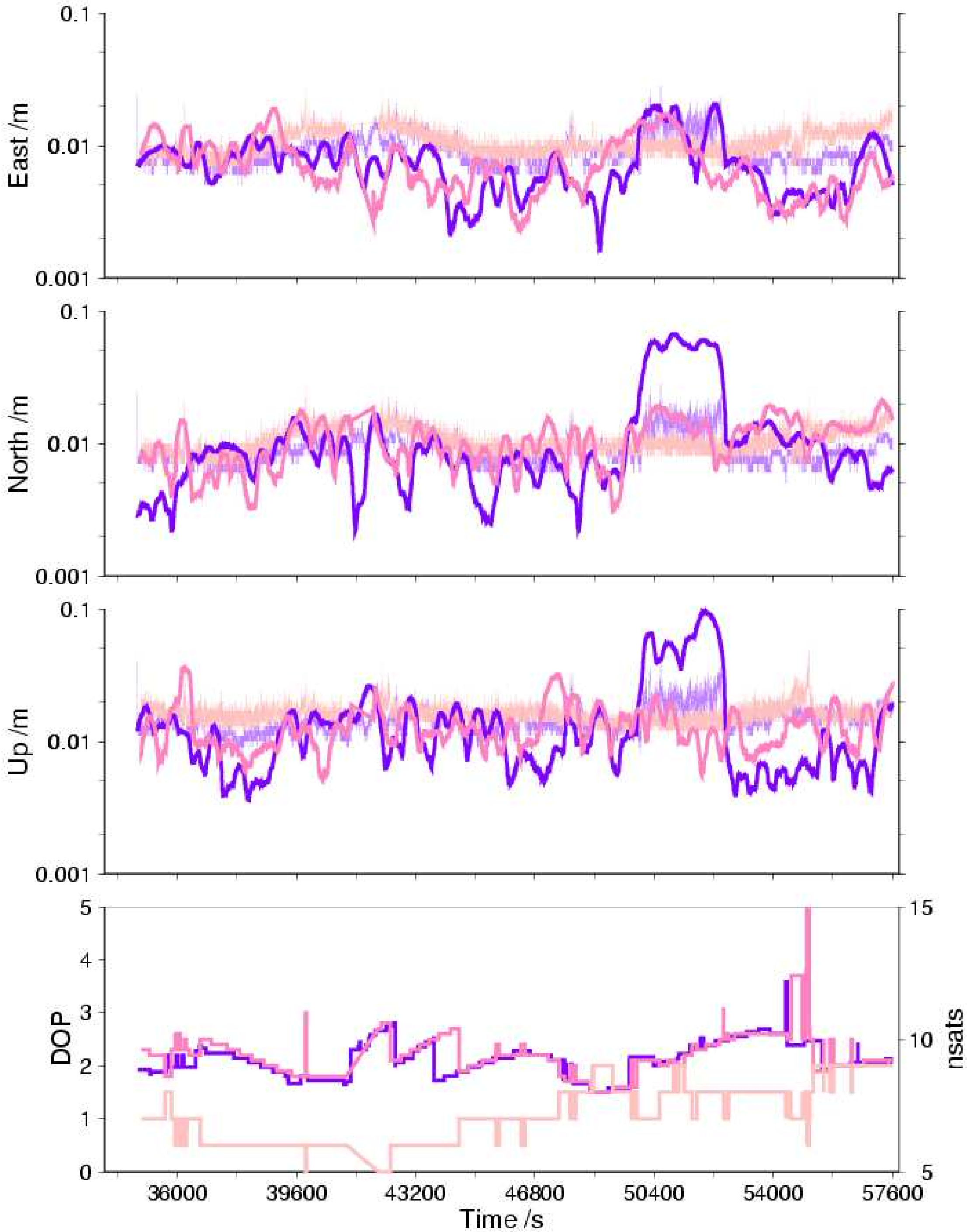

TRET_dop_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

Church **STRE**tton

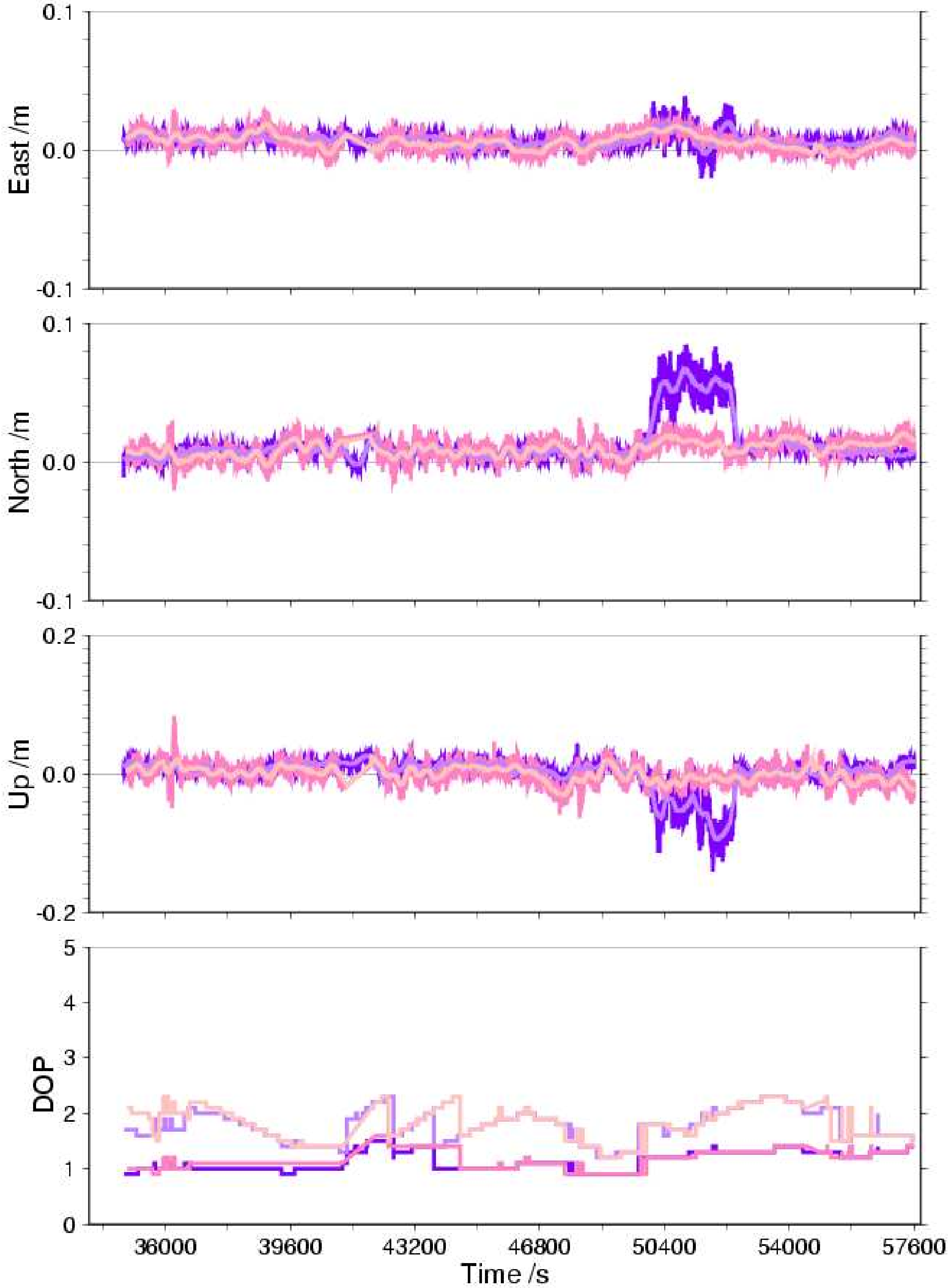
L = 22 – 72 km, σ_L = 48 km
Δh = -255 m, $\sigma_{\Delta h}$ = 257 m

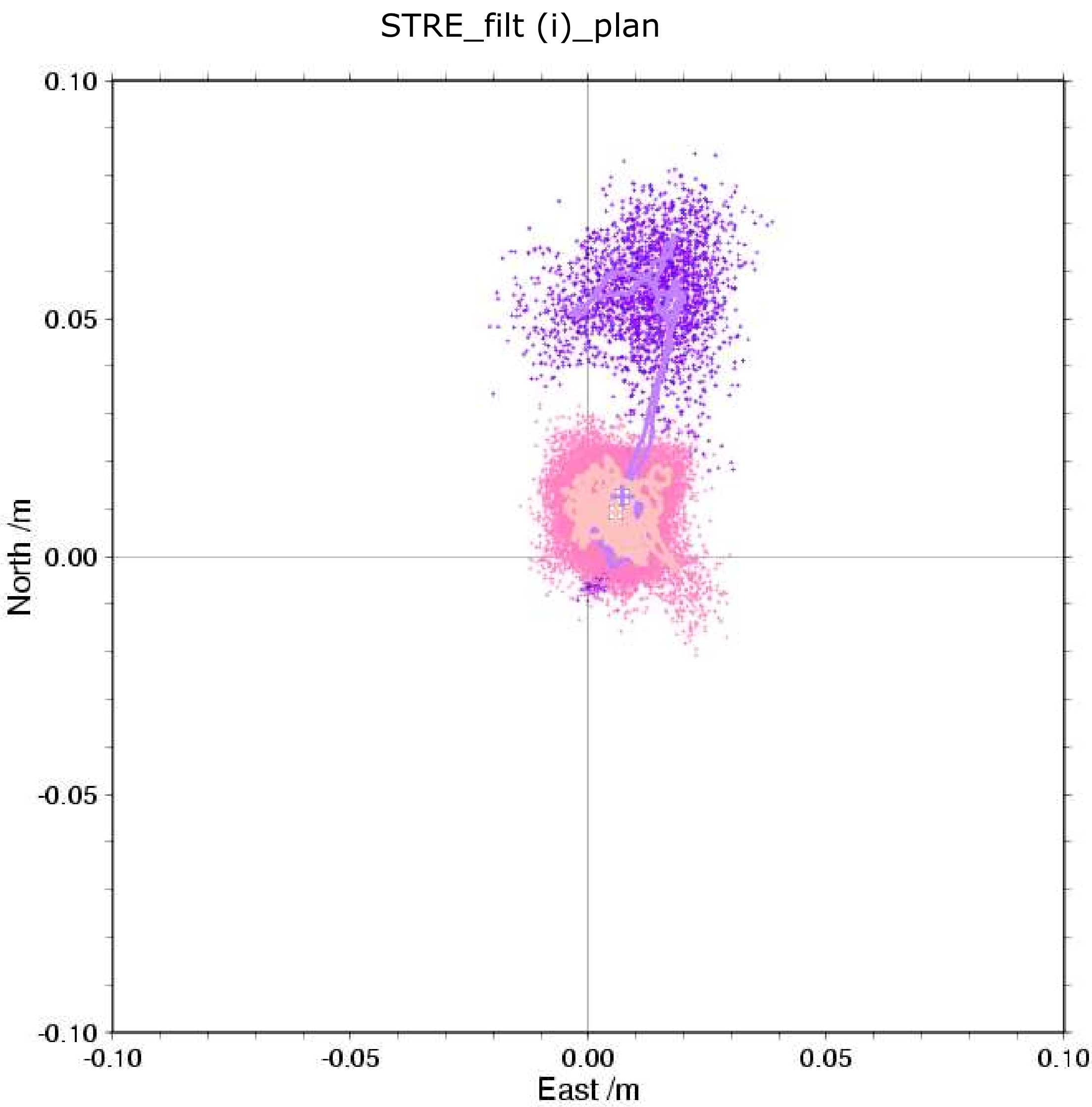


STRE_filt (i) rms_moving window



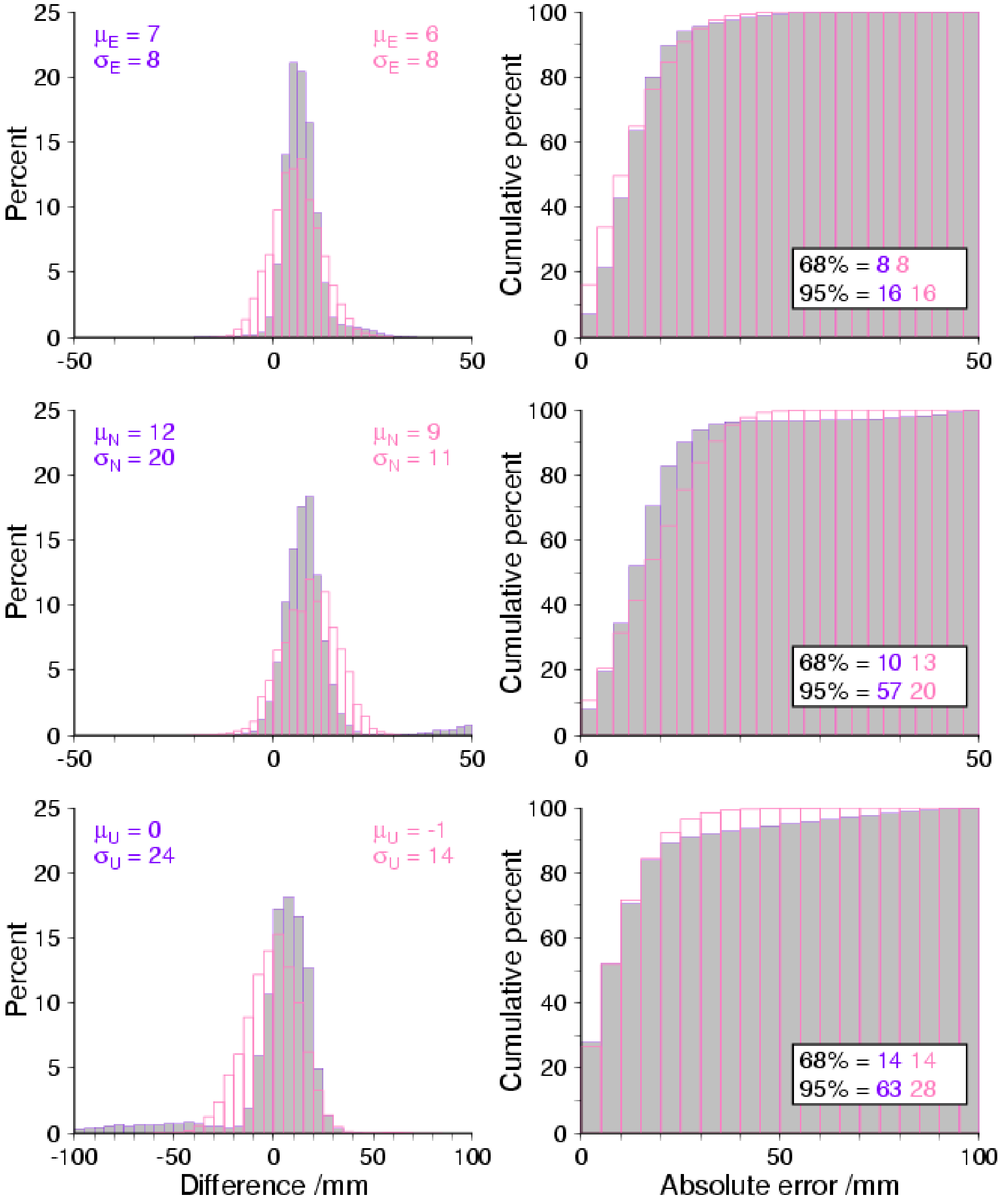
STRE_dop _filt (ii)



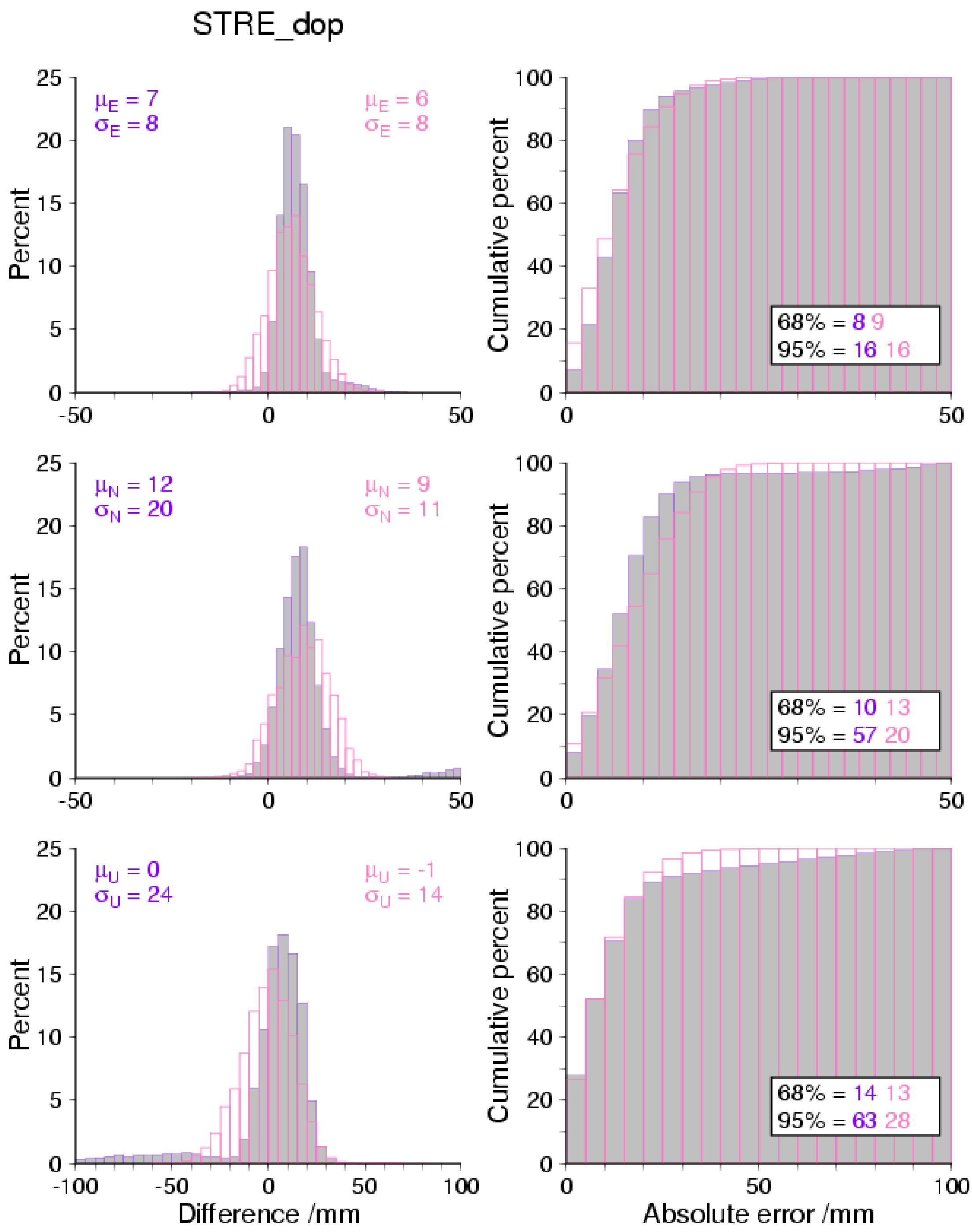


STRE_filt (i)_plan
0.10
0.05
0.00
-0.05
-0.10
North /m
-0.10
-0.05
0.00
0.05
0.10
East /m

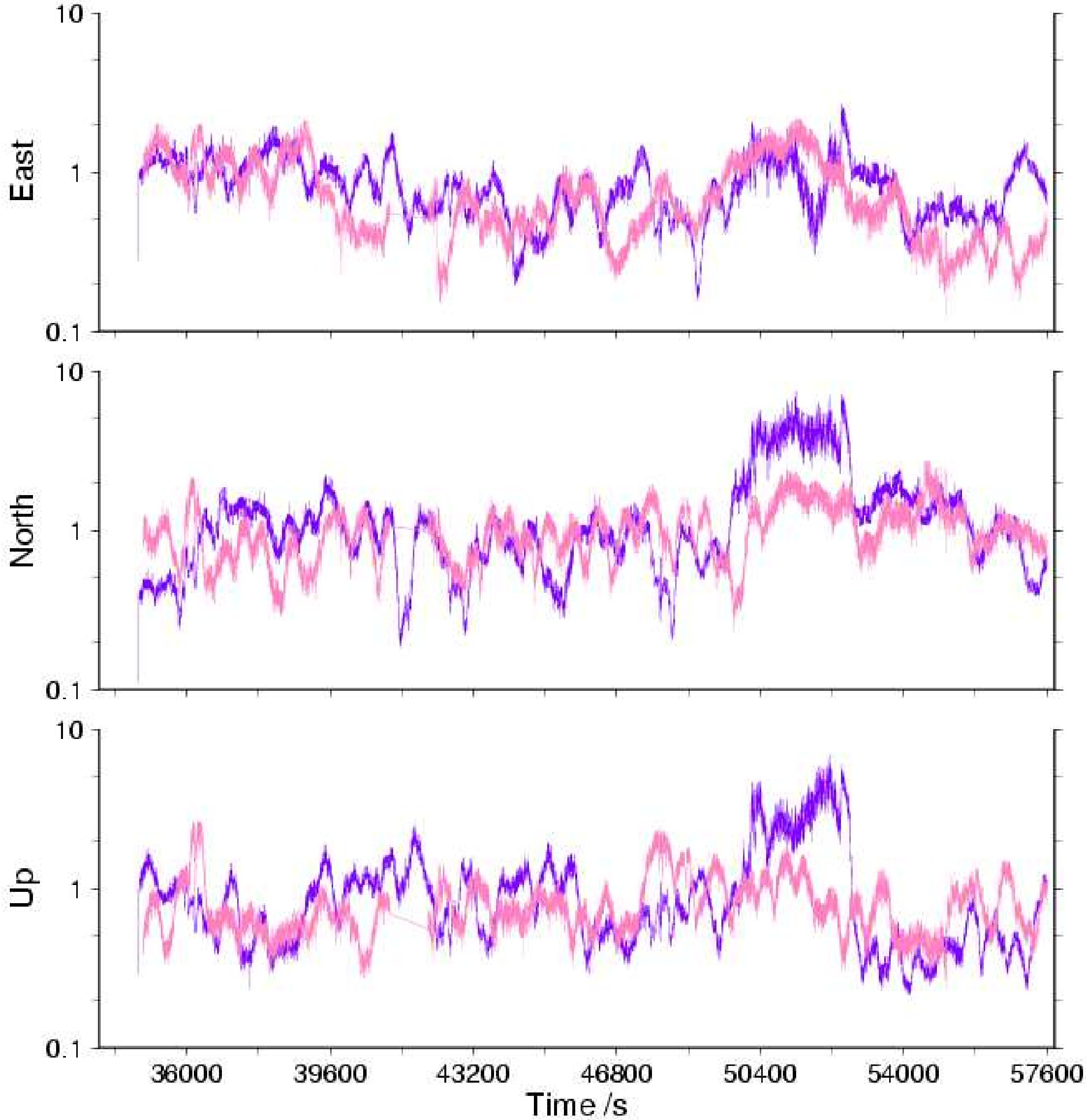
STRE_filt

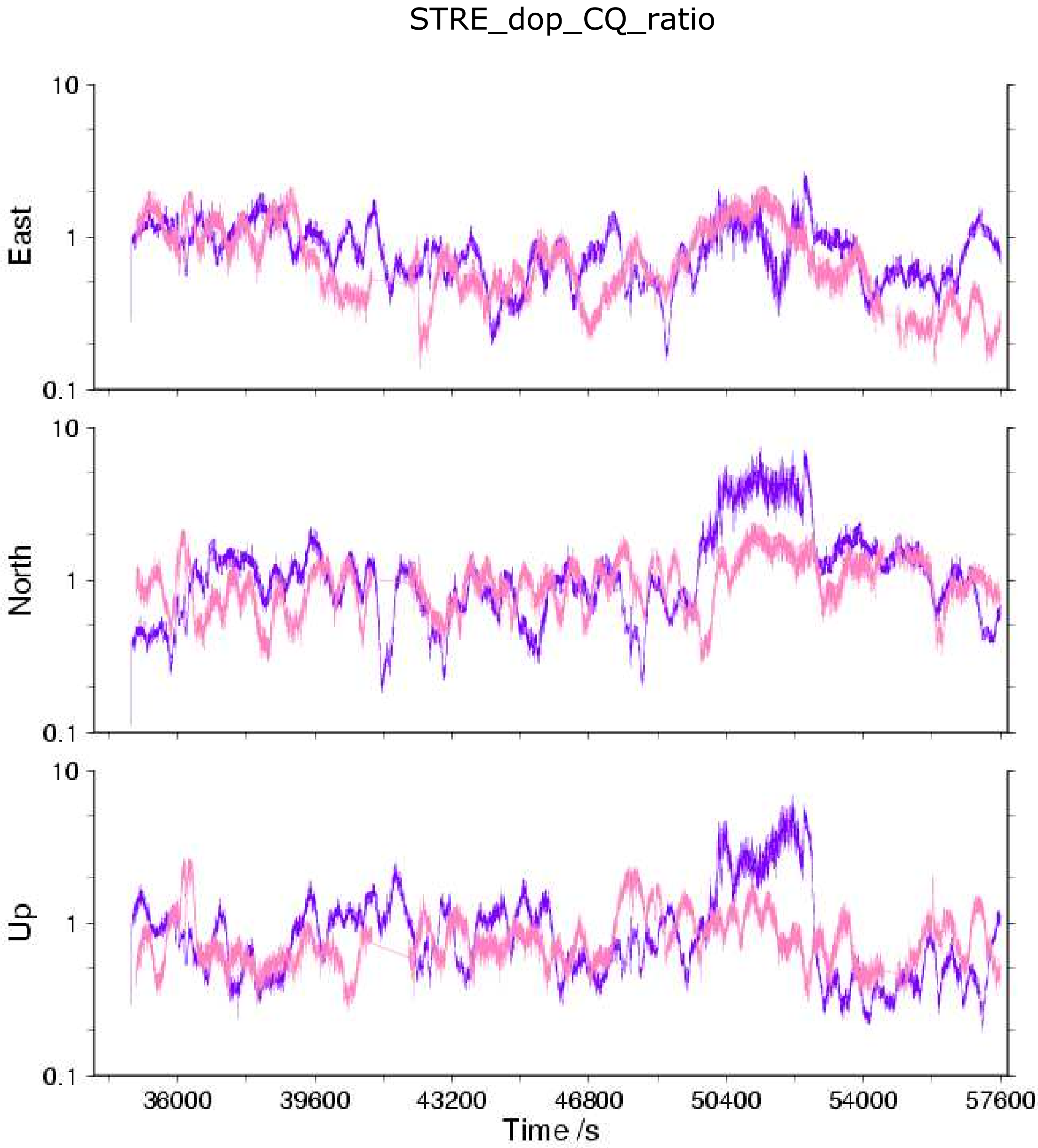


μE = 7
σE = 8
μE = 6
σE = 8
68% = 8 8
95% = 16 16
μN = 12
σN = 20
μN = 9
σN = 11
68% = 10 13
95% = 57 20
μU = 0
σU = 24
μU = -1
σU = 14
68% = 14 14
95% = 63 28
Percent
Cumulative percent
Difference /mm
Absolute error /mm


STRE_dop
$\mu_E = 7$
$\sigma_E = 8$
$\mu_E = 6$
$\sigma_E = 8$
68% = 8 9
95% = 16 16
$\mu_N = 12$
$\sigma_N = 20$
$\mu_N = 9$
$\sigma_N = 11$
68% = 10 13
95% = 57 20
$\mu_U = 0$
$\sigma_U = 24$
$\mu_U = -1$
$\sigma_U = 14$
68% = 14 13
95% = 63 28
Percent
Cumulative percent
Difference /mm
Absolute error /mm

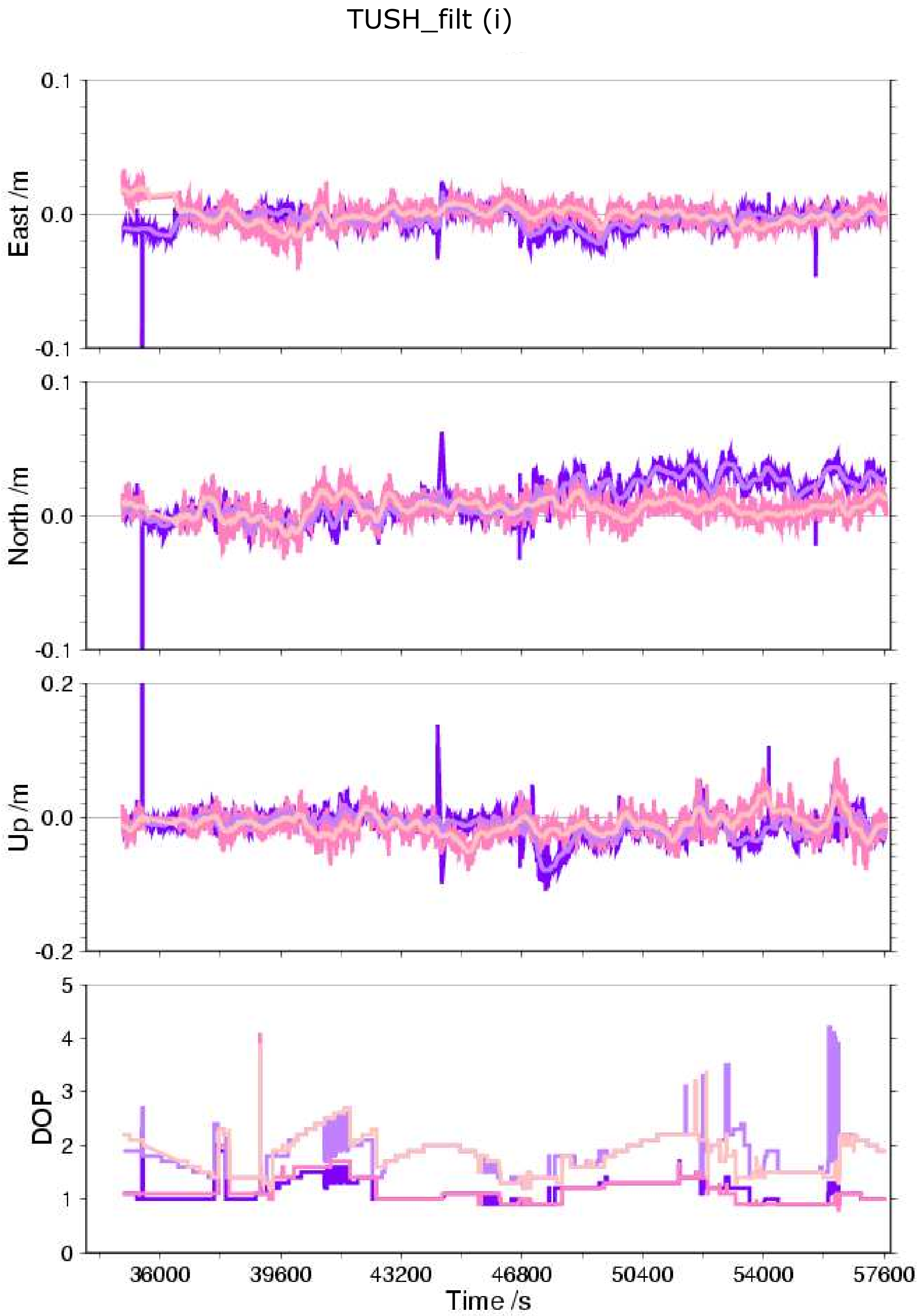
STRE_filt_CQ_ratio



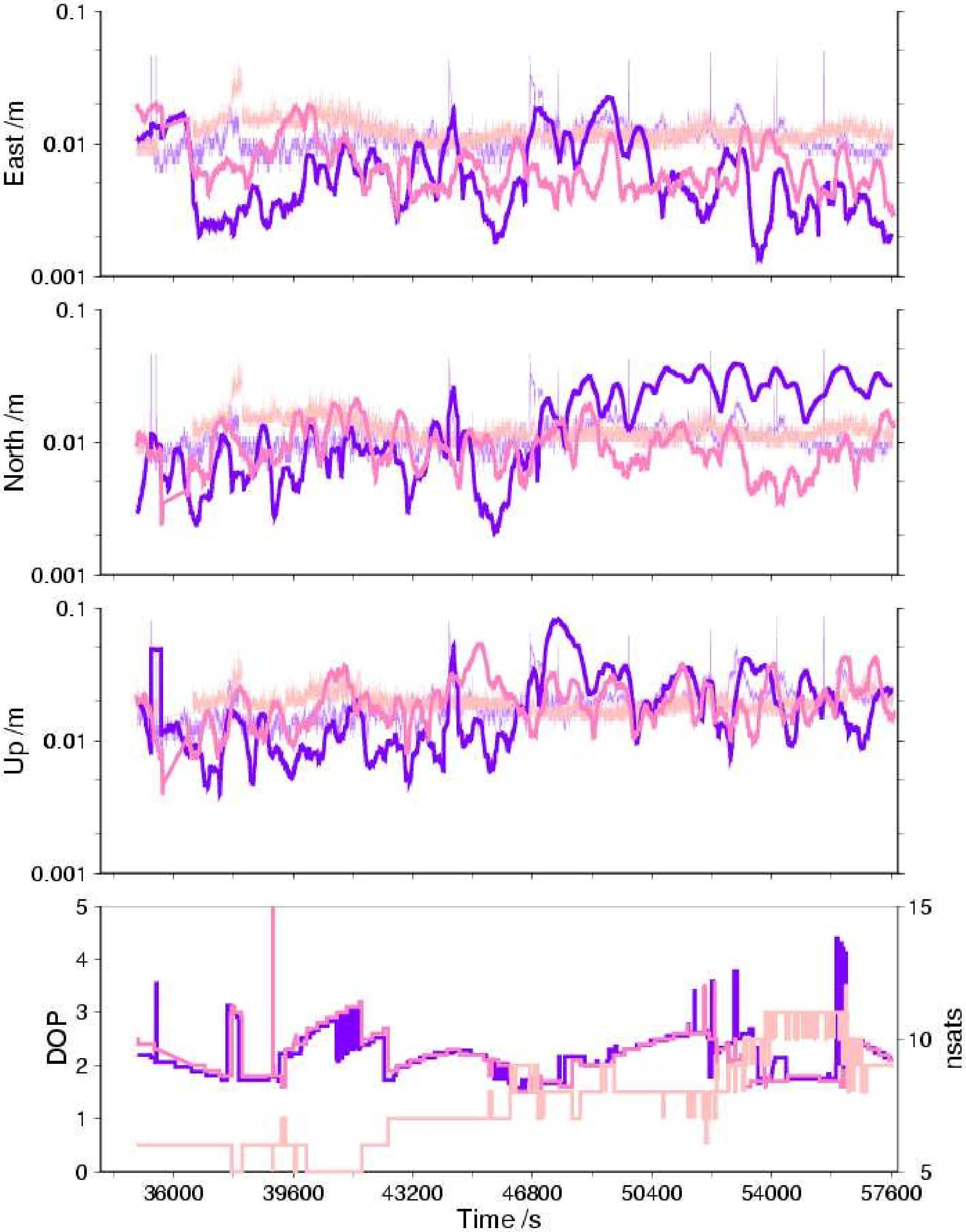

STRE_dop_CQ_ratio
10
1
0.1
East
North
Up
36000
39600
43200
46800
50400
54000
57600
Time /s

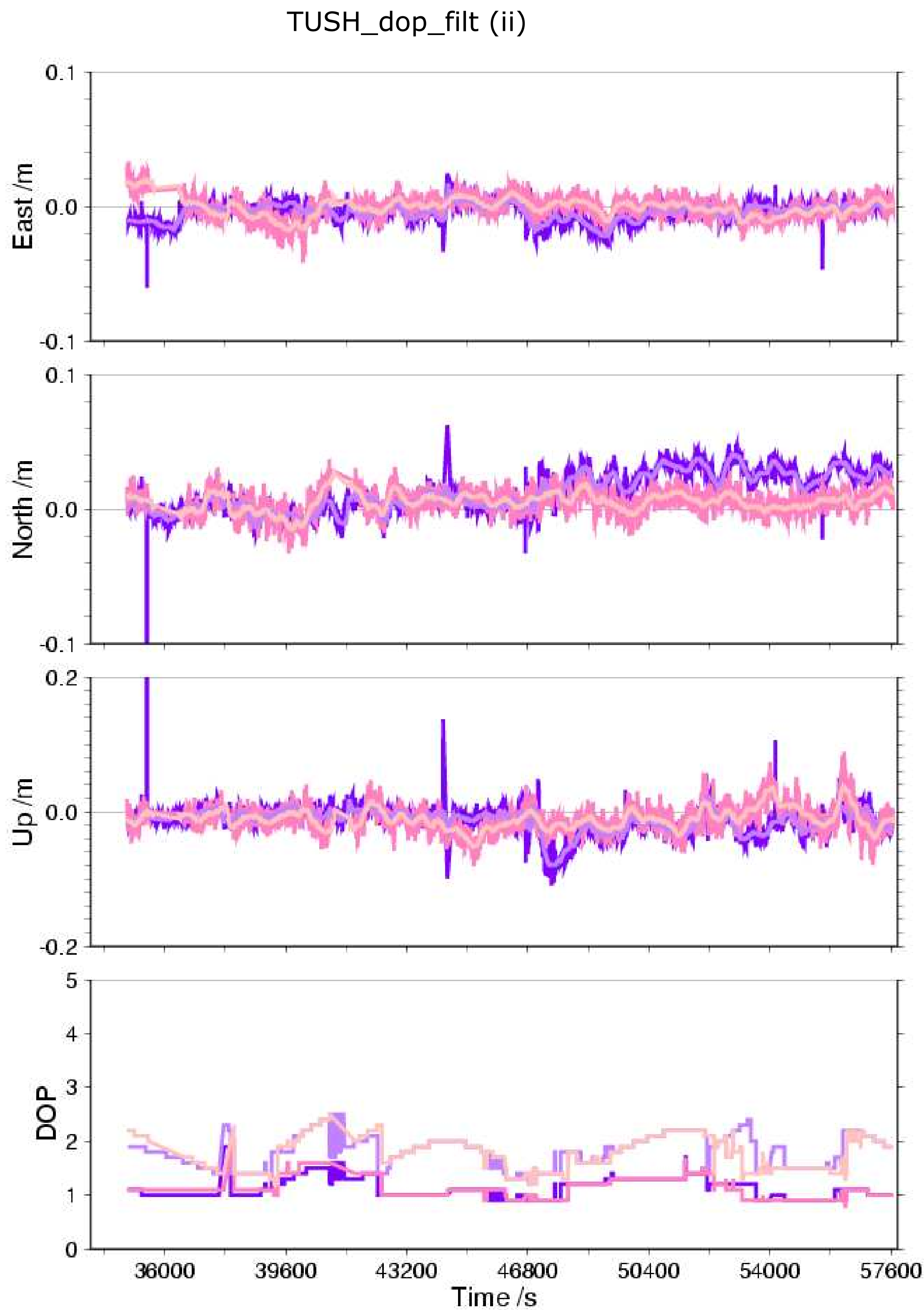
TUSHingham

L = 31 – 69 km, σ_L = 50km
Δh = 16 m, $\sigma_{\Delta h}$ = 108 m

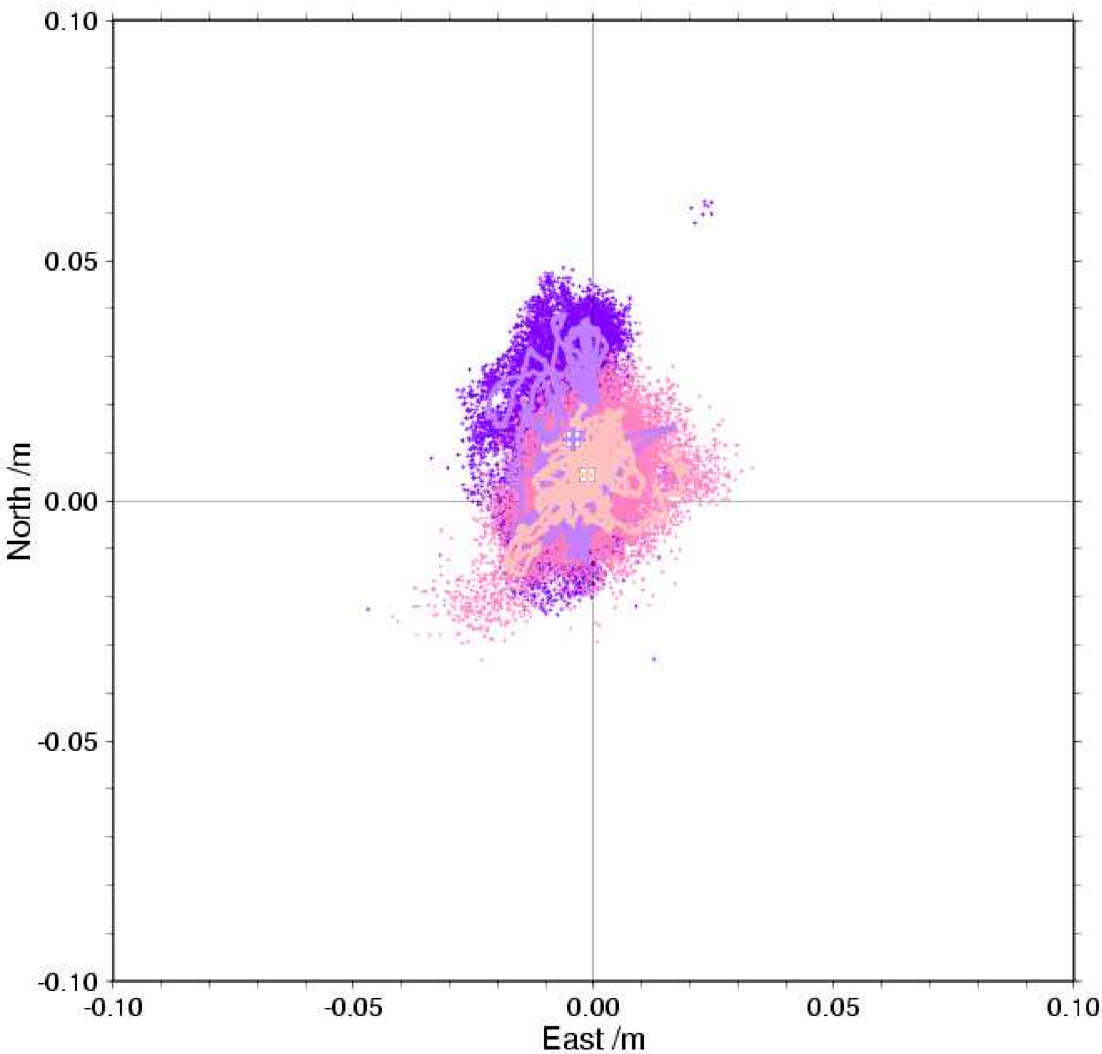


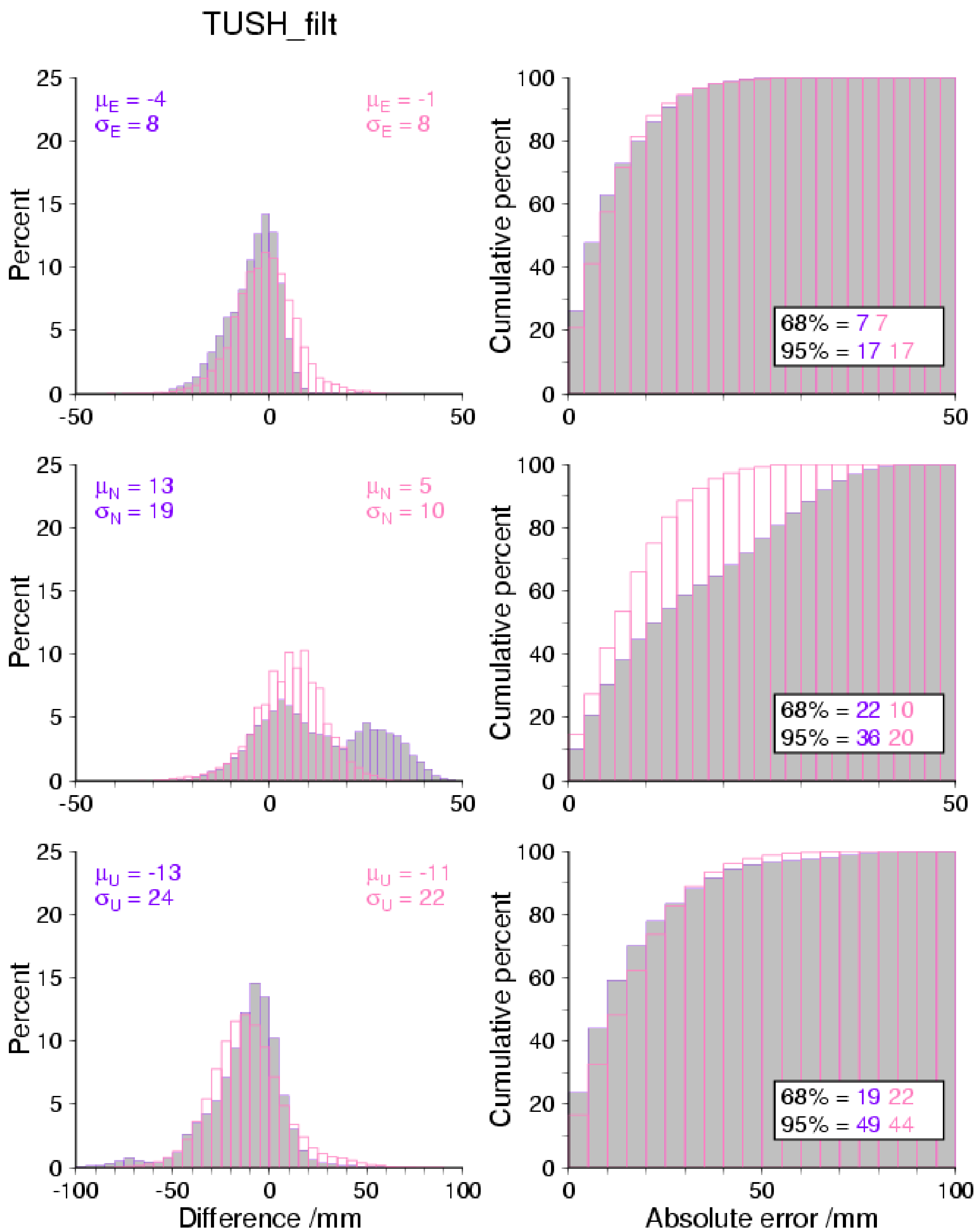
TUSH_filt (i) rms_moving_window



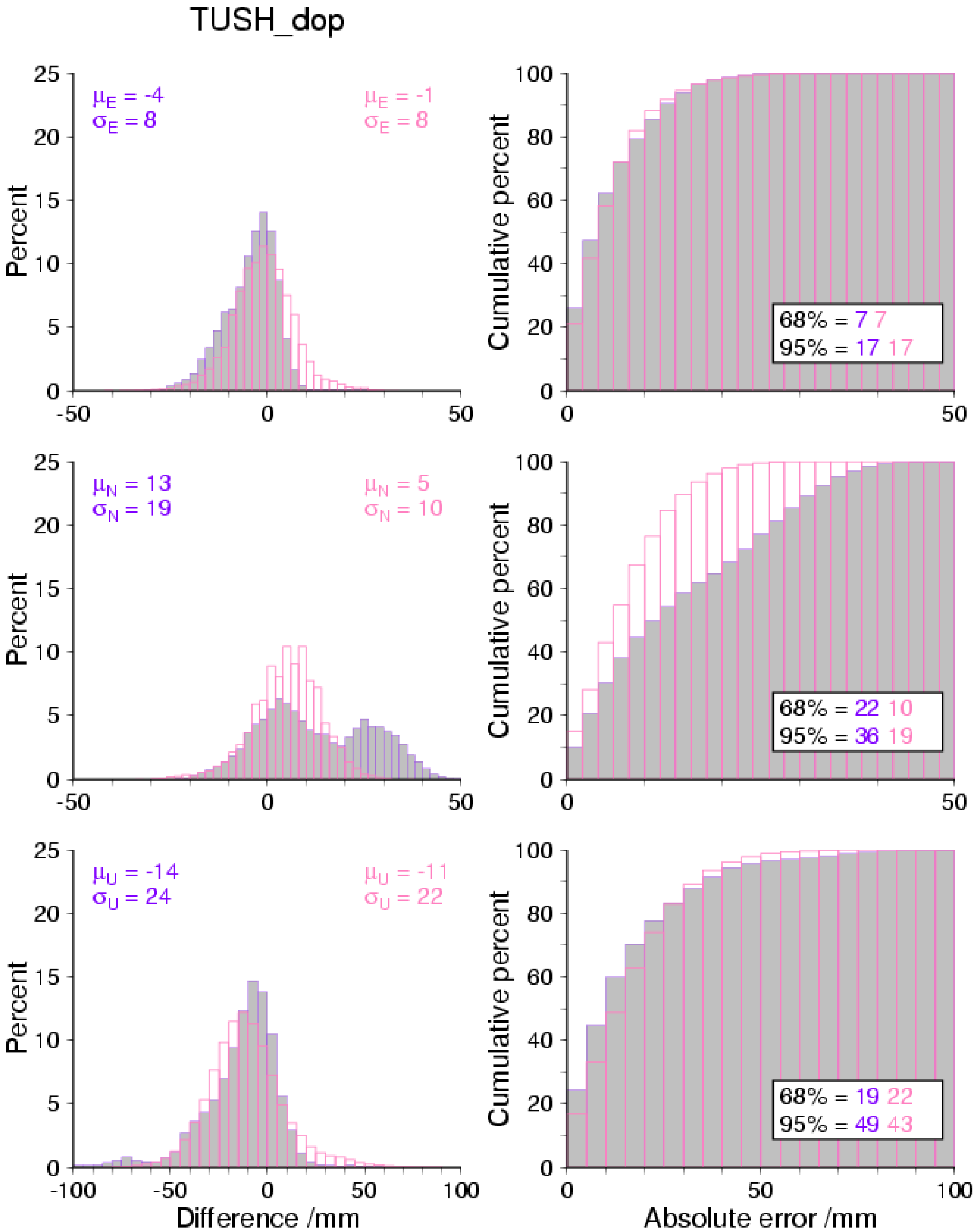

TUSH_dop_filt (ii)
East /m
North /m
Up /m
DOP
Time /s
0.1
0.0
-0.1
0.2
-0.2
0
1
2
3
4
5
36000
39600
43200
46800
50400
54000
57600

TUSH_filt (i)_plan

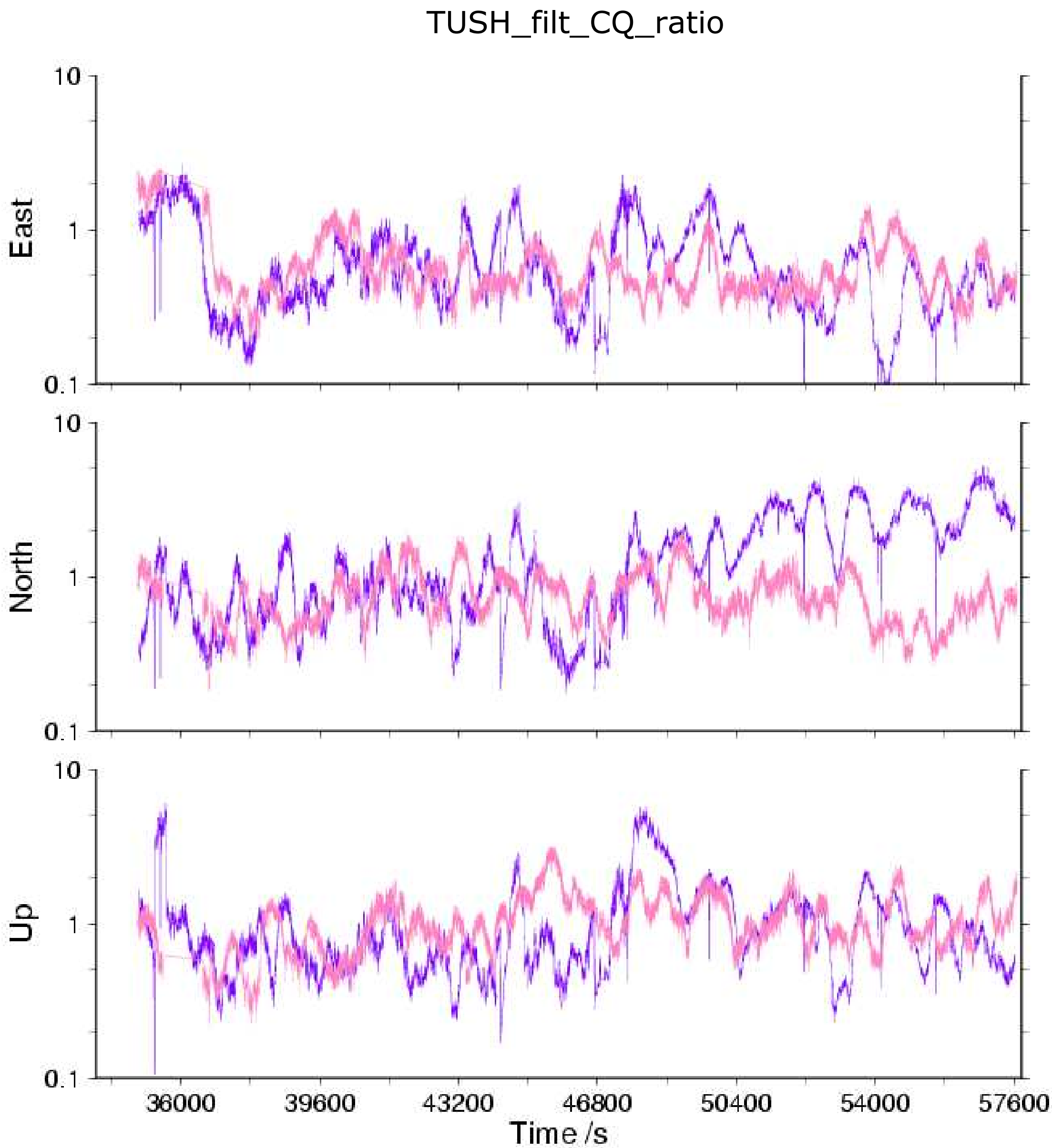




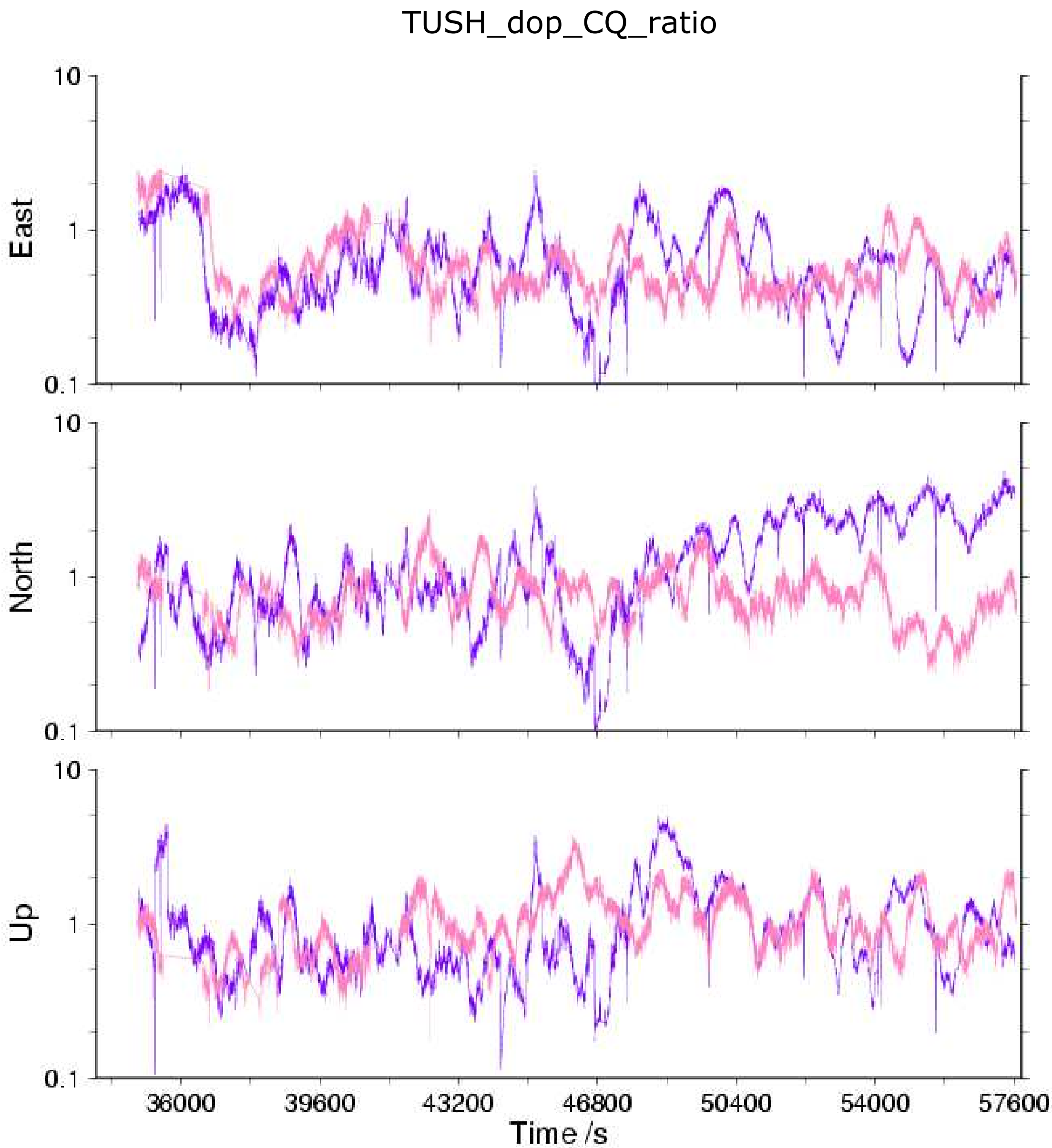
TUSH_filt
μ_E = -4
σ_E = 8
μ_E = -1
σ_E = 8
Percent
Cumulative percent
68% = 7 7
95% = 17 17
μ_N = 13
σ_N = 19
μ_N = 5
σ_N = 10
68% = 22 10
95% = 36 20
μ_U = -13
σ_U = 24
μ_U = -11
σ_U = 22
68% = 19 22
95% = 49 44
Difference /mm
Absolute error /mm



TUSH_dop
μ_E = -4
σ_E = 8
μ_E = -1
σ_E = 8
Percent
Cumulative percent
68% = 7 7
95% = 17 17
μ_N = 13
σ_N = 19
μ_N = 5
σ_N = 10
68% = 22 10
95% = 36 19
μ_U = -14
σ_U = 24
μ_U = -11
σ_U = 22
68% = 19 22
95% = 49 43
Difference /mm
Absolute error /mm

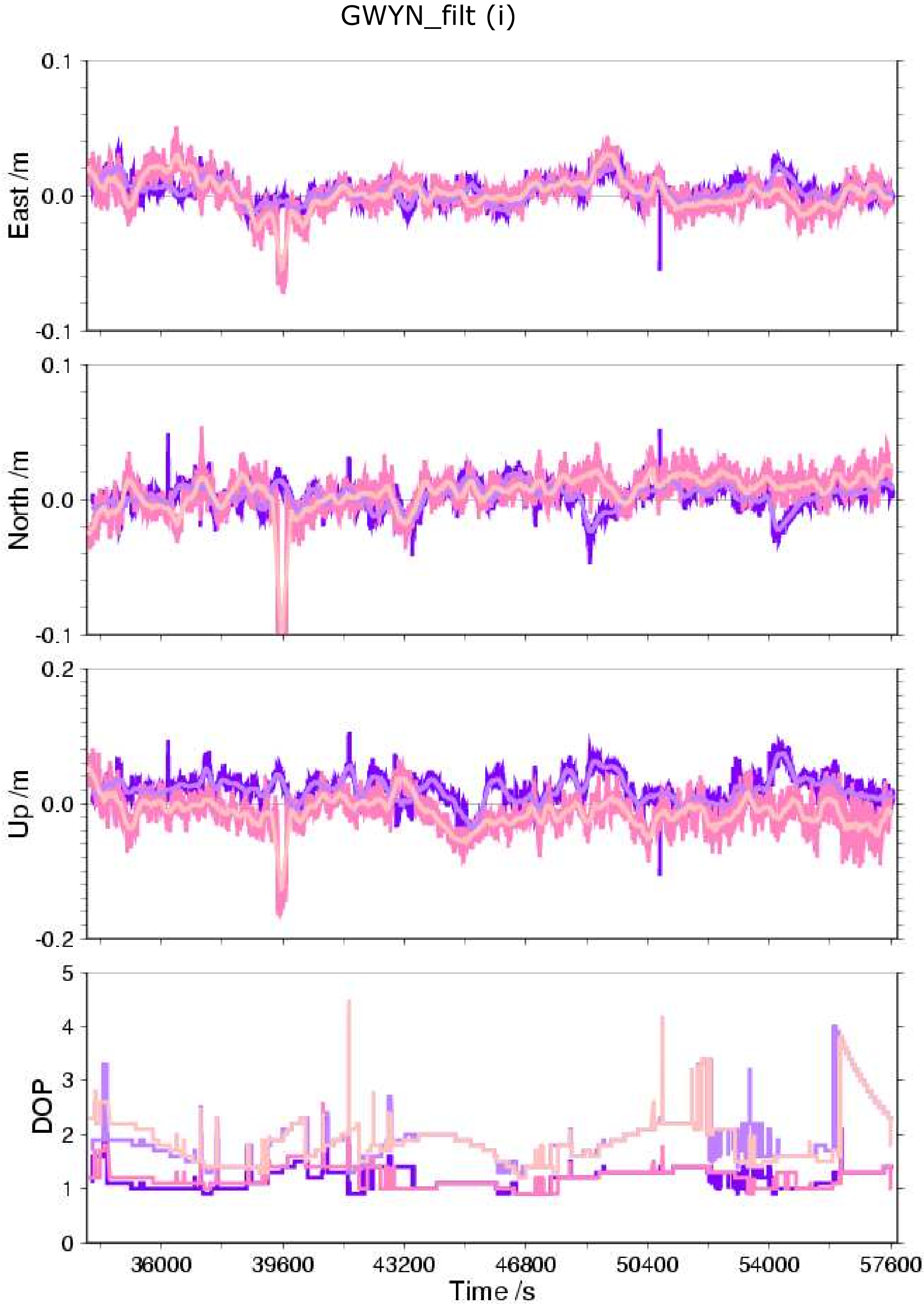


TUSH_filt_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

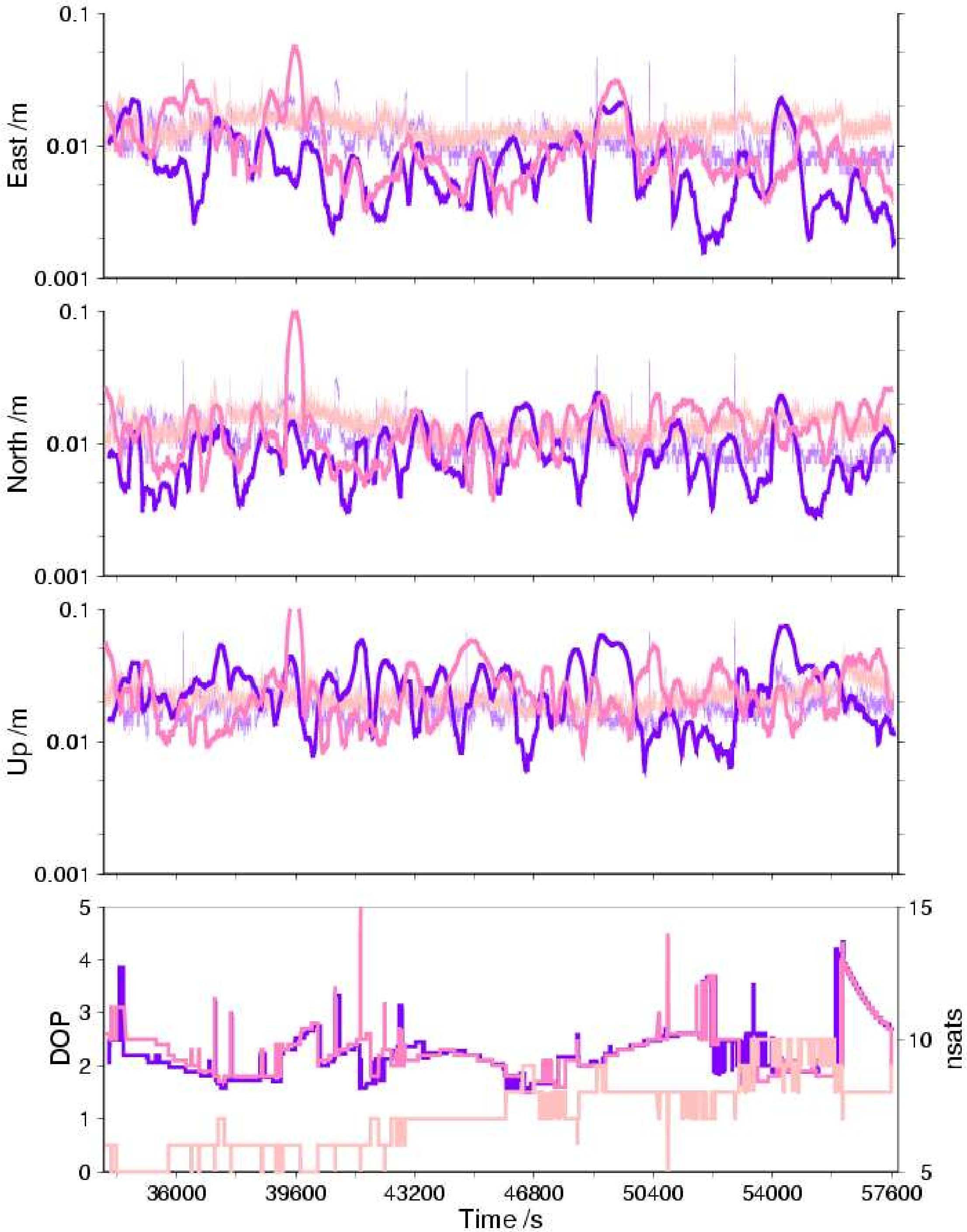

TUSH_dop_CQ_ratio
East
North
Up
10
1
0.1
36000
39600
43200
46800
50400
54000
57600
Time /s

GWYNfryn

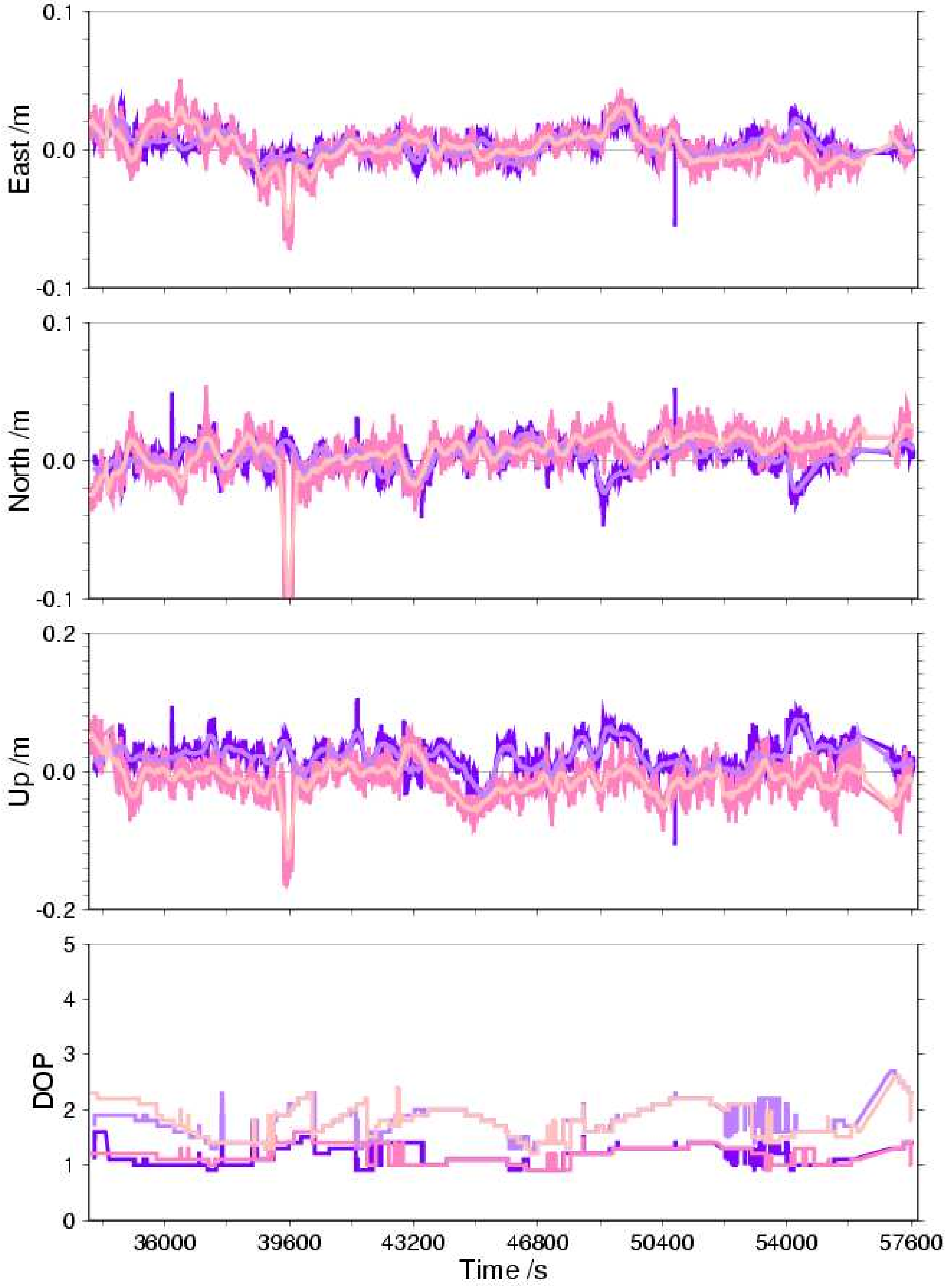
L = 45 - 80 km, σ_L = 64 km
Δh = -245 m, $\sigma_{\Delta h}$ = 279 m

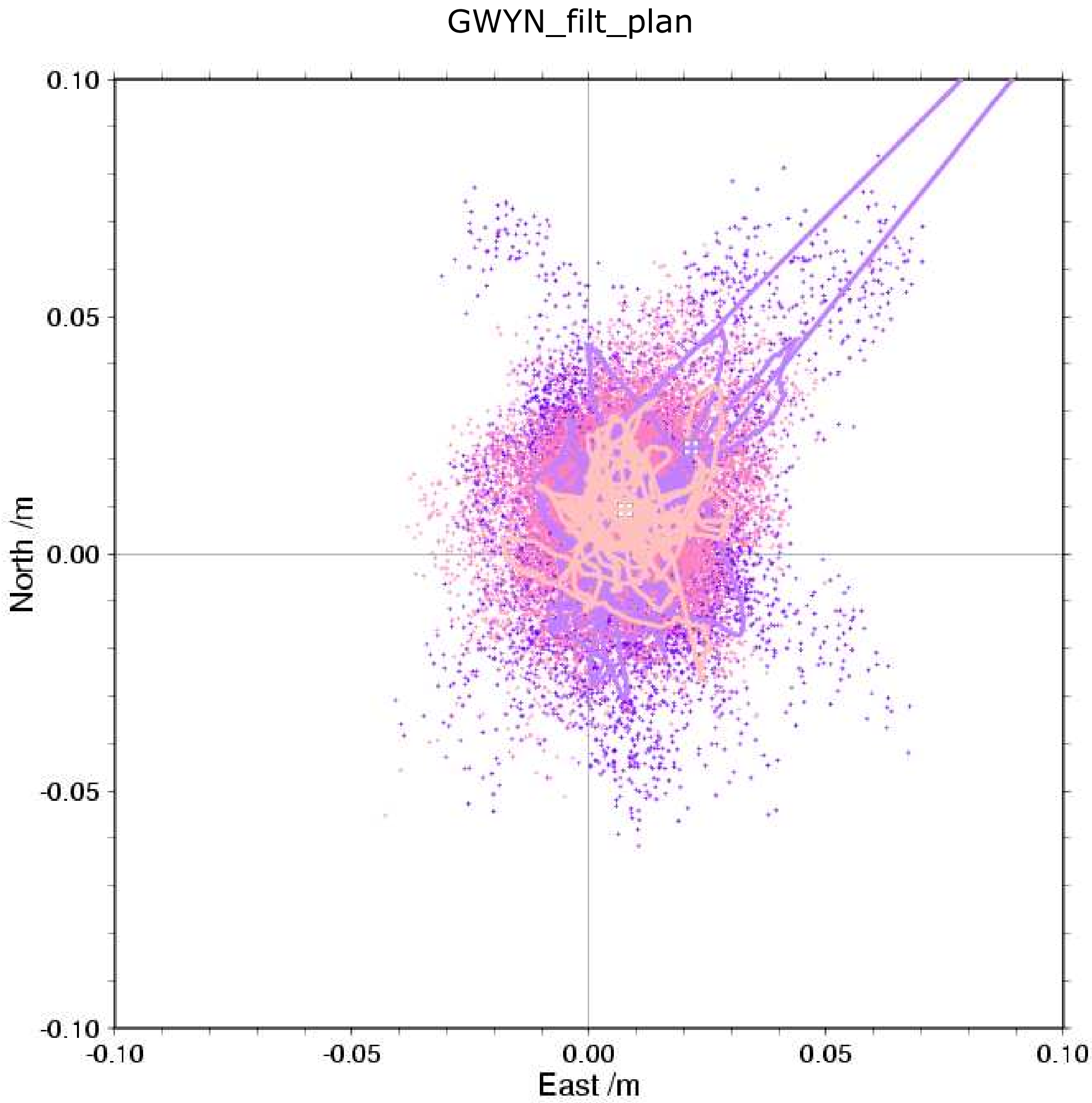


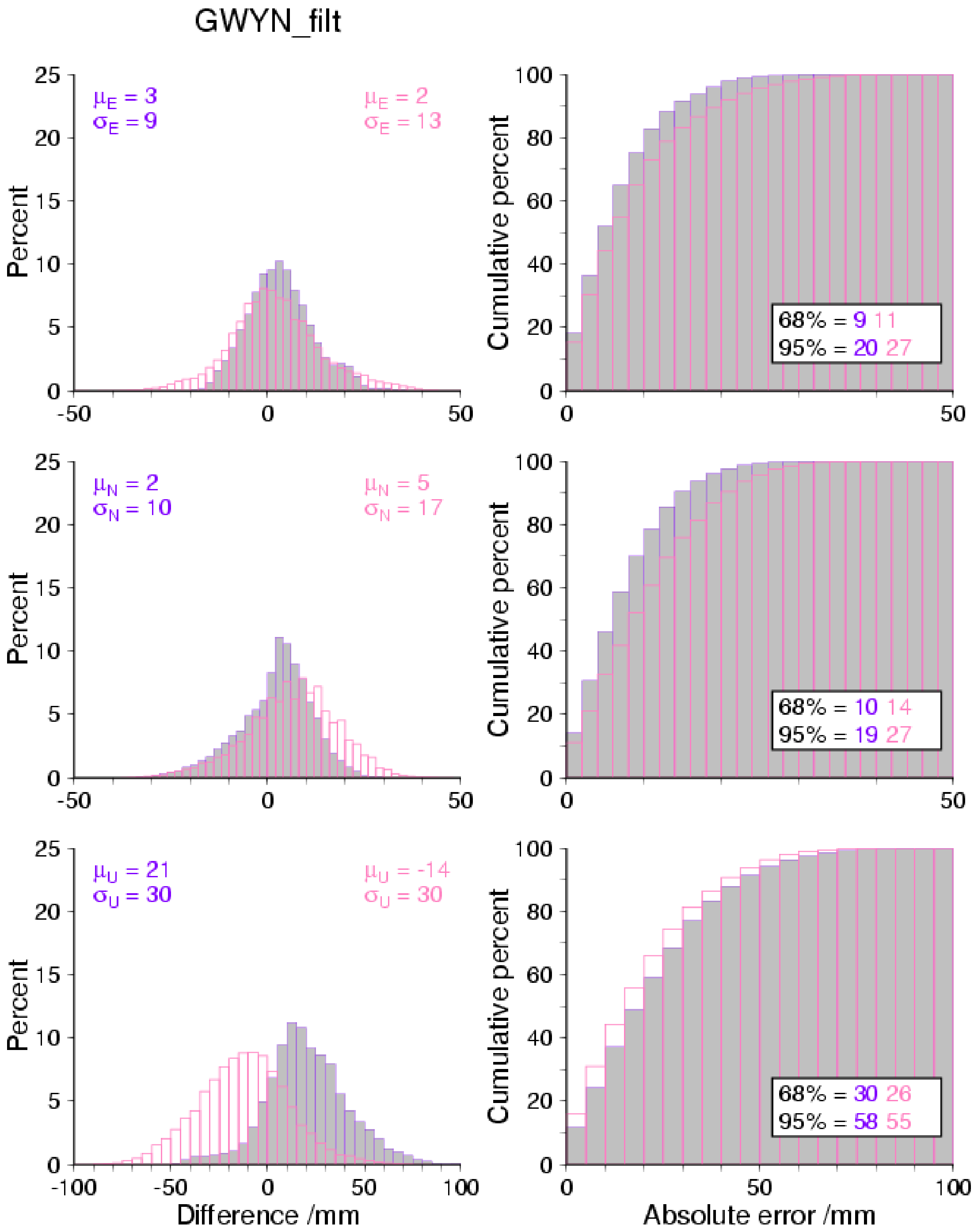
GWYN_filt (i) rms_moving



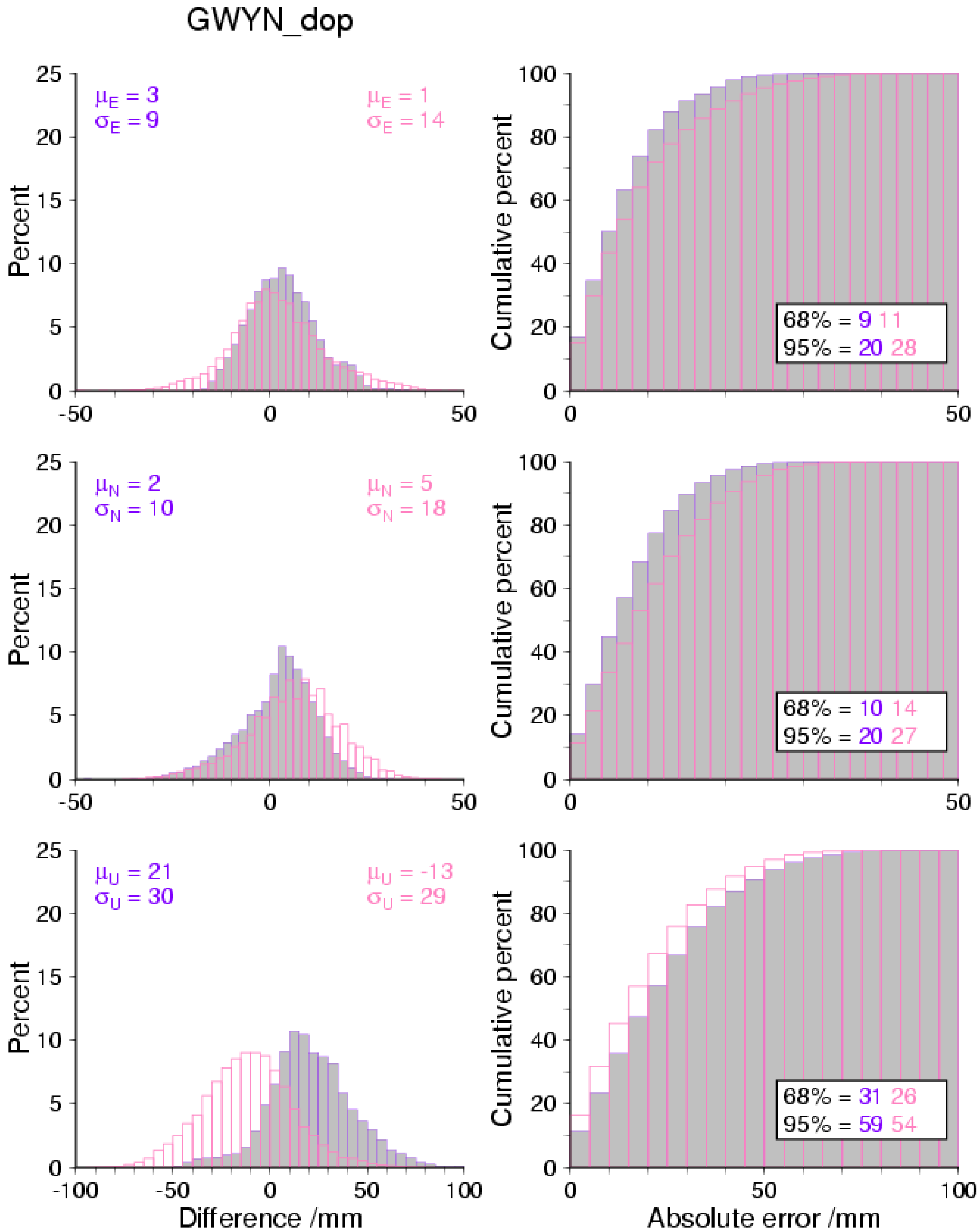
GWYN_dop_filt (ii)



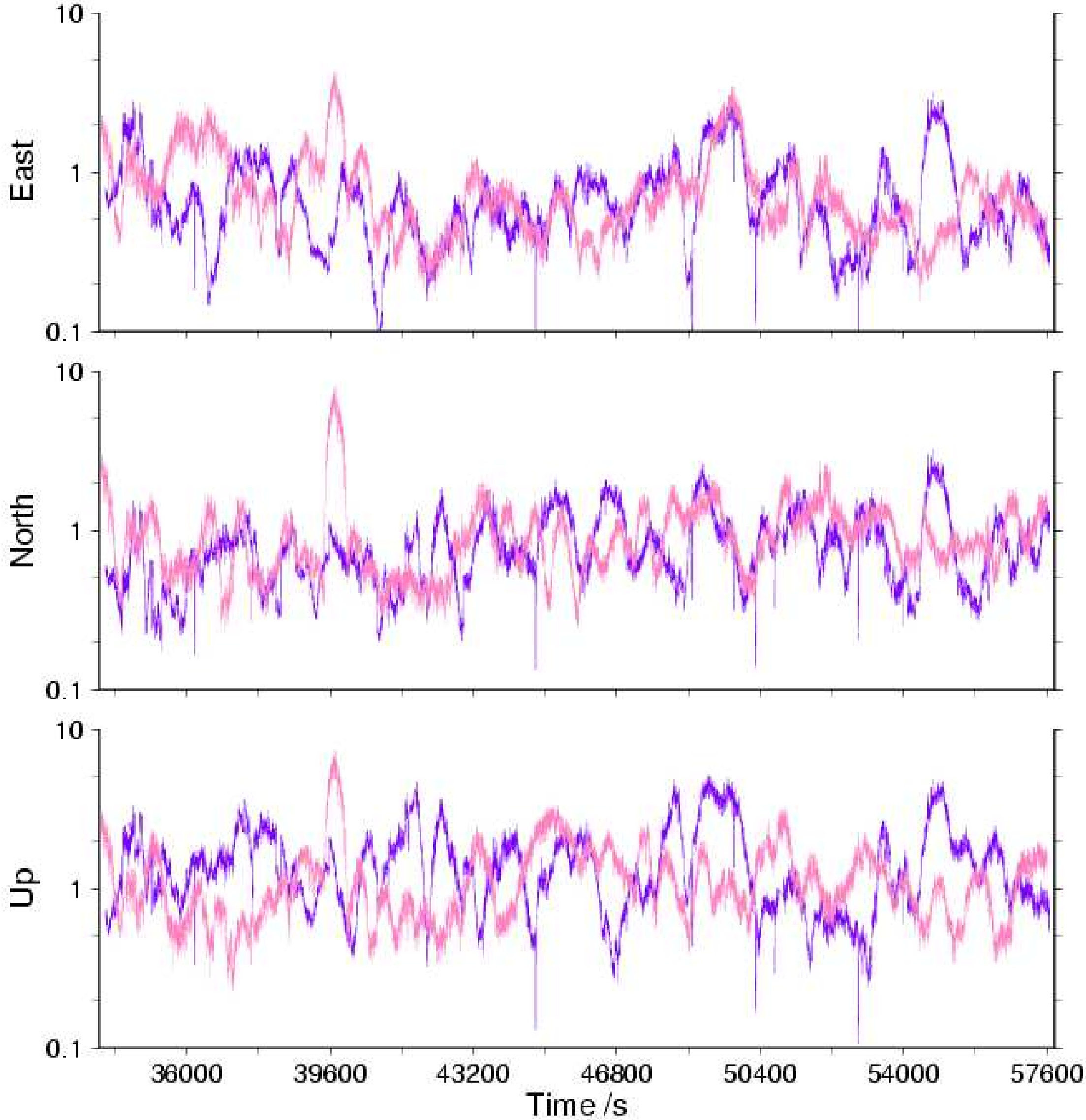

GWYN_filt_plan
0.10
0.05
0.00
-0.05
-0.10
North /m
-0.10
-0.05
0.00
0.05
0.10
East /m



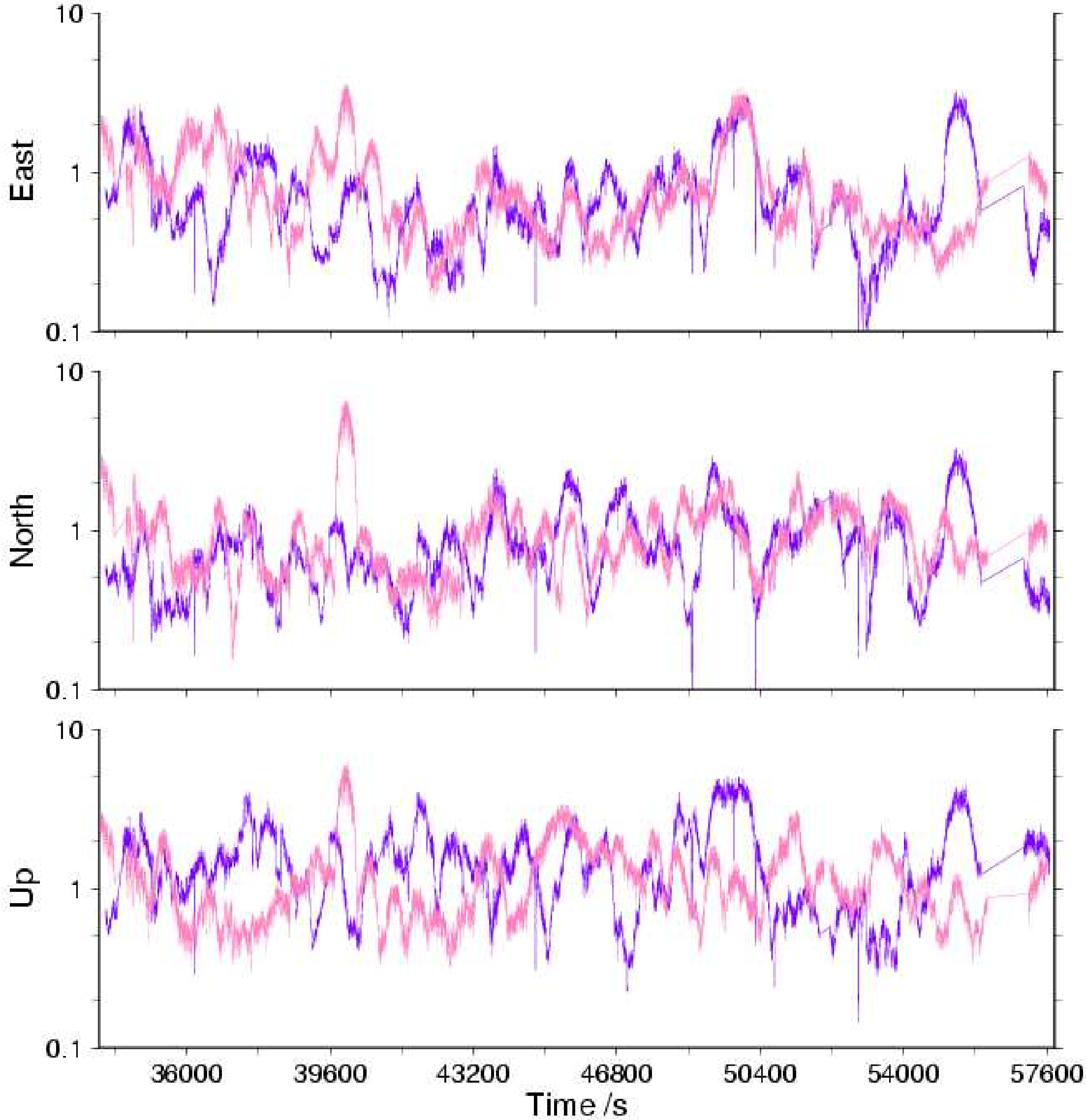
GWYN_filt
$\mu_E = 3$
$\sigma_E = 9$
$\mu_E = 2$
$\sigma_E = 13$
68% = 9 11
95% = 20 27
$\mu_N = 2$
$\sigma_N = 10$
$\mu_N = 5$
$\sigma_N = 17$
68% = 10 14
95% = 19 27
$\mu_U = 21$
$\sigma_U = 30$
$\mu_U = -14$
$\sigma_U = 30$
68% = 30 26
95% = 58 55
Percent
Cumulative percent
Difference /mm
Absolute error /mm


GWYN_dop
μE = 3
σE = 9
μE = 1
σE = 14
Percent
Cumulative percent
68% = 9 11
95% = 20 28
μN = 2
σN = 10
μN = 5
σN = 18
68% = 10 14
95% = 20 27
μU = 21
σU = 30
μU = -13
σU = 29
68% = 31 26
95% = 59 54
Difference /mm
Absolute error /mm

GWYN_filt_CQ_ratio



GWYN_dop_CQ_ratio



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Further information and useful addresses

The Survey Association
http://www.tsa-uk.org.uk/

Newcastle University
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