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Mitigation of GNSS multipath by the use of dual-polarisation observations





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multipath by the use
of dual-polarisation
observations

Report for Royal Institution of Chartered Surveyors

Report written by:

Newcastle University

Dr Kirill Palamartchouk
kirill.palamartchouk@ncl.ac.uk

Prof Peter Clarke
peter.clarke@newcastle.ac.uk

Dr Stuart Edwards
stuart.edwards@newcastle.ac.uk

RICS Research team

Dr. Clare Eriksson FRICS
Director of Global Research & Policy
ceriksson@rics.org

Amanprit Johal
RICS Global Research and Policy Project Manager
ajohal@rics.org

Anthony Walters
RICS Global Research and Policy Project Manager
awalters@rics.org

Pratichi Chatterjee
Global Research & Policy Assistant
pchatterjee@rics.org

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Executive Summary

Multipath (MP), the effect of GNSS signal distortion by mixing with indirect (reflected or scattered) signals, is the most important yet currently unmodelled error source in precise GNSS. Errors caused by multipath reduce reliability, precision, and accuracy of measurements in all of applications of GNSS, including high precision surveying and scientific observations. Multipath effects can be and are being reduced by a number of techniques, including signal polarisation filtering, based on the difference of polarisation direction of the straight-line and multipath signals and implemented in GNSS antenna design. However, the efficiency of these techniques is not sufficient for many of the current applications.

We propose a strategy of multipath mitigation by tracking and analysing both the valuable direct, and undesired multipath components of GNSS signals separately, by using a dual-polarisation GNSS antenna. While observations of right-hand polarised (direct) signals lead to the solution of positioning problem, left-hand polarised signals carry information about indirect (reflected or scattered) signals, that can reduce availability, reliability, accuracy, and precision of surveying. We assume that increased intensity of the signal received by the left-hand polarised channel is an indication of right-hand polarised signal corruption and should be counteracted by assigning lower weights to data from specific satellites and time periods in the coordinate estimation algorithm.

We conducted an experiment involving tracking dual-polarisation data at two locations, with relatively mild and severe multipath environments respectively. Data were processed in a traditional way and using the proposed reweighting strategy. The quality of the results after reweighting increased significantly. Thus we conclude

that the use of dual-polarisation GNSS antennas and receivers offers the potential for user equipment to automatically detect and act upon the measurements affected by multipath.

The results of our research should enable GNSS equipment manufacturers to develop enhanced hardware, i.e. dual polarisation antennas, together with enhanced receiver firmware and processing algorithms at minimal extra cost as the receiver hardware would not need to change significantly. We anticipate that the moderate increase in equipment cost, associated with an antenna capable of tracking both signal polarisations and a doubling of the number of receiver channels, will be offset by improvements in positioning accuracy, precision, reliability, and availability, allowing good measurements made where needed, and not just where the conditions have previously allowed.

Potential beneficiaries of the dual-polarisation surveying equipment and algorithms stemming from the present research include all surveyors, who will be able to produce more accurate and reliable measurements in less time, especially in harsh MP conditions such as urban environments where effective measurement is sometimes impossible with current technology. Further applications include precise vehicle guidance e.g. construction machinery and offshore platform movements.

It is worth noting that the availability of additional GNSS (e.g. GLONASS and Galileo), allowing GNSS positioning in conditions of reduced sky visibility, does nothing for the reduction of MP. Indeed, this availability is likely to increase the amount of precise GNSS positioning that is attempted in such high-MP locations, increasing the significance of the research outlined in the present report.

1.0 Introduction

GNSS (Global Navigation Satellite Systems) technology has become ubiquitous in navigation, surveying, and science, and its importance and influence continues to grow. GNSS technology is being continuously improved: new hardware and software aim at improving productivity, robustness, reliability, availability, precision, and accuracy. In order to deal with all these aspects of measurement quality a good understanding of potential errors is essential.

Over the passing of time and with improvements in signal processing and measurement modelling the accent in GNSS development has been shifting: at each particular epoch it is logical to address the uncorrected error source that is the largest in magnitude. During the early 1990s, among the error sources attracting the most attention was the accuracy of satellite orbit determination; in the early 2000s focus has shifted to receiver and satellite antenna calibrations and estimation of tropospheric delays; in the 2010s it is deformation of global reference frames due to different kinds of loading. Currently the most influential error in high precision surveying and scientific applications of GNSS is associated with degradation of the satellite signals due to reflections from objects surrounding the antenna.

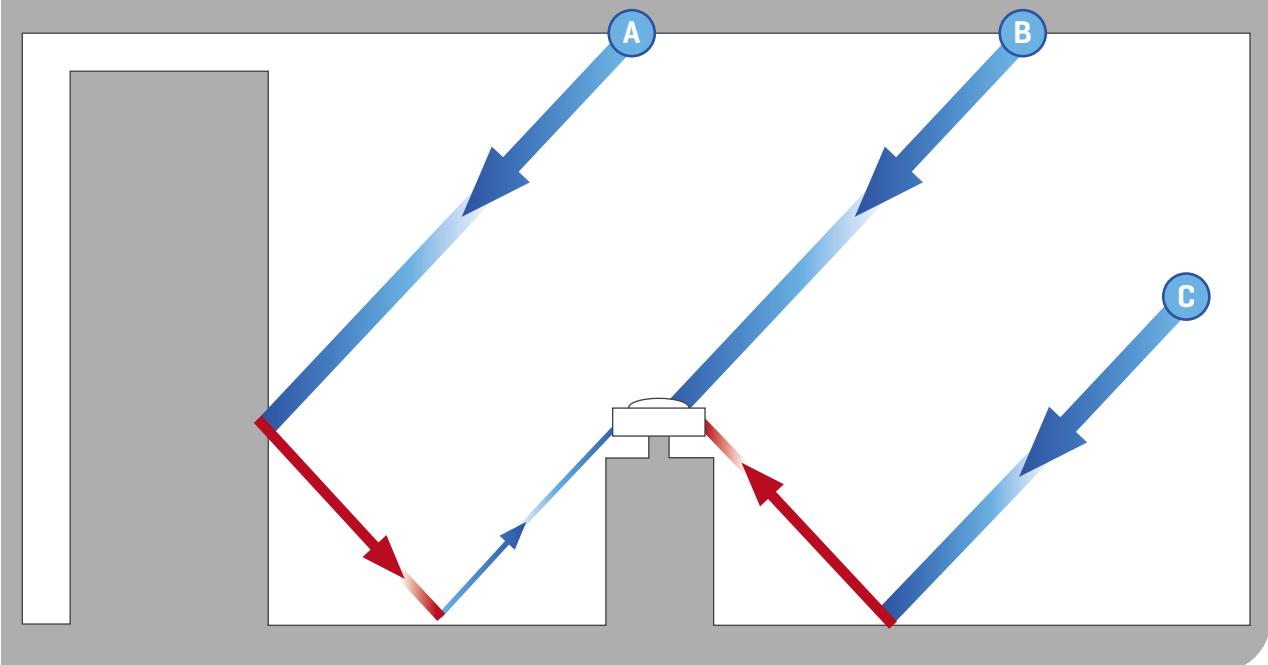
GNSS positioning algorithms rely on determinations of distances from the satellites to the receiver via the measurement of signal time delays. It is important that

these distances are measured accurately and directly along the line of sight; otherwise, the geometric relation does not hold and the coordinate solution is distorted.

Multipath (MP) is the effect of GNSS signal distortion caused by contamination of the desirable direct (straight line) signal by nuisance non-line-of-sight (NLOS) signals, which may be reflected or scattered from the objects surrounding the antenna (Bilich and Larson, 2007). Examples of possible reflectors include ground and water surfaces, buildings, walls, electric power transmission line pillars, oil rigs, etc. Severe MP is frequently observed in cities, especially in “urban canyons” where tall buildings are situated either side of narrow streets. MP leads to systematic and random errors in the reported coordinates of surveyed points due to distortions of the measured ranges, which also impact the ability to correctly resolve integer carrier phase cycle ambiguities (in severe cases preventing a precise position solution of any sort). Every GNSS user suffers from some levels of MP; in many cases MP can significantly delay or even prevent signal acquisition. Although MP can in principle be modelled (Lau and Cross, 2007), only very limited progress has been made in this direction as the models rely on an exact knowledge of reflecting/scattering properties of the objects surrounding the antenna, as well as their geometry, that is almost never possible in practice

Figure 1 Simplified geometry of multipath signals.

Blue colour denotes predominantly RHCP signals, red – predominantly LHCP. Thickness of the lines reflects their relative power.



2.0 Existing counter-multipath measures

Multipath has always been seen as a quality reducing factor and some MP countermeasures have been introduced in GNSS by design. All current GNSS (including GPS, GLONASS, Beidou, and Galileo) emit Right-Hand Circular Polarised (RHCP) radio signals. Circularly polarised signals change polarisation direction when reflected: a RHCP signal after single reflection becomes Left-Hand Circularly Polarised (LHCP). Therefore, the use of GNSS antennas sensitive only to RHCP signals can help in reducing the influence of unwanted reflected NLOS signals. Typically the level of LHCP attenuation ranges from 5dB for low-grade mobile GNSS antennas and up to 20dB for surveying/geodetic antennas, for vertically incident signals. The efficiency of polarisation filtering decreases for lower elevation angles, although this is where it is especially desired because of the increasing likelihood of NLOS signals from low-elevation reflectors. Significant amounts of NLOS signal are still able to pass through the polarisation filter and contaminate the measurements.

Other commonly used MP countermeasures are:

- 1.** Use of ground-wave reducing antennas, e.g. antennas with ground planes, especially choke-ring antennas (Tranquilla et al 1994). This method is based on the fact that most of the NLOS signals are coming to the antenna either from below the horizon or at low elevation angles.
- 2.** Rejection of all measurements below a conservatively chosen elevation cut-off angle.

One common drawback of all the above-mentioned MP countermeasures is their aggressive character: they all reject 'suspicious' rather than proven bad data, thereby decreasing the amount of data available for positioning and quality control. Further approaches to developing MP characterisation and reduction arising from a number of studies by the scientific community include:

- 3.** Sidereal filtering, which relies on repeating GPS satellite tracks and multipath patterns from day to day. Applicable only to GPS and only for static positioning (Ragheb et al 2007).
- 4.** Use of beam-forming antenna arrays to block signals from specific directions (Seco-Granados et al 2005). Applicable only where the direction of the incoming MP signal can be identified.
- 5.** Use of the Signal to Noise ratio (S/N) of RHCP signal allowing detection of MP and choice of optimal data-weighting strategies (Bilich and Larson 2007).
- 6.** Analysis of phase residuals: use of wavelet analysis, adaptive filters, including MP in estimation algorithms (Ge et al 2000, King and Watson 2010).
- 7.** Fuzzy tracking using particle filters (Jwo and Wang 2007; Giremus et al 2007).

All the above scientific approaches to MP reduction are at best developmental strategies, and we are not aware of any successful practical implementations of these methods that passed the initial research stage and are commonly available in off-the-shelf equipment or software. Furthermore, we note that limited proprietary solutions based on the analysis of tracking-loop correlation data and carrier phase residual time series exist (e.g. Leica, Trimble), but these are not perfect either.

We propose a strategy of MP effects reduction by tracking and analysing not only the valuable RHCP signals, but also the nuisance LHCP signals, received by a dual-polarisation GNSS antenna. LHCP channel, being especially sensitive to MP signals, can be used to assess the MP environment and therefore to construct site- and time-specific optimal data-weighting strategies (passive MP defence). In the future LHCP can also be used in conjunction with RHCP to estimate MP corrections that can be subsequently applied to RHCP observations to increase their quality (active MP defence). Use of LHCP signals in GNSS has not received enough attention yet, except in studies limited to MP characterisation (Manandhar et al 2001, Brenneman et al 2007, Groves et al 2010) and the use of MP measures in scientific non-positioning applications such as determination of soil moisture, snow depth, or sea level (e.g. Löfgren et al 2011).



3.0 Assessing the quality of GNSS data

The question of GNSS data quality control has attracted a lot of attention since the very beginning of GNSS usage for precise positioning, and a number of quality indicators have been developed. Among the most widely used are:

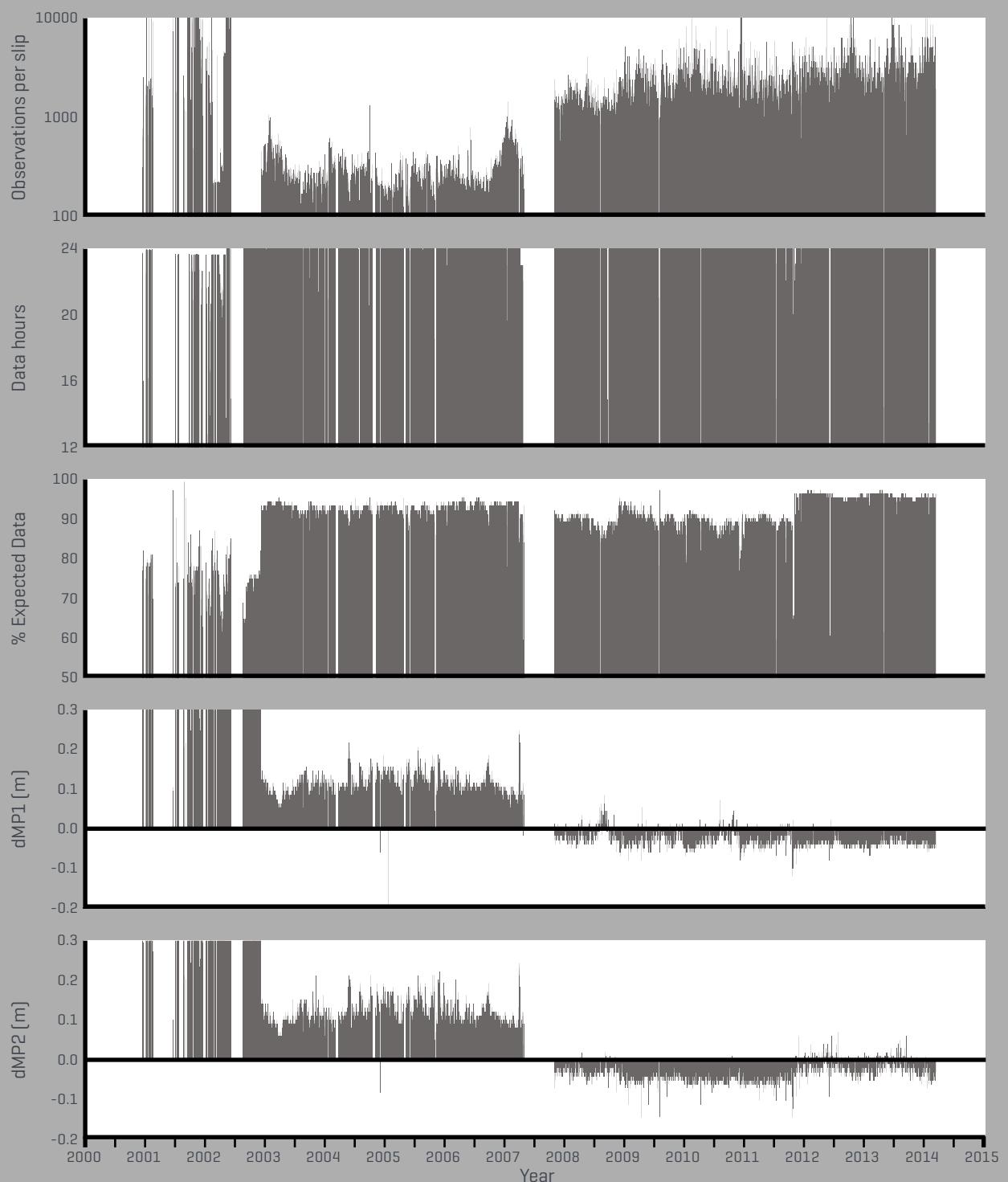
- 1.** The ratio of the numbers of actually recorded phase and code tracking data to the potential numbers. Values of significantly lower than 100% can indicate presence of problems like signal obstructions, antenna/cable/receiver fault, in-band or strong out-of-band interference or jamming, and also severe multipath.
- 2.** Mean time interval between the cycle slips found in the phase data: according to the internal receiver firmware or to the analysis with some post-processing software. Most currently available receivers are able to mark the epochs when the cycle slip is suspected by a loss-of-lock indicator (LLI), and it is also possible to search for cycle slip events by analysing linear combinations of GNSS observables, e.g. the geometry-free combination. Severe MP, rapid changes in the ionosphere's total electron content, and unexpected antenna accelerations can cause real or perceived cycle slips. Instead of the interval its inverse (average number of epochs per cycle slip) can be used.
- 3.** Signal-to-noise ratio (SNR) for each of the used frequencies. SNR is expected to be maximal at higher elevations, and decreasing at lower elevations, where NLOS signals most frequently come from. Anomalously high SNR for the LHCP may indicate strong undesired NLOS signal.
- 4.** RMS of so called "Multipath Observable" (Estey and Meertens 1999), that is a linear combination of the phase and code pseudorange on the same frequency, cancelling the geometric range. This indicator characterises almost exclusively the code pseudorange MP. This indicator is strongly dependent on the make, model, settings, and in some cases firmware version of the receiver, as different receivers may or may not implement different code smoothing algorithms.

Figure 2 shows an example of multi-year time series of the above-mentioned quality indicators for a GNSS site Morpeth, computed using the 'teqc' software (Estey et al 1999).

Quality indicators presented in such form can be valuable in assessing observation quality and its changes in time. However, they do not improve the actual quality of the data and subsequently its value as reference data, or the precision and accuracy of the derived site position solutions.

Figure 2

Quality indicators for a typical GNSS reference site MORP [Morpeth, England].



"Observations per slip", "Data Hours", and "% Expected Data" are desired to be as high as possible, the MP statistics [dMP1 and dMP2] – as low as possible. Noticeable changes at 2003 and 2007.5 are associated with site equipment [antenna and/or receiver] changes.

4.0 Studying GPS data quality indicators

In order to investigate whether quality indicators can be used in improving the quality of geodetic solutions we developed software allowing summarising and representing above-mentioned indicators on sky maps. We collected data using dual-polarisation antennas (AntCom type 3G1215RL)¹ at two sites in Newcastle: one with relatively mild multipath conditions (site codes: RHCP/LHCP, see Figure 3) and one with severe MP (site code: DPNR/DPNL). Data for each polarisation was tracked using a separate GPS receiver. RHCP data from these sites are

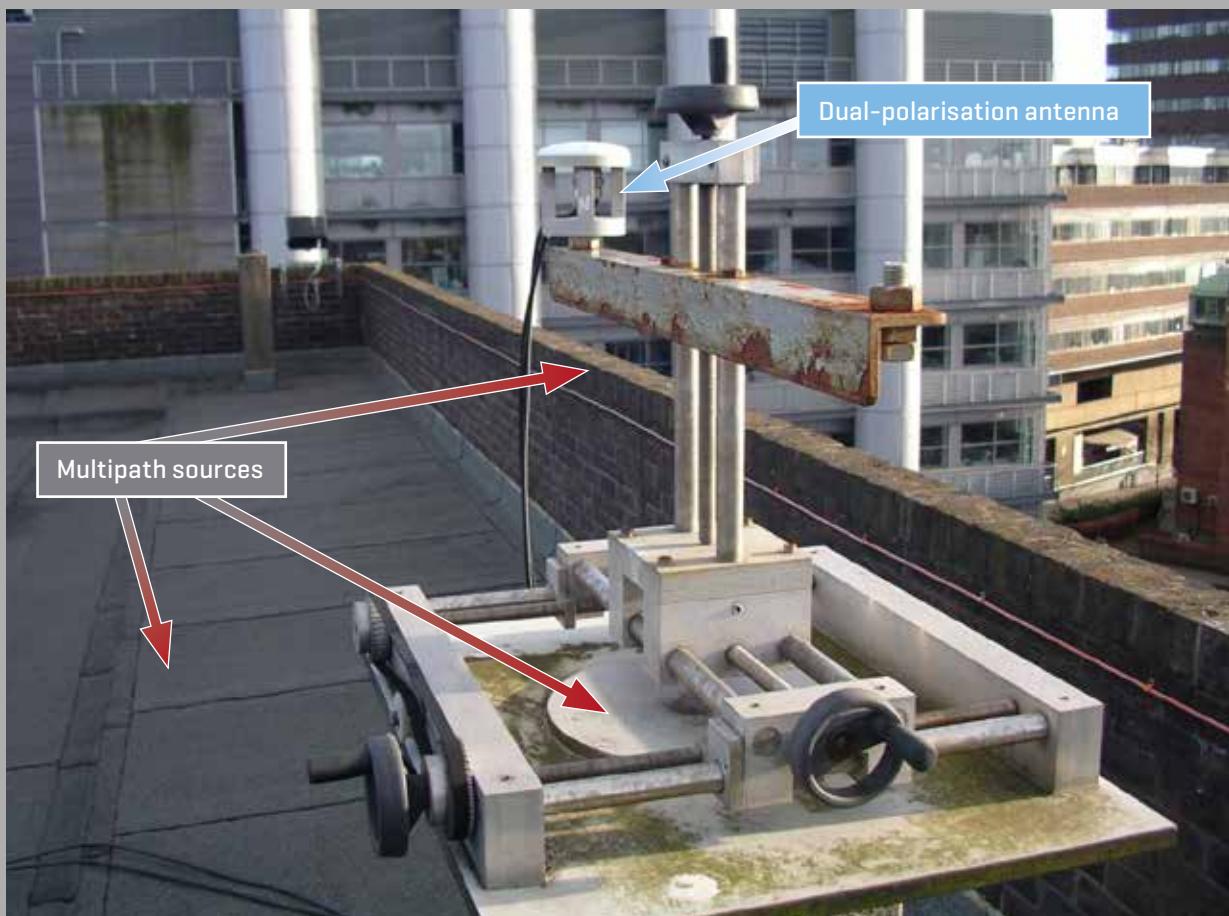
thought to be comparable to data from a typical surveying measurement session; LHCP data are not available to most current GNSS users, but may provide valuable information on the presence of NLOS signals.

The following figures present typical distributions of some of the quality indicators for the static GPS site RHCP in relatively mild MP conditions. Blue colours indicate preferred ranges of the parameters, red colours denote undesired ranges.

Figure 3

RHCP/LHCP: a GPS site with relatively mild multipath conditions.

Multipath is due to NLOS signals reflected/scattered from the roof surface, parapet walls, and the massive metal plate below the antenna.



1. http://www.antcom.com/documents/catalogs/Page/3G1215RL-PP-XS-X_RevA_RHCP-LHCP-V-H-L1L2GPSAntennas.pdf

Figure 4 Sky map of the missing data frequency for a site with relatively mild MP conditions

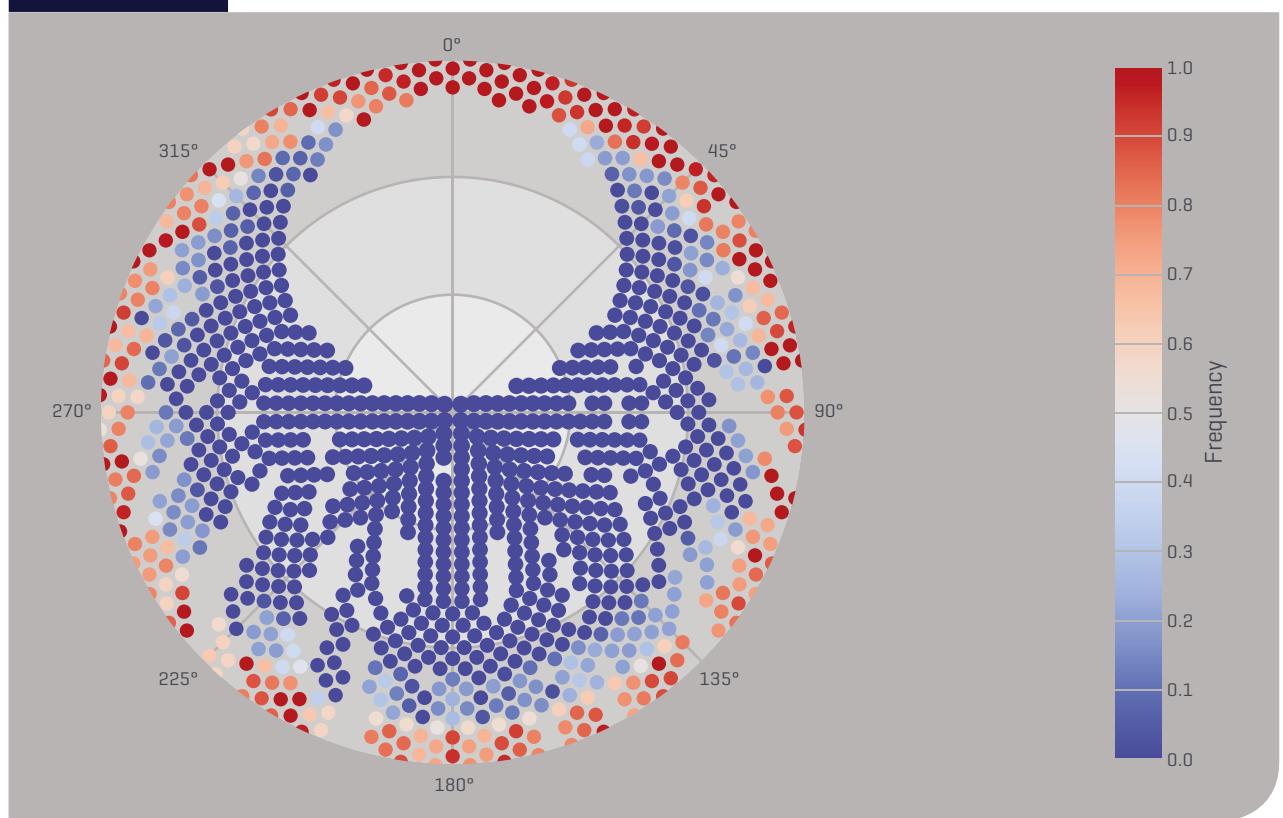


Figure 5 Sky map of S/N ratio for L1 for a site with relatively mild MP conditions

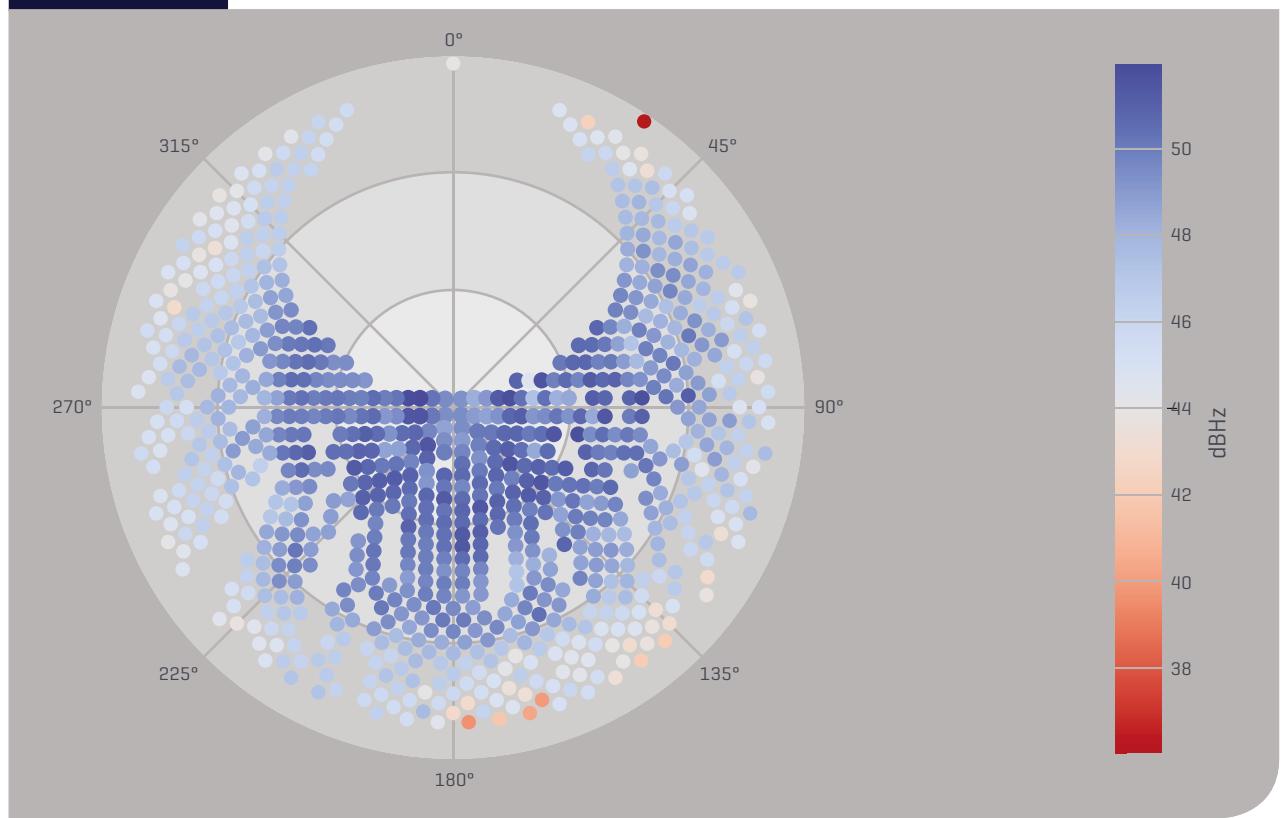


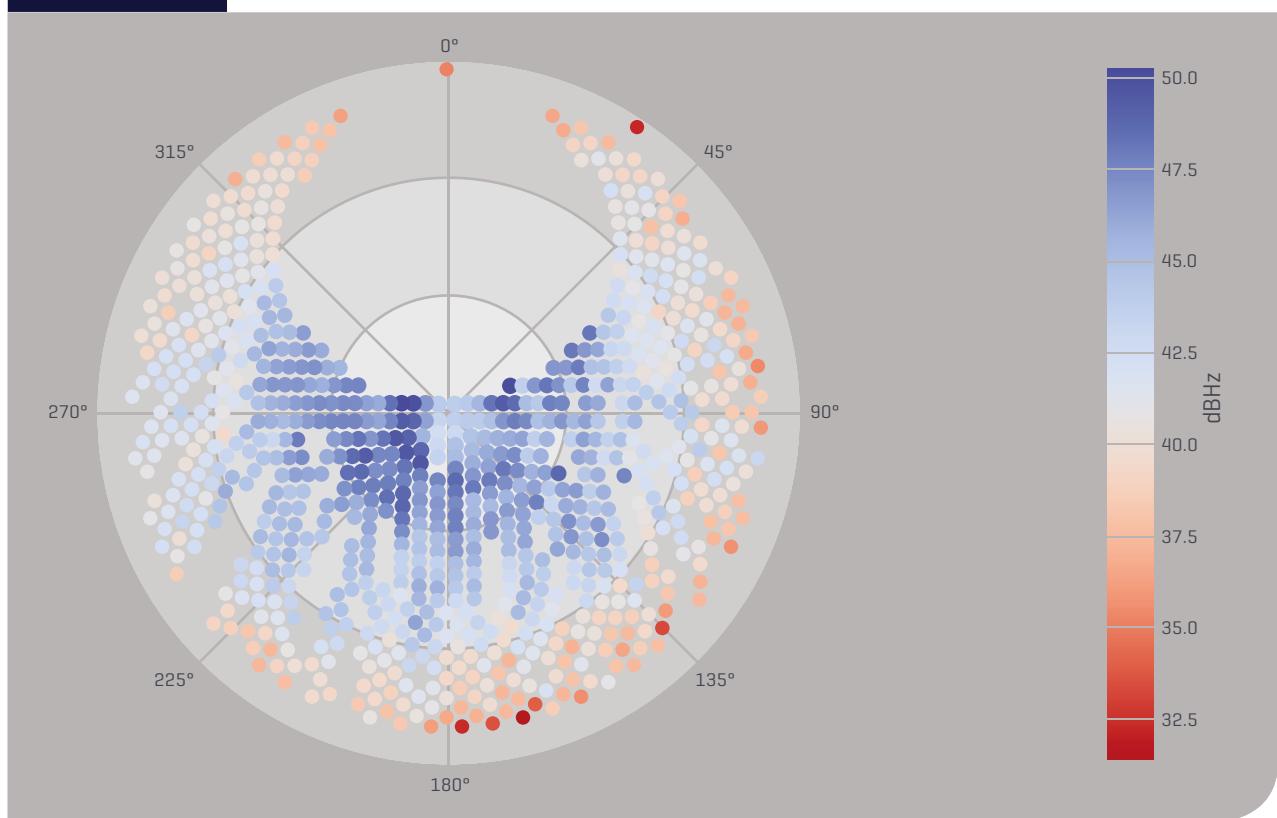
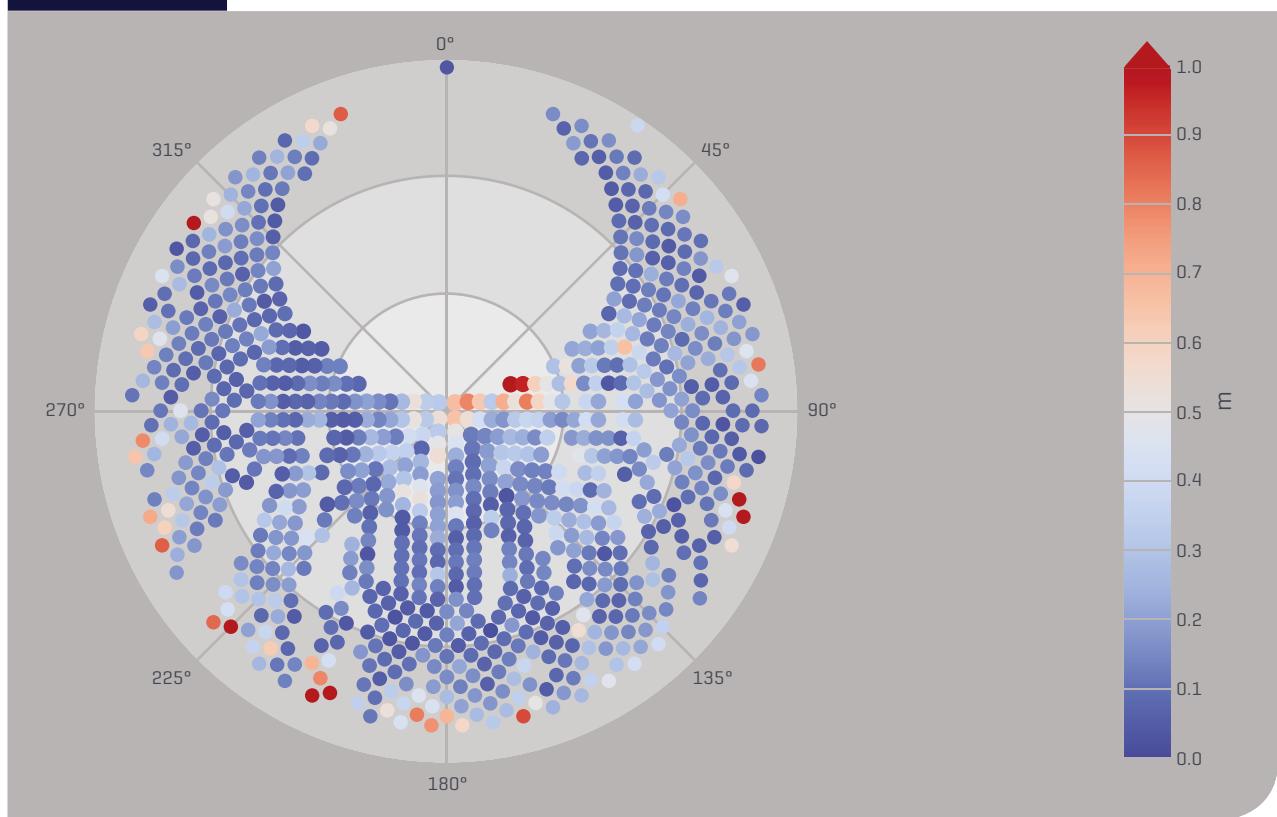
Figure 6**Sky map of S/N ratio for L2 for a site with relatively mild MP conditions****Figure 7****Sky map of teqc MP1 observable for a site with relatively mild MP conditions.**

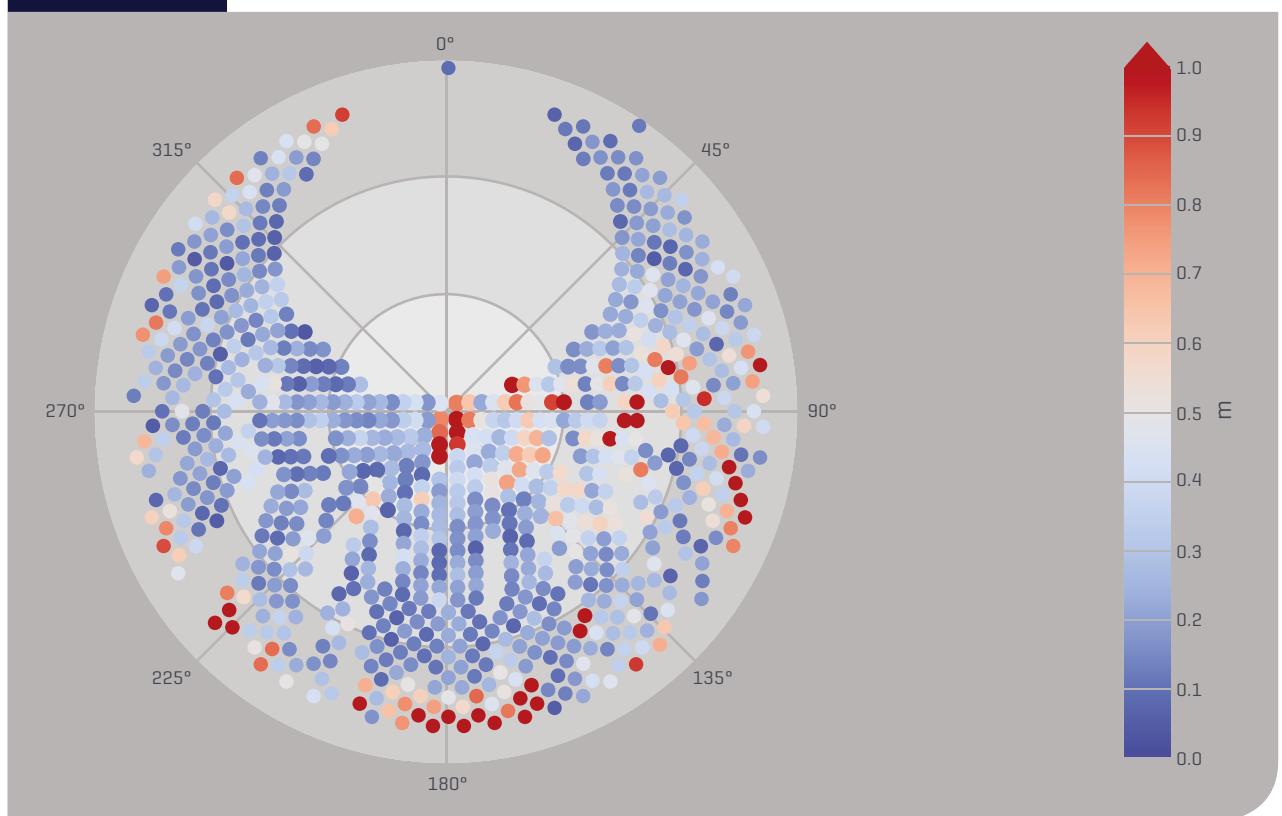
Figure 8**Sky map of teqc MP2 observable for a site with relatively mild MP conditions.**

Figure 4 shows the map of the frequency in which data gaps are present in the observations. The large circularly shaped void in the northern direction is the polar gap, explained by the inclination of GPS orbits being close to Newcastle latitude. It is evident that most of missing data are at relatively low elevations; almost no data are missing above 30°.

It can be seen that the received signal strength with respect to noise (Figure 5 and Figure 6) is best at higher elevations and gradually decreases for lower elevations. This is caused mostly by the shape of the antenna's gain pattern, chosen this way to lower the influence of NLOS signals which come more frequently from lower elevation angles.

Although there is a similar tendency in the MP1 and MP2 (Figure 7 and Figure 8) code pseudorange multipath observable behaviour, smaller scale features are prevalent. We can tentatively identify the zenith patch of increased MP1 and MP2 with the MP created by the reflection from metal plate just below the antenna (see Figure 3). It is much more difficult to match other patches of increased MP with other objects surrounding the antenna, because it is impossible to precisely know their reflection/scattering characteristics. Potential presence of multiple reflections further complicates the picture; double reflection/scattering can result in higher MP than a single one, due to double change of polarisation: from original RHCP to LHCP and back to RHCP, that is being received by the antenna.

Elevation-dependent weighting strategies have been previously proposed (e.g. in King and Watson 2010) as a measure lowering the influence of data from low elevations on the final positioning result. They are based on belief that MP mostly influences the signals from low satellites. Figure 7 and Figure 8 show that this is not always the case.

5.0 Using dual-polarisation observations for detection of high multipath signals

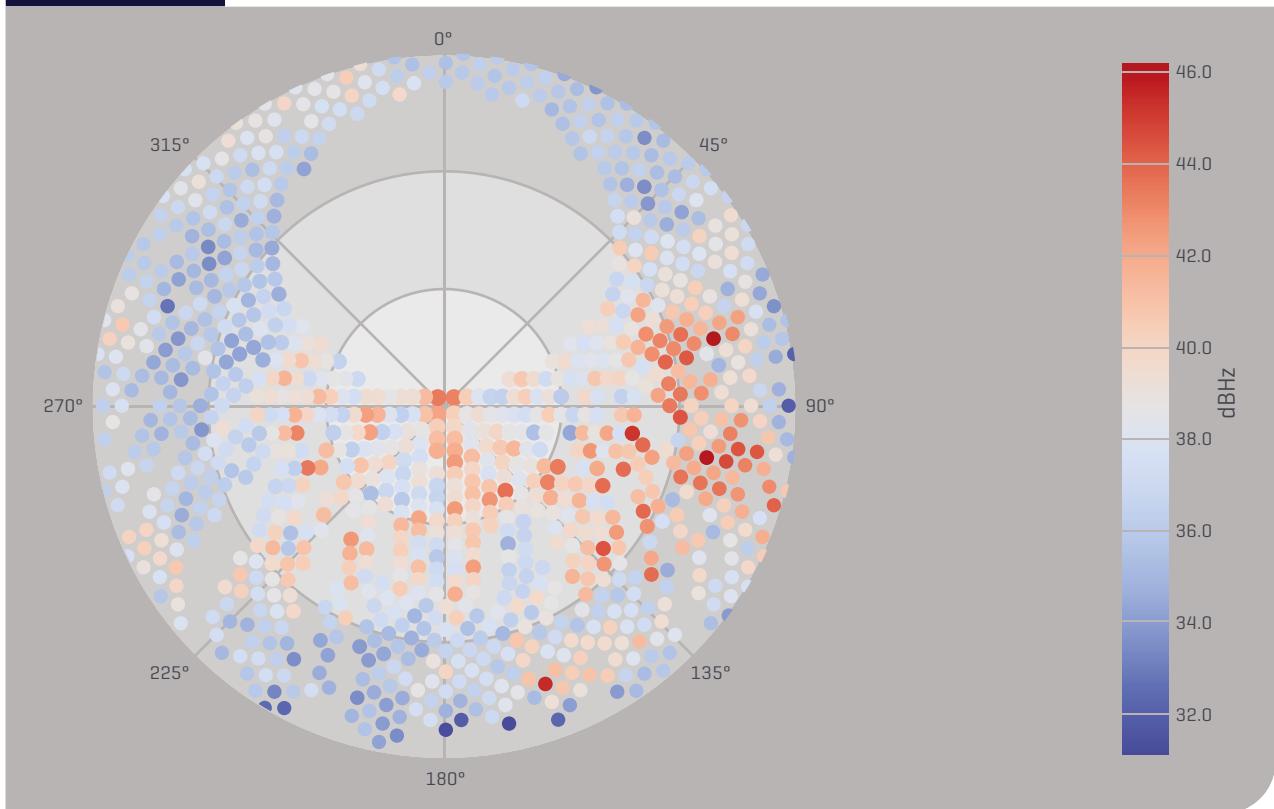
Our supposition is that the intensity of the signal received by the LHCP antenna channel can be used as a proxy for the relative intensity of NLOS signals infiltrating the RHCP channel. This is only an approximation to reality, as it relies on the assumptions that the initial GNSS signal is purely RHCP, that both the RHCP and LHCP antenna channels are only sensitive to the corresponding signals, that only single reflections exist, and that each reflection perfectly inverts the polarisation. The aim of our project was to test these assumptions by implementing a weighting strategy based on the LHCP S/N ratios, and evaluating the improvement in positioning.

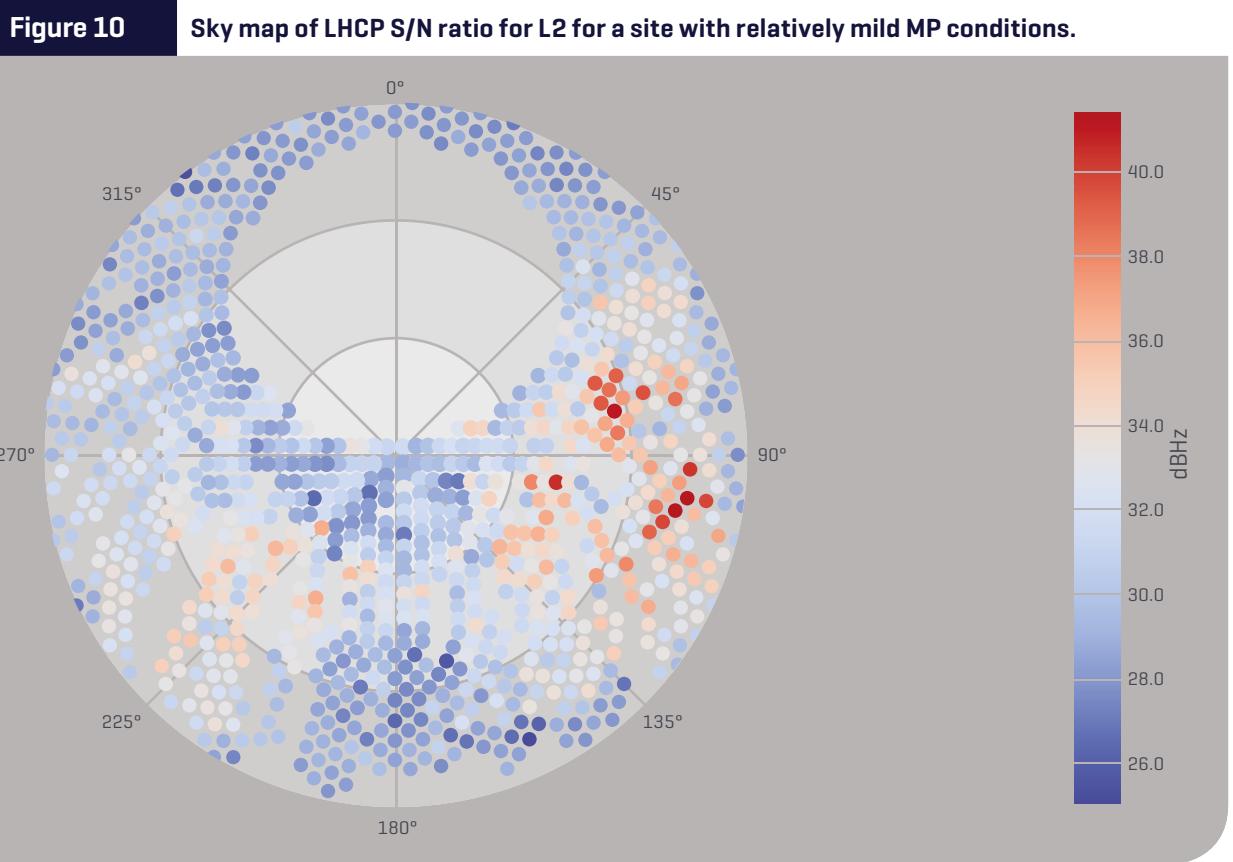
Figure 9 and Figure 10 show the sky maps of LHCP S/N for the same site as in Figure 5 and Figure 6. It can be seen that there is much more information in these images, and the features resemble the features apparent on the sky maps of the MP observables for the RHCP channel (Figure 7 and Figure 8).

It should be noted that the use of LHCP data provides independent means for detecting MP signals, in contrast with other methods based on the use of RHCP data solely (such as forming MP linear combinations or computing phase residuals).

Figure 9

Sky map of LHCP S/N ratio for L1 for a site with relatively mild MP conditions.





6.0 Testing the reweighting algorithm in a kinematic positioning application

In order to test our approach further we established another site in even harsher MP conditions (site codes: DPNR/DPNL, Figure 11). In total about 6 days of data from site DPNR and 5 days from site RHCP were collected at 1 s sampling interval.

RHCP data from each of the two sites were processed in kinematic Precise Point Positioning (PPP) mode using the GIPSY software v. 6.2.1 (Zumberge et al 1997). Each epoch was treated as an independent observation.

Tropospheric delays were not estimated; fixed values derived from ECMWF database (Boehm et al 2009) were used. Precise orbit and satellite clock products from the Jet Propulsion Laboratory (JPL) were used. Parameters of cycle slip detection algorithm were chosen suboptimal to test the algorithms with the most challenging data. Ambiguities were resolved to integer values wherever possible. The resulting time series are presented in Figure 12 through Figure 17 with dark blue lines.

Figure 11

DPNR/DPNL: a GPS site with severe multipath conditions.

Multipath is due to reflections and scattering from the horizontal roof surface, air conditioner units, and corrugated metal constructions.



Figure 12

Original and reweighted kinematic position solutions for RHCP [mild multipath conditions] over a period of one day (DOY 228 of 2013).

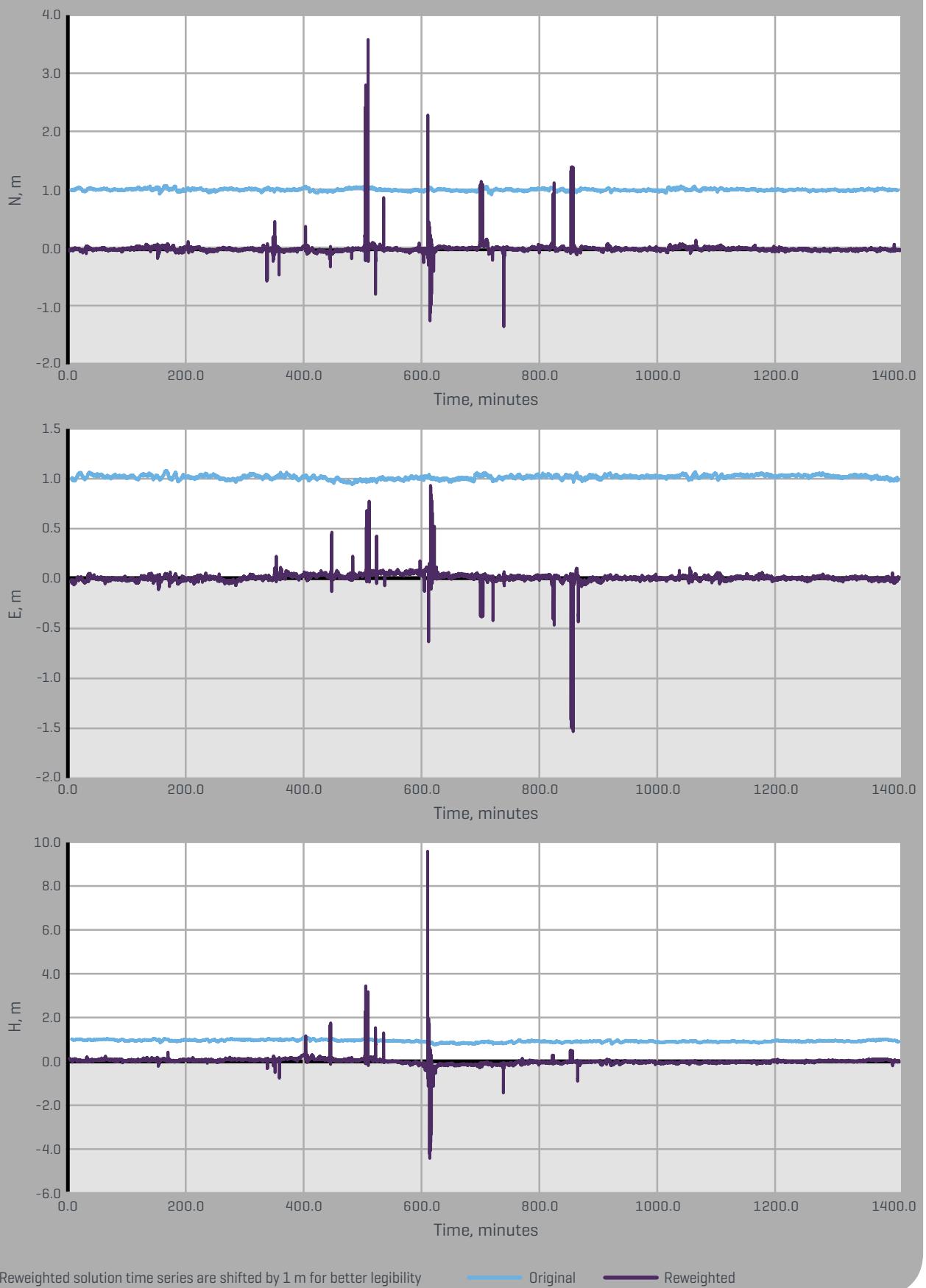
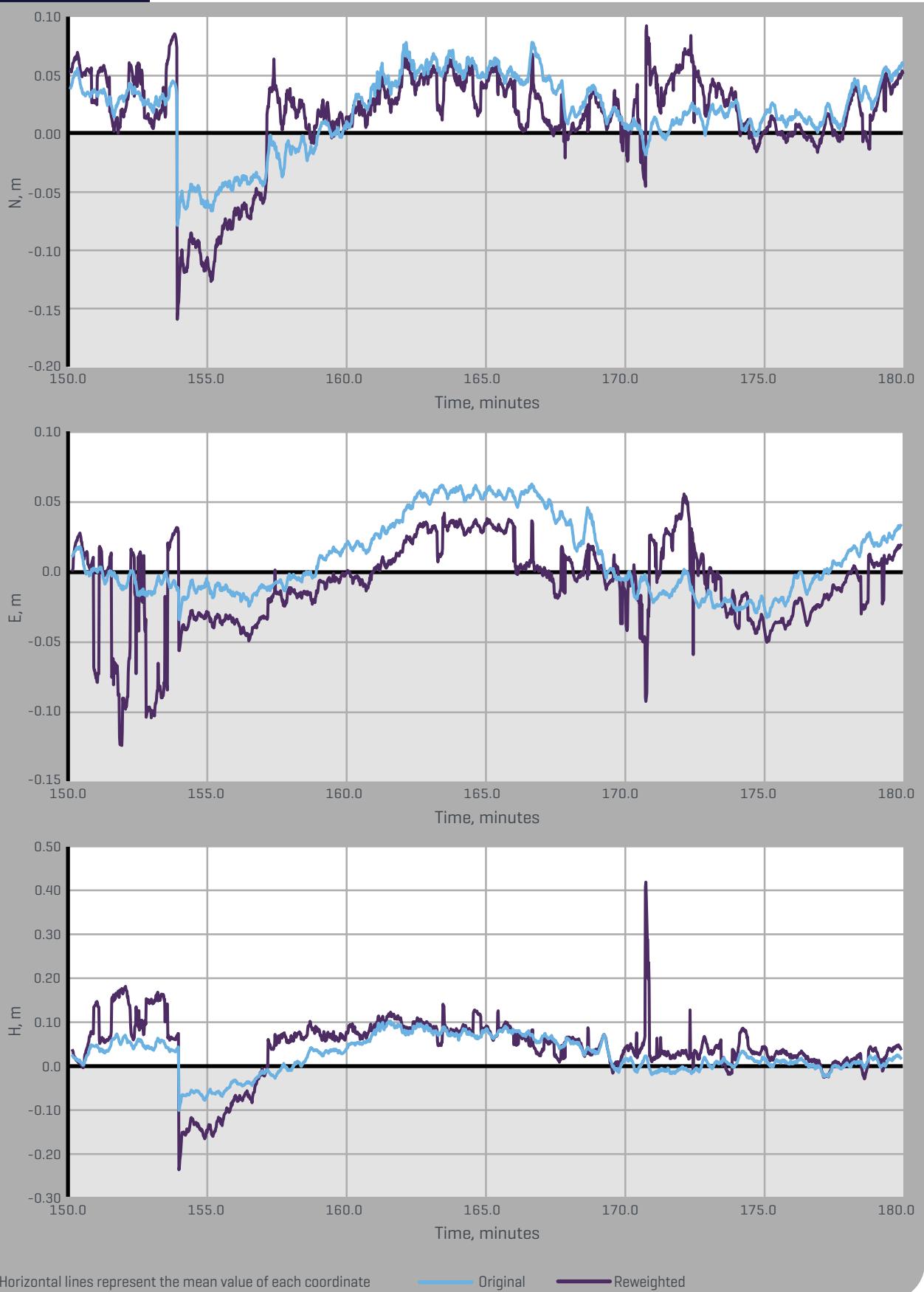


Figure 13

Kinematic position solutions for RHCP [mild multipath conditions] over a period of 30 minutes [selected to be free from gross outliers].



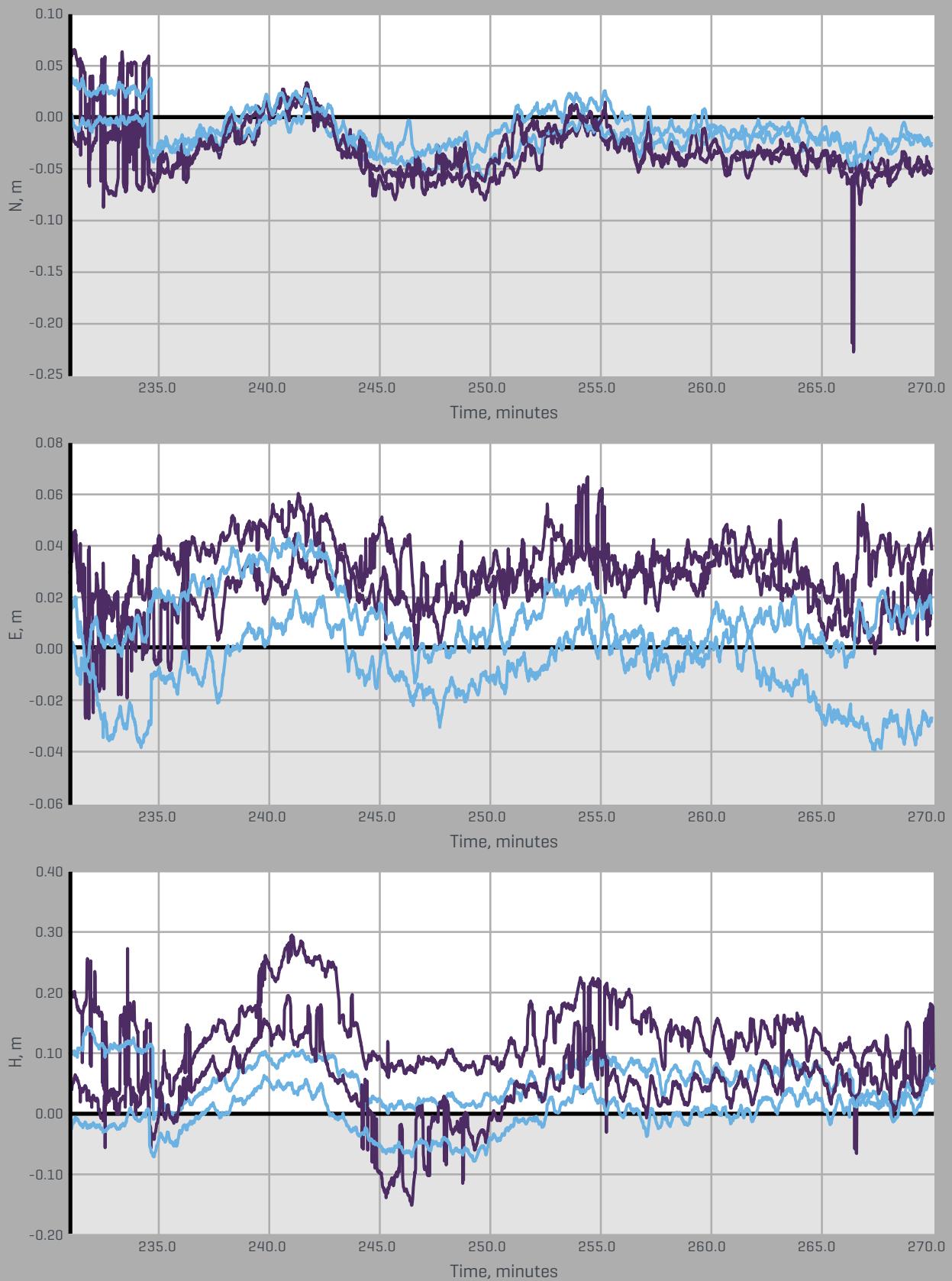
Horizontal lines represent the mean value of each coordinate

Original

Reweighted

Figure 14

Kinematic position solutions for RHCP [mild multipath conditions] over a period of 40 minutes for two adjacent days [DOYs 228, 229 of 2013].



The time series for DOY 229 were shifted by 4 minutes to accommodate the sidereal geometry repeat period. Horizontal lines represent the mean value of each coordinate

— Original — Reweighted

Figure 15

Original and reweighted kinematic position solutions for DPNR (severe multipath conditions) over a period of one day (DOY 095 of 2013).

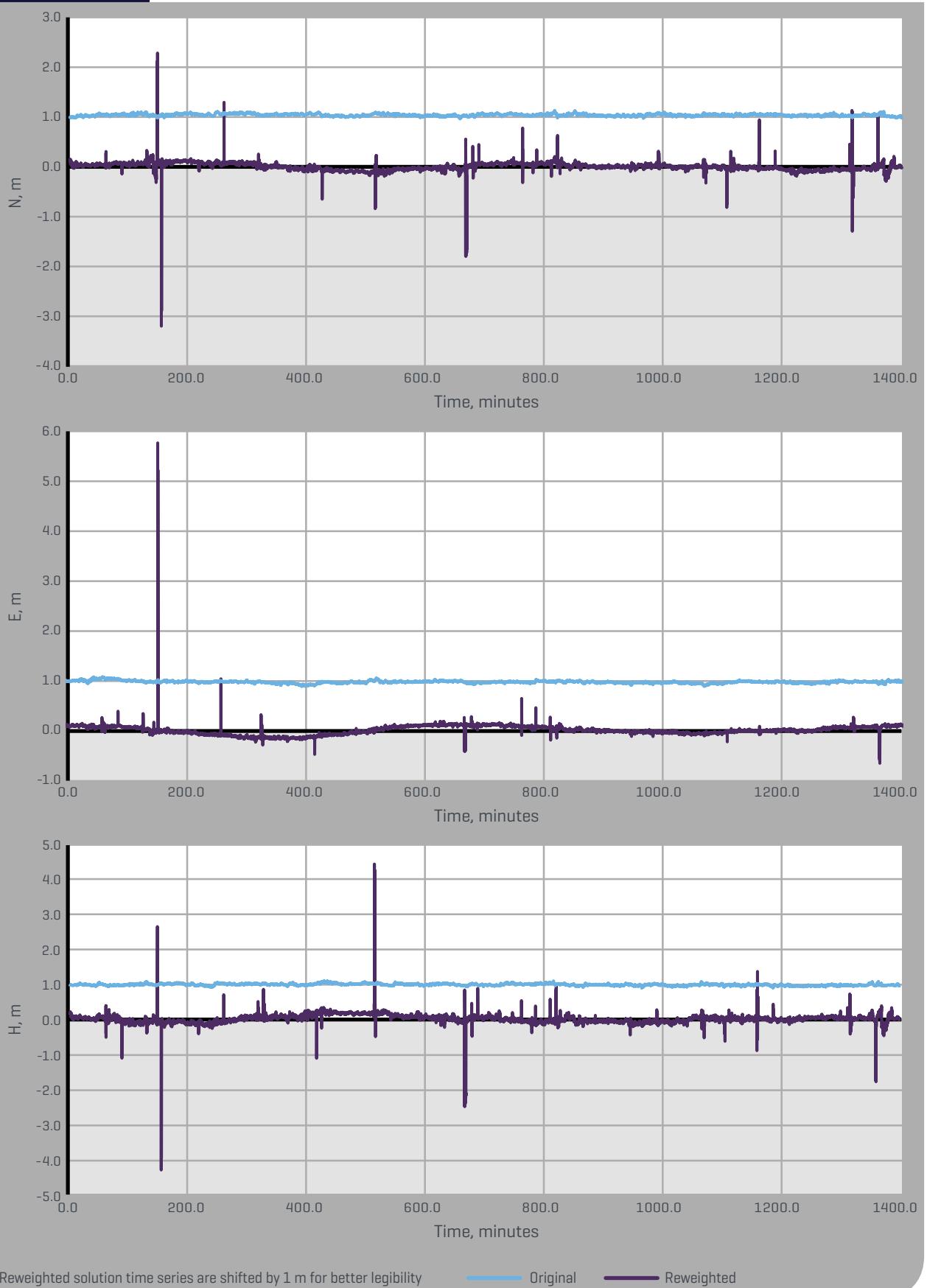
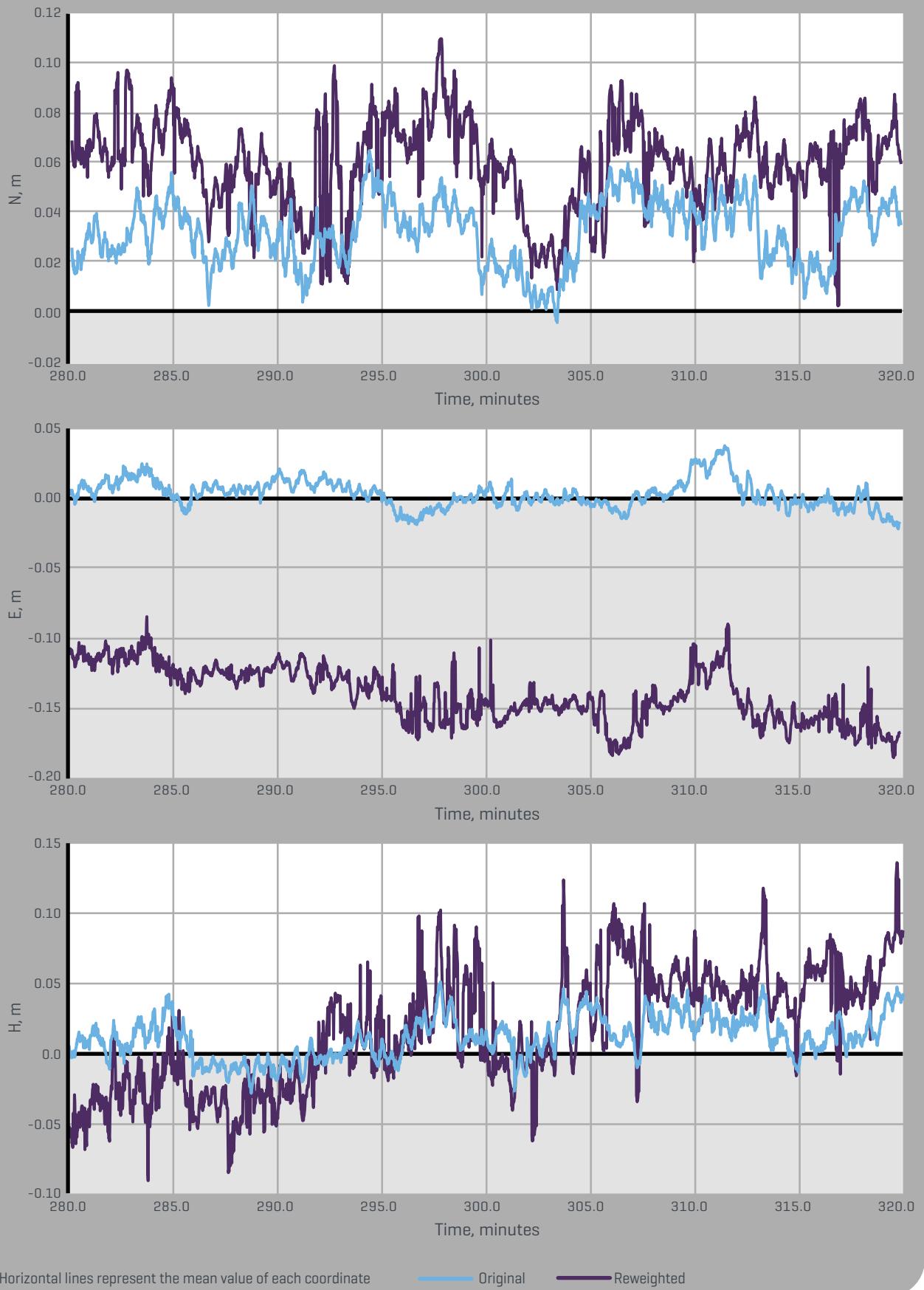


Figure 16

Kinematic position solutions for DPNR (severe multipath conditions) over a period of 40 minutes [selected to be free from gross outliers].



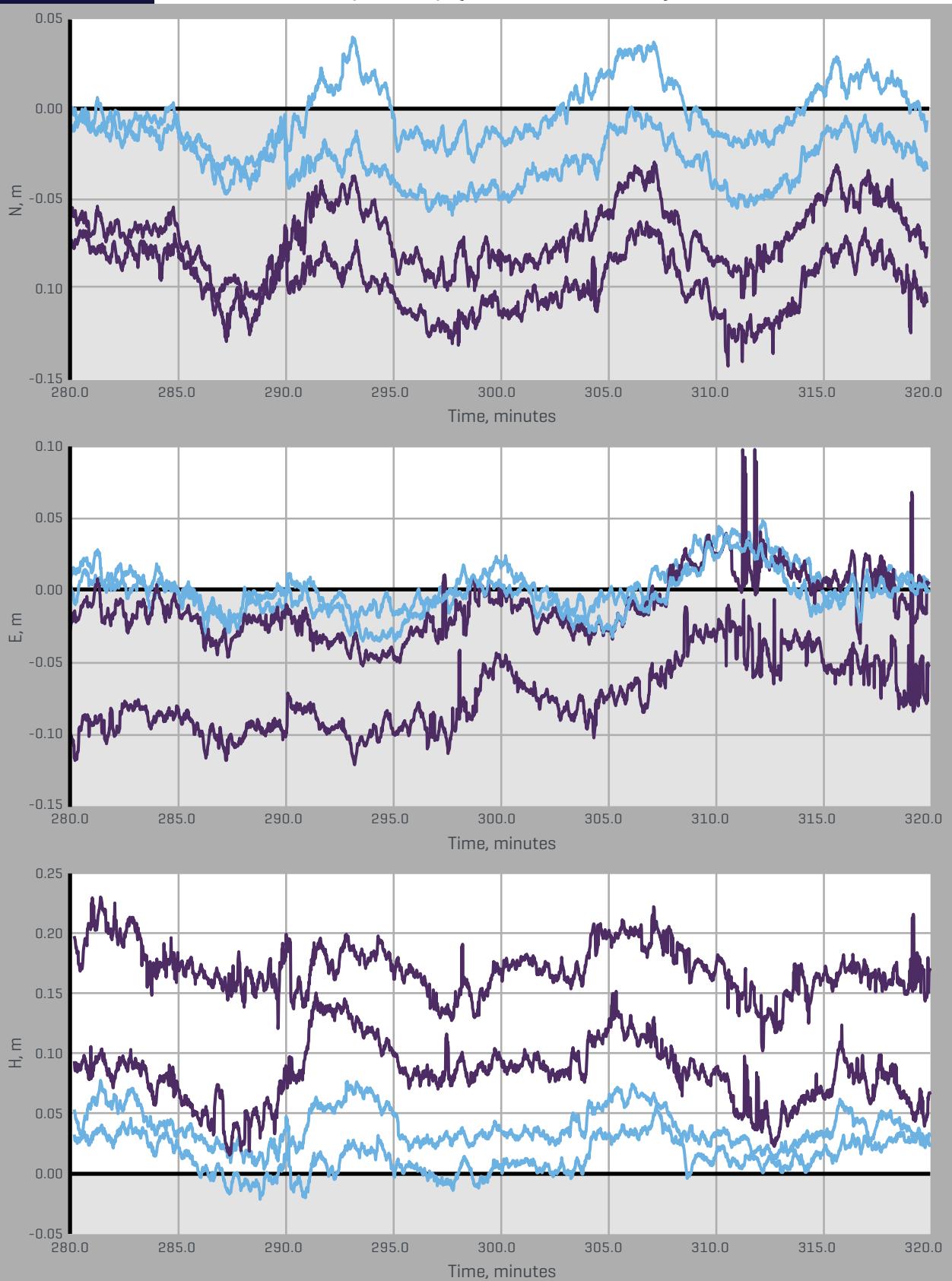
Horizontal lines represent the mean value of each coordinate

Original

Reweighted

Figure 17

Kinematic position solutions for RHCP [mild multipath conditions] over a period of 40 minutes for two adjacent days [DOYs 228, 229 of 2013].



The time series for DOY 229 were shifted by 4 minutes to accommodate the sidereal geometry repeat period. Horizontal lines represent the mean value of each coordinate

— Original — Reweighted

The time series for both sites can be characterised as very noisy, with a high number of outliers.

In our processing we used PPP and not relative positioning, although the latter is more common in current surveying practice. We note however that PPP is gaining in popularity in both the scientific and industrial communities. Unlike relative positioning, PPP is a single site strategy, which does not cancel any of the geographically correlated errors, including tropospheric delay. However, the processing strategy means that outliers cannot be attributed to the influences of unmodelled geographically correlated errors. Furthermore, comparisons of the time series from consecutive days reveal a striking similarity (Figure 14, Figure 17), indicating that multipath is the prevailing error source (Ragheb et al 2007).

In order to partially mitigate the influence of MP we used data collected from LHCP channels of dual-polarisation antennas on both sites (Figure 9, Figure 10) as a proxy for the relative magnitude of NLOS signal received by RHCP channel, and thus corrupting the measurement. The sky map of relative uncertainty was constructed, in which higher uncertainties were associated with areas of low S/N ratios for either of the two GPS frequencies. Commonly used elevation-dependent term was also incorporated into this map. Versions of this map for both geometric linear combinations of phase and code observables, differing in scale factor, were created (Figure 18, Figure 19).

Figure 18

Relative geometric LC uncertainty for RHCP [mild multipath conditions] sky map

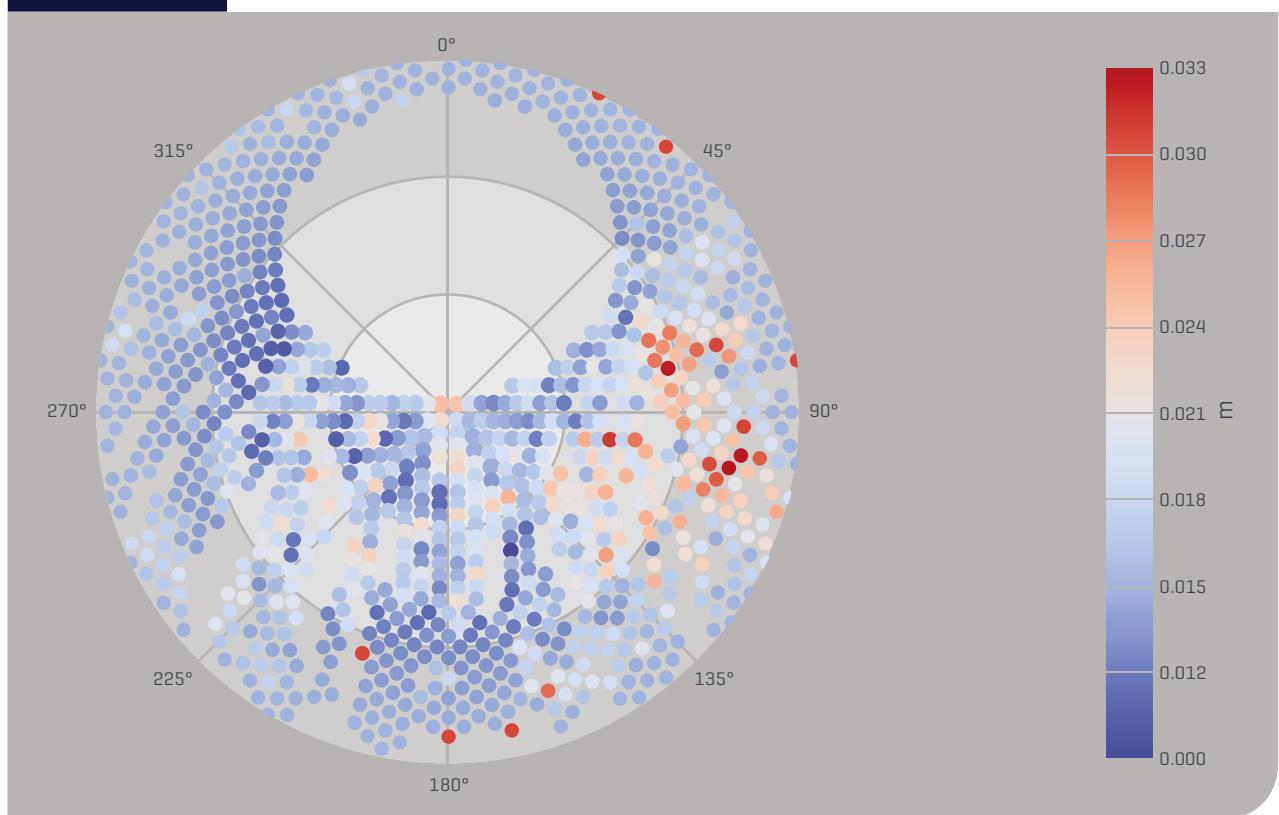
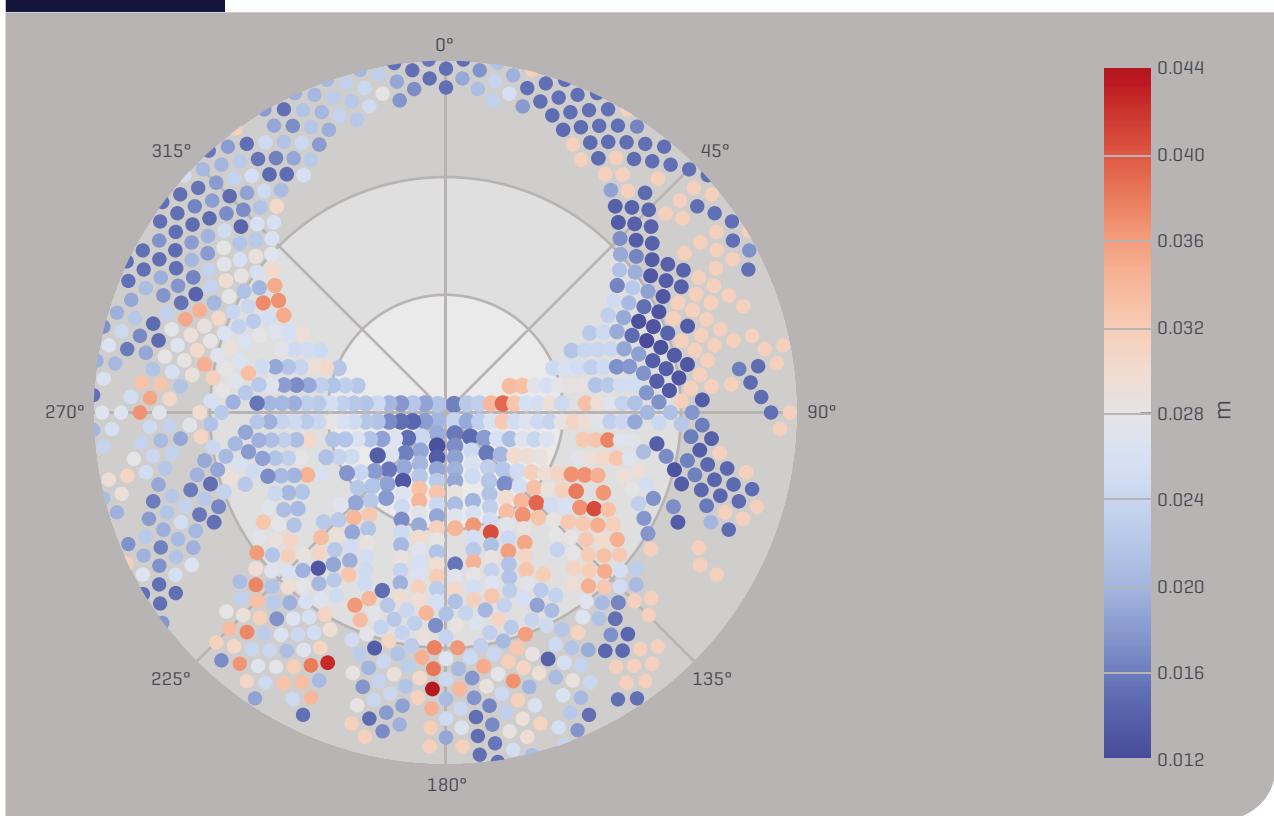


Figure 19**Relative geometric LC uncertainty for DPNR [severe multipath conditions] sky map**

PPP computations were repeated with the same strategy with the exception of assigning varying weights according to the uncertainty maps of the raw data. Positioning results are presented in Figures 12-17 as light blue lines.

It can immediately be seen that reweighted results are almost free from outliers and their noise level is generally lower. We surmise that a large number of outliers in the original unweighted case are a consequence of incorrect ambiguity resolution, conditioned by unreasonably optimistic uncertainties associated with MP-tainted phase data and suboptimal cycle slip detection parameters. The use of a reweighting strategy allows us to introduce much more realistic uncertainties for suspicious data, while not downweighting clean data.

We used a robust version of RMS (RRMS), computed as an RMS of all the values within 6 standard deviations of the median value of each coordinate, to characterise the quality of time series, as well as the conventional RMS. These characteristics for each of the sites and each of the days in table form are presented in the Appendix. The bar charts of these quantities are presented in Figure 20. It can be seen that the coordinate RMSs for DPNR (severe MP site) are higher than the RMSs for RHCP (mild MP) by a factor of 2 - 3. RRMSs are significantly lower than RMSs for unweighted solutions, in which a large number of outliers is present.

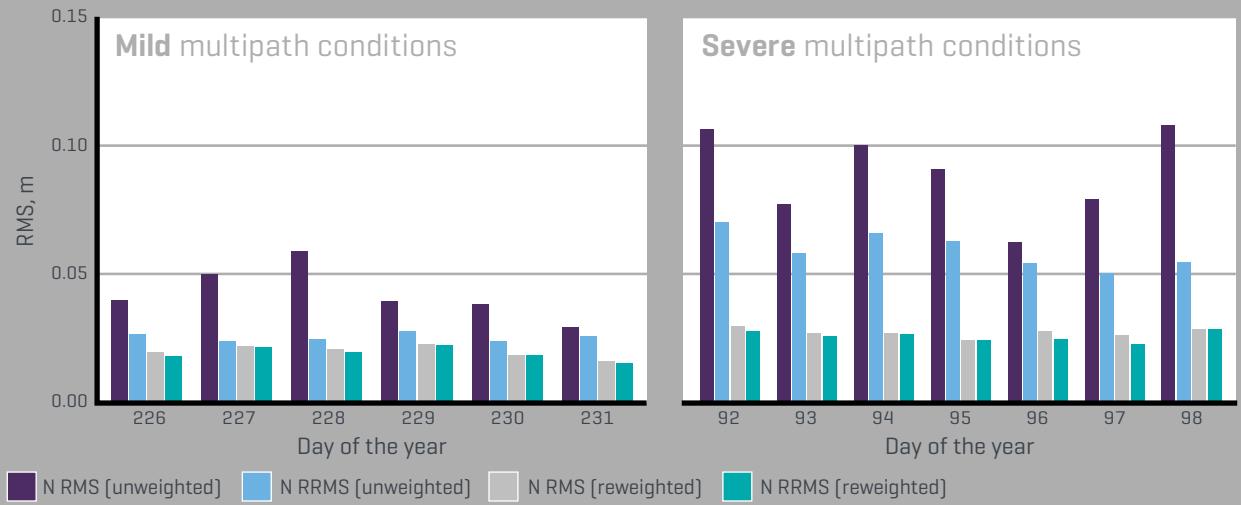
Both the RMS and RRMS for reweighted solutions are significantly lower than for the unweighted solutions. The improvement is more pronounced for the severe MP site. RMS and RRMS values for the reweighted solutions are at the same level, as the reweighted time series contain very few outliers.

Although the reweighting strategy clearly improves solution quality, we cannot say that we have succeeded in removing the multipath error completely. Reweighted solutions still display clear similarities in the time series between adjacent days, which is a clear indication of multipath. It may be possible that increased resolution of S/N and uncertainty sky maps can lead to improved performance. Furthermore, it can be noted that the RMS of the reweighted vertical time series for RHCP (mild MP) is higher than the same for DPNR (severe MP). Although this seems counterintuitive, it can be explained by the presence of large powerful reflector right below the RHCP antenna, whose influence is strongest in the vertical and could not be fully mitigated with reweighting.

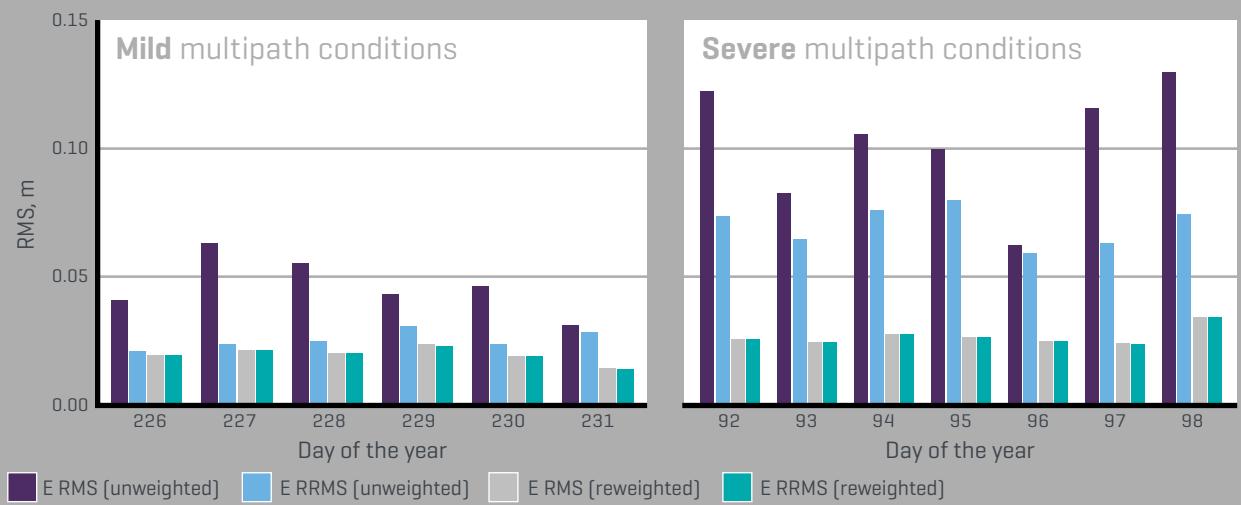
Figure 20

Time series quality indicators for original (unweighted) and reweighted coordinate solutions for sites with mild (left) and severe (right) multipath conditions

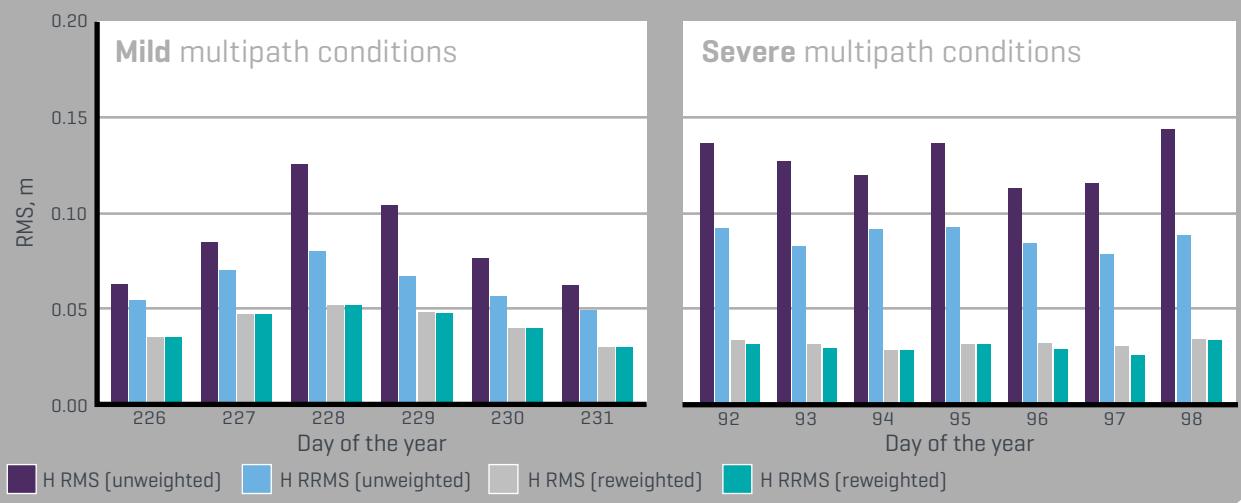
North residuals RMS



East residuals RMS



Vertical residuals RMS



7.0 Conclusions

We conducted an experiment involving collection of dual polarisation code pseudorange and carrier phase data in mild and severe MP environments, and processed these data using traditional methodology (utilising only RHCP data), and a RHCP data reweighting strategy based on the SNR of the LHCP signal. Reweighting leads to a significant improvement in positioning precision and reliability. While the results of traditional computations are distorted by frequent outliers and high noise, reweighting removes the outliers almost completely and reduces position RMS by a factor of 2–3, depending on site conditions.

The use of dual-polarisation GNSS antennas and receivers can therefore allow user equipment to automatically detect and act upon the measurements affected by MP, the main source of errors in high-precision surveying and scientific applications. We anticipate that moderate increase in equipment cost associated with an antenna capable of tracking both signal polarisations and doubling the receiver channel number will be more than compensated through improvements in positioning accuracy, precision, reliability, and availability, allowing good measurements made where needed, and not only where the site conditions allow.

It is worth noting that the availability of additional GNSS (GLONASS and Galileo), allowing GNSS positioning in more obstructed environments, does nothing for the reduction of MP. Indeed, this development is likely to increase the amount of precise GNSS positioning that is attempted in such high-MP locations, increasing the significance of the research outlined in the present report.

The results of our research should enable GNSS equipment manufacturers to produce enhanced hardware, i.e. dual polarisation antennas, together with enhanced receiver firmware and processing algorithms at minimal extra cost, as receiver hardware would not need to change significantly.

Potential beneficiaries of the dual-polarisation surveying equipment and algorithms, stemming from the present research, are all surveyors, who will be able to produce more accurate and reliable measurements in less time, especially in harsh MP conditions such as urban environments where effective measurement is sometimes impossible with current technology. Further applications include precise vehicle guidance e.g. construction machinery.



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e contactrics@rics.org

t +44 [0]24 7686 8555

f +44 [0]20 7334 3811

United Kingdom

Parliament Square

London SW1P 3AD

United Kingdom

t +44 [0]24 7686 8555

f +44 [0]20 7334 3811

contactrics@rics.org

Europe

[excluding United Kingdom and Ireland]

Rue Ducale 67

1000 Brussels

Belgium

t +32 2 733 10 19

f +32 2 742 97 48

ricseurope@rics.org

Asia

3707 Hopewell Centre

183 Queen's Road East

Wanchai

Hong Kong

t +852 2537 7117

f +852 2537 2756

ricsasia@rics.org

Americas

One Grand Central Place

60 East 42nd Street

Suite 2810

New York 10165 – 2811

USA

t +1 212 847 7400

f +1 212 847 7401

ricsamericas@rics.org

South America

Rua Maranhão,

584 – cj 104

São Paulo – SP

Brasil

t +55 11 2925 0068

ricsbrasil@rics.org

Africa

PO Box 3400

Witkoppen 2068

South Africa

t +27 11 467 2857

f +27 86 514 0655

ricsafrica@rics.org

Ireland

38 Merrion Square

Dublin 2

Ireland

t +353 1 644 5500

f +353 1 661 1797

ricsireland@rics.org

Oceania

Suite 1, Level 9

1 Castlereagh Street

Sydney, NSW 2000

Australia

t +61 2 9216 2333

f +61 2 9232 5591

info@rics.org

Middle East

Office G14, Block 3

Knowledge Village

Dubai

United Arab Emirates

t +971 4 375 3074

f +971 4 427 2498

ricsmenea@rics.org

India

48 & 49 Centrum Plaza

Sector Road

Sector 53,

Gurgaon – 122002

India

t +91 124 459 5400

f +91 124 459 5402

ricsindia@rics.org