Surveying Rover Applications

Improvement of Positioning Performance Using Standardized Network RTK Messages

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ABSTRACT

A working group within RTCM SC104 for the standardization of network RTK messages has consolidated various message proposals put before the committee over the past 3 years and interoperability testing is currently underway. Therefore, an industry-wide network message standard is forthcoming.

Euler and Zebhauser (2003) and Euler et al. (2003) investigated the feasibility and benefits of standardized network corrections for rover applications. The Master-Auxiliary concept, described in Euler et al. (2001), as the network RTK message format. The analysis, focused primarily in the measurement domain, demonstrates that double difference phase errors can be significantly reduced using standardized network corrections.

This paper extends the analysis of standardized network RTK messages for rover applications to the position domain. The results of baseline processing demonstrate effective, reliable and homogeneous ambiguity resolution performance for long baselines (>50km) and short observation periods (>45 sec). Overall horizontal and vertical positional accuracy is also improved when network corrections are employed.

INTRODUCTION

Network RTK has received considerable attention in the survey industry over the past five years. In principle, the technique uses the observations of multiple reference stations to improve the reliability, accuracy and efficiency of RTK positioning. The need for a data standard to represent the network information was recognized, for example, in Euler et al. (2001).

Subcommittee SC104 of RTCM established a working group to define a set of network RTK messages for interoperability by utilizing RTCM v2.3 (RTCM 2001) or the new up-coming standard v3.0. The working group considered several message proposals including Townsend et al. (2000), Euler et al. (2001), Zebhauser et al. (2002) and RTCM66 (2002). Euler et al. (2002) provides a comparison of these proposals, highlighting the advantages and disadvantages of each.

Although RTCM SC104 is yet to publish a network RTK message standard, the working group has consolidated the various message proposals and interoperability testing is currently underway. Therefore, an industry-wide data transmission standard is forthcoming.

Recently, Euler and Zebhauser (2003) and Euler et al. (2003) have shown the feasibility and benefits of standardized network RTK messages for rover applications. In the absence of an accepted network RTK data standard the Master-Auxiliary concept, as described in Euler et al. (2002), was used to describe the network information. The Master-Auxiliary concept closely resembles the format adopted by the RTCM network RTK working group. The primary focus of the analysis undertaken in this work was in the observation domain.

This paper extends the analysis of standardized network RTK messages for rover applications to the position domain. The Master-Auxiliary concept is used to describe network information. The results of baseline processing demonstrate effective, reliable and homogeneous ambiguity resolution performance for long baselines (>50km) and short observation periods (>45 sec). Overall horizontal and vertical positional accuracy is also improved when network corrections are employed.

MASTER-AUXILIARY CONCEPT

The Master-Auxiliary concept uses so-called dispersive and non-dispersive phase correction differences to compress network RTK information without the need for standardized correction models (Euler et al., 2001 and Zebhauser et al., 2002).

The description of correction differences begins with the following definition of the single difference L1 phase equation $\Delta\Phi_{km,1}^{j}$ between stations k and m and satellite j

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$$\Delta\Phi^{j}_{km,1}(t) = \Delta s^{j}_{km} + \Delta d\,r^{j}_{km}(t) + c\cdot\Delta dt_{km,1} + \Delta T^{j}_{km}(t) - \frac{\Delta I^{j}_{km}(t)}{f_1^2} + \frac{c}{f_1}\cdot\Delta N^{j}_{km,1} + \Delta e_1 \tag{1}$$

where

Δs^{j}_{km}	geometric range term including antenna phase centre variations which have been applied by the network processing software.
$\Delta d\,r^{j}_{km}$	broadcast orbit error.
Δdt_{km}	receiver clock error.
ΔT^{j}_{km}	tropospheric refraction error.
ΔI^{j}_{km}	frequency dependent ionospheric delay.
ΔN^{j}_{km}	frequency dependent integer ambiguity.
Δe	frequency dependent random measurement error.
t	epoch.
c	speed of light.
f_1	frequency of L1.

An analogous equation for the L2 single difference phase equation can be written by replacing the index of the frequency dependent terms with 2.

Correction differences are formed by subtracting the ambiguity-leveled phase corrections, RTCM v2.3 type 20 corrections for example, of a designated master reference station from the equivalent corrections of the remaining, or auxiliary, reference stations in the network such that

$$d\Delta\Phi^{j}_{km,1} = \Delta s^{j}_{km}(t) - \Delta\Phi^{j}_{km,1}(t) + c\cdot\Delta dt_{km,1} + \frac{c}{f_1}\cdot\Delta N^{j}_{km,1} \tag{2}$$

The generation of the integer ambiguity level, a key feature of Master-Auxiliary concept, is detailed in Euler et al. (2001).

To further reduce the amount of data transmitted to the rover, equation (2) can be separated into a dispersive component, consisting mainly of ionospheric refraction, and a non-dispersive component consisting primarily of tropospheric refraction and orbit errors. The dispersive and non-dispersive correction differences are given by

$$d\Delta\Phi^{j,\ disp}_{km,1} = \frac{f_2^2}{f_2^2 - f_1^2}\,d\Delta\Phi^{j}_{km,1} - \frac{f_2^2}{f_2^2 - f_1^2}\,d\Delta\Phi^{j}_{km,2} \tag{3}$$

$$d\Delta\Phi^{j,\ non-disp}_{km,1} = \frac{f_1^2}{f_1^2 - f_2^2}\,d\Delta\Phi^{j}_{km,1} - \frac{f_2^2}{f_1^2 - f_2^2}\,d\Delta\Phi^{j}_{km,2} \tag{4}$$

This alternate representation of the correction differences has some specific benefits. Unlike the correction differences described in (2), the dispersive and non-dispersive components vary at different rates. In general, non-dispersive errors change slowly over time, while dispersive errors vary more rapidly, especially in times of high ionospheric activity. Therefore, optimizing the transmission rates of the dispersive and non-dispersive components can maximize data-link throughput.

In addition to the correction differences, the raw carrier phase information for the master reference station, described via RTCM v3.0 standard messages or type 18 or 20 messages as defined in v2.3 (RTCM 2001), must also be streamed to the rover. Using the phase data of the master station and the correction differences, the rover can reassemble and apply the raw phase information of the auxiliary stations in conventional baseline processing schemes. Alternatively, optimal correction differences can be interpolated for any position in the network and used to correct rover data. Interpolation of the correction differences, which is described in the next section, is possible because they share a common integer ambiguity level.

INTERPOLATION OF CORRECTION DIFFERENCES ON THE ROVER

Optimal correction differences can be interpolated for the position of the rover, due to the common integer ambiguity level described in the previous section, and used to improve the double difference phase residuals of the master-rover baseline. Euler and Zebhauser (2003) used the following distance weighted interpolation technique.

Suppose that the rover receives network RTK information, as described for the Master-Auxiliary concept, from n reference stations in a network. The first station represents the master and stations 2 to n denote the auxiliaries. Correction differences for the rover's position can be interpolated using

$$CD_{rover} = \frac{\sum_{i=2}^{n} CD_i / S_i}{\sum_{i=1}^{n} 1/S_i} \tag{5}$$

where

S_i	the distance between reference station i and the rover.
CD_i	the dispersive or non-dispersive correction difference associated with the reference station i.

CD_{rover}	the interpolated dispersive or non-dispersive correction difference.

Euler et al. (2003) compared the distance weighted interpolation technique described in (5) with a plane surface represented by

$$f(E,N) = a \cdot (E - E_o) + b \cdot (N - N_o) + c \qquad (6)$$

where

a, b, c	coefficients defining the plane.
E, N	easting and northing of the interpolation point.
E_o, N_o	easting and northing of the origin.

The results presented in Euler et al. (2003) showed that the plane surface better modeled the regional trends of the correction differences across the network. The same two interpolation techniques are used for the numerical analysis in this paper.

TEST NETWORK

Four hours of 1 Hz data was collected on the 27th November 2003 for a network of 12 reference stations in Bavaria, Germany for the numerical analysis. These stations form part of the SAPOS permanent reference station network. The data was prepared for generating correction differences by first removing cycle slips. The double-differenced phase ambiguities between the reference stations were then resolved and eliminated from the data. The resulting ambiguity-leveled data was used to form RTCM type 20 phase corrections for each reference station.

Stations 274 and 272, situated at the boundary of the network, were chosen as master reference stations. The remaining stations served as auxiliaries, except for stations 256 and 271, which were used as rovers. The distribution of network stations in relation to the rovers is shown in Figure 1 and Figure 2.

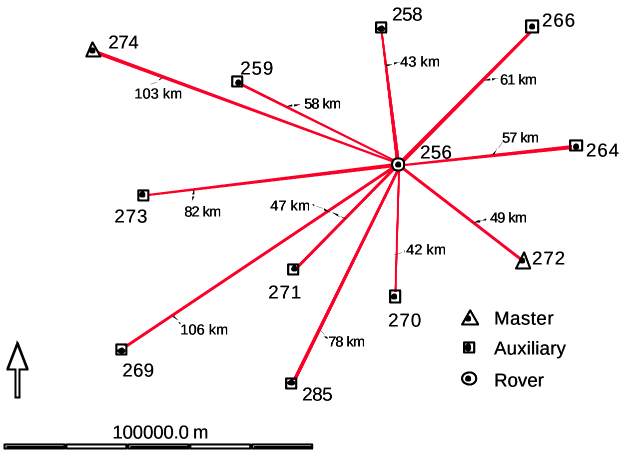

Figure 1 Distribution of reference stations in relation to the rover station 256. Stations 274 and 272 were used alternatively as master reference stations.

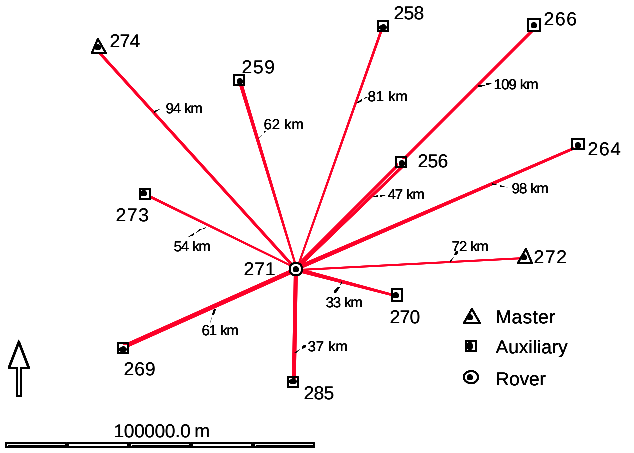

Figure 2 Distribution of reference stations with respect to rover station 271. Stations 274 and 272 were used alternatively as master reference stations.

The lengths of the various master-rover baseline combinations used throughout the paper are summarized in Table 1.

Table 1 Master-rover baseline lengths.

Baseline	Length (km)
272 – 256	49
274 – 256	103
272 – 271	72
274 – 271	94
270 – 271	33

Dispersive and non-dispersive correction differences, as described in equations (3) and (4), were computed for the first four baselines in Table 1. The table also includes the shortest baseline in the network (33km) between rover station 271 and the auxiliary station 270. This baseline is used in the analysis to evaluate the improvements of network corrected solutions over conventional, or uncorrected, baseline solutions. No correction differences were calculated using station 270 as a master.

NUMERICAL ANALYSIS

Uncorrected double difference dispersive and non-dispersive phase residuals were computed for each master-rover baseline combination. The dispersive errors scaled to L1 cycles are shown in Figure 3 for the 94km baseline (274 – 271).

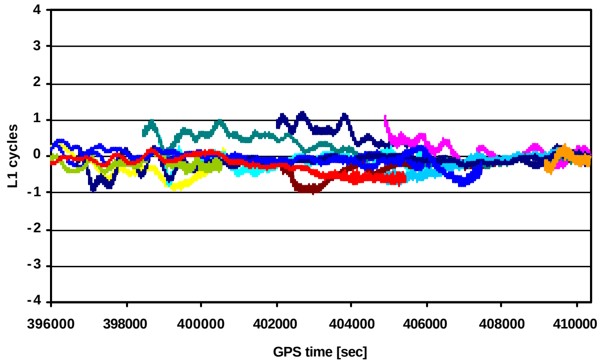

Figure 3 Dispersive errors (274 – 271).

The example is representative of the effects seen for the other baselines. The magnitude of the dispersive errors is relatively small and generally less than ±1 cycle. The double difference phase errors for the non-dispersive component are shown Figure 4.

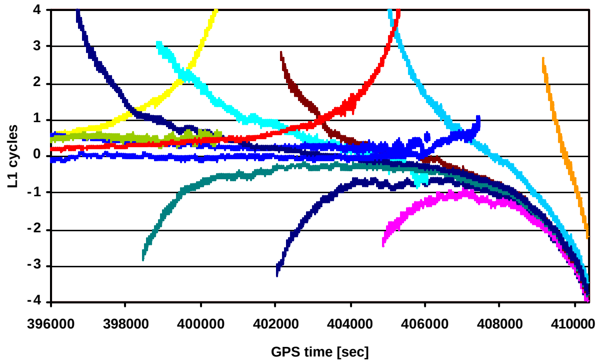

Figure 4 Non-dispersive errors (274 – 271).

The non-dispersive errors in Figure 4 contain the full double difference tropospheric refraction and orbit biases. Large non-dispersive biases greater than ±4 cycles are recognizable. However, a model for reducing the tropospheric refraction is normally applied in baseline processing schemes. Figure 5 shows the non-dispersive errors for the same baseline reduced by a Hopfield tropospheric model and temperature, humidity and pressure values for a standard atmosphere.

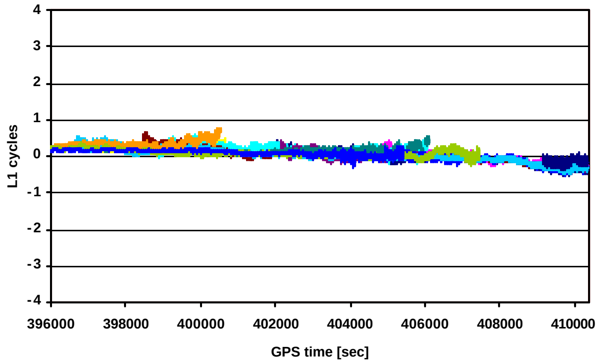

Figure 5 Non-dispersive errors reduced by a tropospheric model (274 – 271).

The tropospheric model successfully reduced the magnitude of the non-dispersive errors to less than ±1 cycle. The remaining errors can be attributed to orbit biases and residual tropospheric errors. The results illustrate the favorable atmospheric conditions under the data was collected.

The dispersive and non-dispersive errors were grouped into elevation bins 1 degree in size according to the elevation of the lowest satellite used to build the double difference. For each elevation bin, the average error and mean true error of the dispersive and non-dispersive components was calculated. The mean true error $\bar{e}$ is given by

$$\bar{e} = \sqrt{\frac{[ee]}{n}} \tag{7}$$

where e is the true error and n is the number of observations. The results for the same baseline 274 – 271 are presented below. Again, the example is typical of the results for the other baselines.

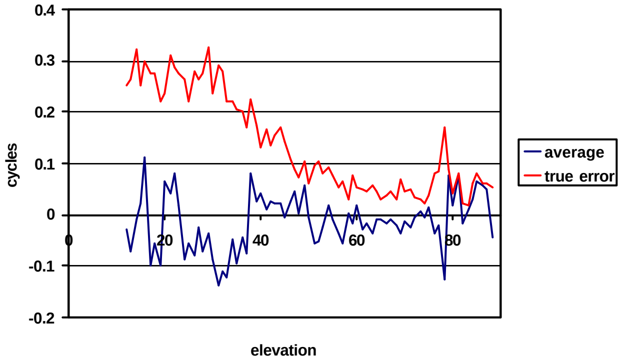

Figure 6 Average and true dispersive errors (274 – 271).

The dispersive errors, shown in Figure 6, are not highly correlated with satellite elevation, which is illustrated by the apparent random nature of the average error. The average and true errors for the non dispersive component is shown in Figure 7.

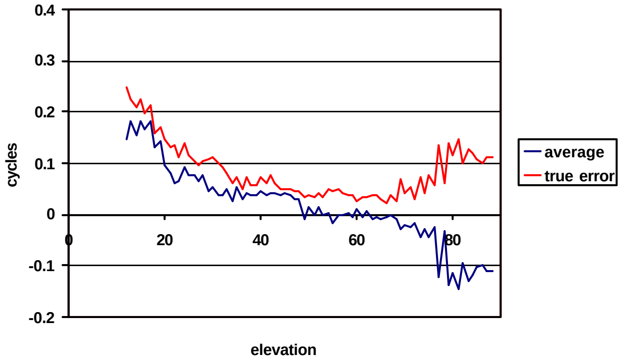

Figure 7 Average and true non-dispersive errors (274 – 271).

The average and mean true error lines for non-dispersive errors are all most parallel. This illustrates the correlation of the non-dispersive component with respect to elevation angle. An exception is apparent for high elevation satellites and the cause is still under investigation. Furthermore, the magnitude for both dispersive and the non-dispersive true errors increases for satellites below an elevation of 20 degrees.

In the next tests, correction differences were used to evaluate the benefits of network RTK corrections for rover applications. The dispersive and non-dispersive correction differences related to the two master stations were interpolated for each rover position using the distance weighted and plane interpolation techniques. An update rate of 15 seconds was adopted for the non-dispersive correction differences, as proposed by RTCM SC104. An update rate of only 10 seconds was considered sufficient for the dispersive contribution since the data did not exhibit high ionospheric effects. In addition, a delay equal to the update rate was applied to the correction differences in order to simulate the real-time data flow. The interpolated corrections were then applied at the rover and the corrected double difference phase errors computed.

Figure 8 and Figure 9 show the dispersive and non-dispersive errors on the same 94km baseline (274 – 271) after correction differences interpolated using a plane were applied.

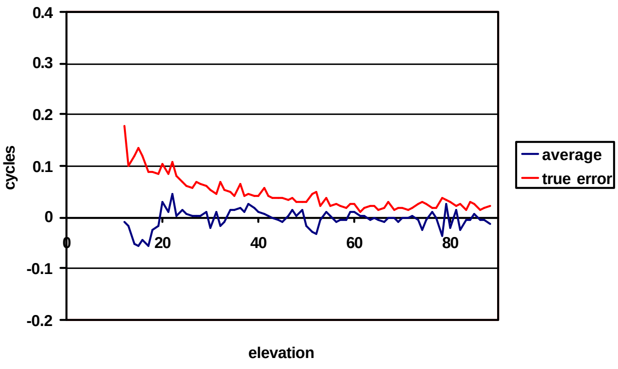

Figure 8 Corrected dispersive errors using the plane interpolation technique (274 – 271).

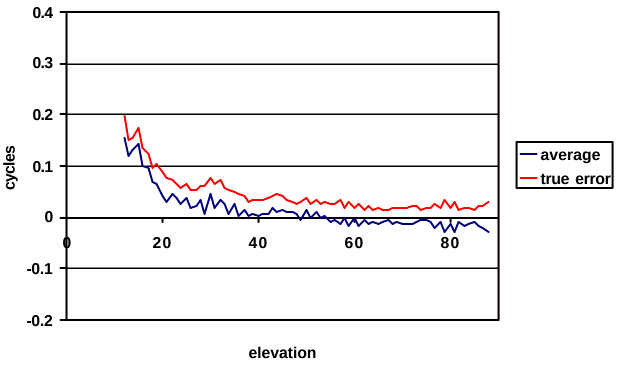

Figure 9 Corrected non-dispersive errors using the plane interpolation technique (274 – 271).

In general, the magnitude of dispersive and non-dispersive the errors have been reduced and the unexplained bias affecting the non-dispersive errors of high elevation satellites is no longer evident. The magnitude of the improvement for the example baseline is given in Figure 10 and Figure 11 for the dispersive and non-dispersive true errors.

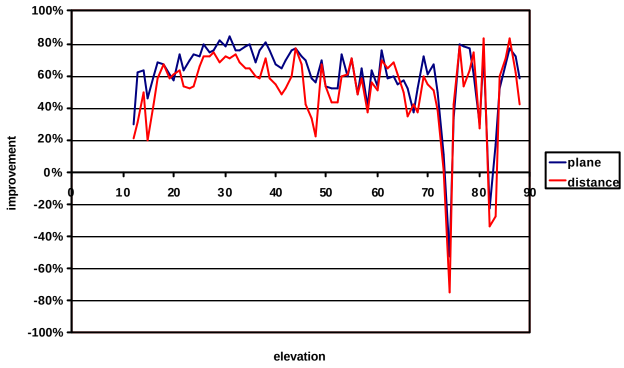

Figure 10 Improvement in the dispersive true errors (274 – 271).

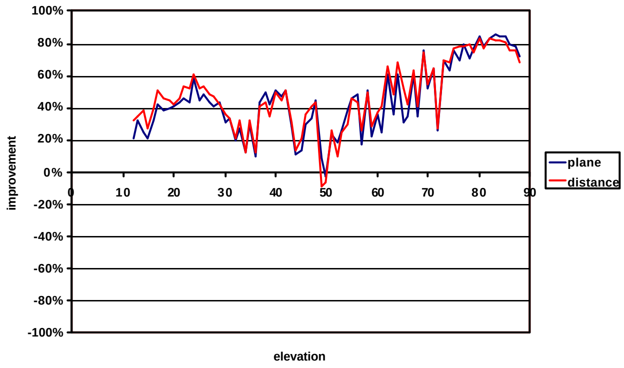

Figure 11 Improvement in the non-dispersive true errors (274 – 271).

The network RTK corrections reduce approximately 60%-80% of the dispersive effects and between 40%-80% of non-dispersive effects over all elevation bins. The plane interpolation technique better models the dispersive component for satellites below an elevation of 30 degrees. The improvements are less significant than those shown previously in Euler et al. (2003). Nevertheless, the improvements are mainly positive. Negative improvements are seen for example in high elevation dispersive errors. These results are due to already marginal biases in the uncorrected data. Small additional corrections may result in such cases in a nominal negative improvement but will not affect overall performance.

The previous results show that network corrections can reduce dispersive and non-dispersive errors on a long (94km) baseline. However, rover data is normally processed using information from the closest reference station. It is important for the applicability of the network correction procedure that corrected observations exhibit less error than the uncorrected double difference errors computed using the closest reference station. Otherwise, it would be more beneficial to use the observations nearest reference station directly.

Station 270 is the nearest reference station to the rover station 271 (Figure 2). This also represents the shortest baseline in the network (33km). Uncorrected double difference dispersive and non-dispersive errors were computed for this baseline as previously described. Figure 12 and Figure 13 compare the improvement of the corrected true errors of the long baseline 274 – 271 with the uncorrected true errors for the short baseline 270 – 271.

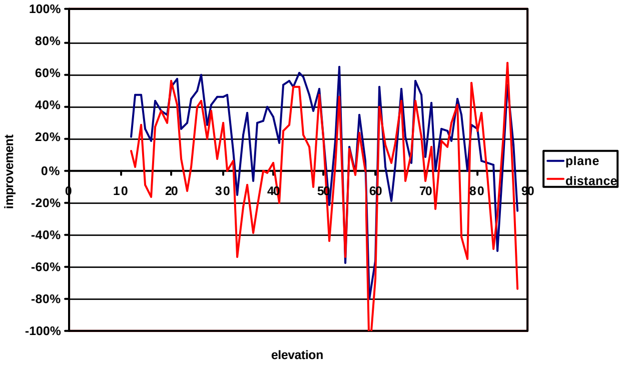

Figure 12 Improvement of dispersive true errors using the correction differences.

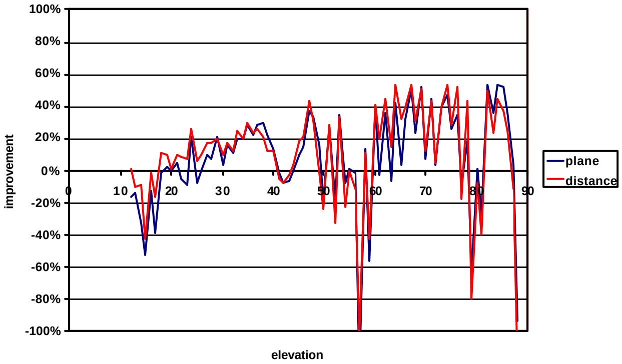

Figure 13 Improvement of corrected non-dispersive true errors over data applied from the nearest reference station.

The improvement in the magnitude of dispersive and non-dispersive errors reduced by network corrections is less significant when compared to the improvement achieved over the long uncorrected baseline, i.e. Figure 10 and Figure 11. Furthermore, in some cases the double difference phase errors are degraded. In general, as the separation between the rover and reference decreases, so to will the effectiveness of network RTK corrections to improve phase residuals. In this example, the border is close to 30km. However, this boundary is not static and will depend on the distribution of the reference stations, the observing conditions and the ability of the interpolation technique to accurately model regional trends. The Master-Auxiliary concept is flexible in this regard because the rover has the choice of how to apply network information. The data stream contains the necessary information to reconstruct the raw observables for all the reference stations in the network. This information can be applied directly if preferred.

BASELINE PROCESSING RESULTS

The previous analysis focused on the benefits of network RTK corrections in the measurement domain. The following experiments show the potential of network information to improve positioning performance. For this analysis, the four-hour data set was divided into discrete blocks of 90 second, 60 second and 45 second observation lengths.

The baselines shown in Table 1 were processed with and without applied network corrections for the 3 observation periods using a 15-degree elevation mask. Figure 14 shows the percentage of correctly fixed solutions for the baseline 94km baseline.

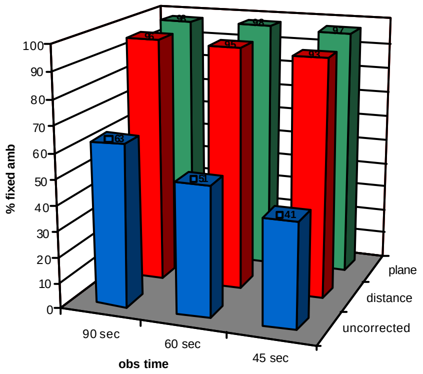

Figure 14 Percentage of fixed solutions for baseline 274 – 271 using 90 second, 60 second and 45 second observation times and a 15 degree elevation mask.

As expected, the percentage of fixed solutions for the uncorrected baseline increases with longer observation times. Even so, only 60% of the solutions could be fixed for the longest observation interval. Conversely, more than 95% of the solutions were fixed when network corrections were applied; regardless of the observation period. Unlike the uncorrected baseline, there is no discernable improvement in the percentage of fixed solutions with longer observation times. However, a higher percentage of fixed solutions is achieved when the network corrections interpolated using the plane are applied.

The percentage of correctly fixed solutions for the four different baselines and a 45 second observation period are presented in Figure 15.

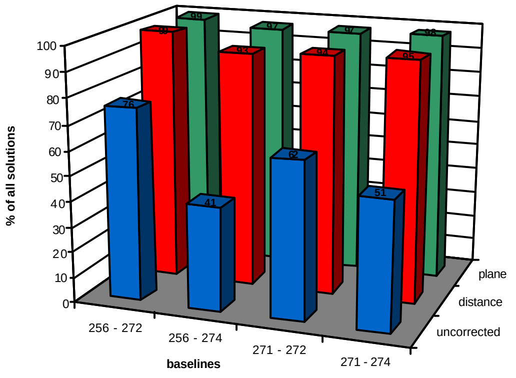

Figure 15 Percentage of fixed solutions for all baselines using a 45 second observation length and a 15-degree elevation mask.

The percentage of fixed solutions for uncorrected baselines increases as the baseline length decreases. This is consistent with the performance of conventional baseline processing. Even so, only 76% of all solutions could be fixed for the shortest baseline 256 – 272 (49km). In comparison, more than 93% of solutions could be fixed when network corrections were applied regardless of the distance between the master and rover stations. Furthermore, there is also no discernible improvement in the percentage of fixed solutions as the baseline length decreases. However, a higher percentage of fixed solutions are achieved when network corrections interpolated using the plane are applied.

Figure 15 also illustrates that effective ambiguity resolution is possible for long baselines (>50km) and short observation periods (>45 sec) when network corrections are utilised. The reliability of fixing solutions is also an important metric for assessing overall ambiguity resolution performance. Figure 16 shows the percentage of wrongly fixed solutions.

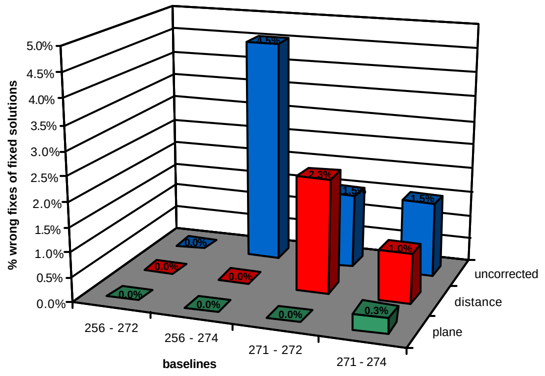

Figure 16 Percentage of wrongly fixed solutions for all baselines using a 45 second observation period and a 15 degree elevation mask.

The reliability of ambiguity resolution for uncorrected baselines decreases as the baseline length increases. For the uncorrected baseline 256-274 (103km), 4.5% of solutions were incorrectly fixed. Reliability increased significantly when network corrections, interpolated using the plane, were utilised.

As discussed previously, it is important that network corrections improve RTK positioning performance when compared to the use of data from the nearest reference station directly. The uncorrected baseline 270 – 271 (33km) was processed using the 45-second observation segments and a 15-degree elevation mask. In 89% of the cases the integer ambiguities could be fixed, however, two of the solutions wrongly fixed. Referring back to Figure 15, over 95% of solutions could be fixed when network corrections were applied.

The final two plots compare the horizontal and vertical position errors of the rover station 271 as a result of baseline processing with uncorrected data from station 270 (33km baseline) and network corrected data from station 272 (72 km baseline).

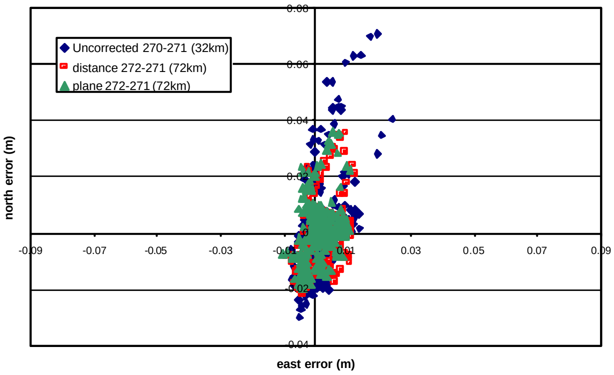

Figure 17 Horizontal position error of rover 271 using a 45 second observation period and a 15-degree elevation mask.

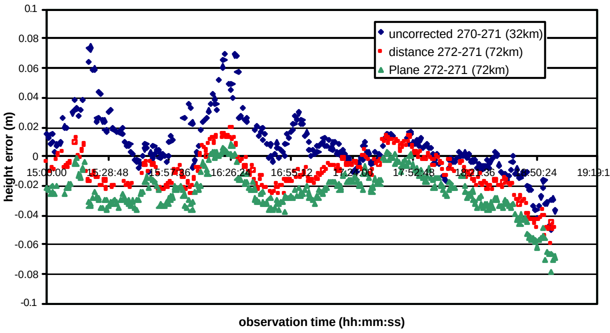

Figure 18 Height error of station 271 using a 45 second observation period and a 15-degree elevation mask.

As mentioned above, two solutions were incorrectly fixed for the uncorrected 33km baseline. No solutions were wrongly fixed for the network corrected baseline. The horizontal accuracy of station 270 shows an improvement when network corrections are utilized, especially when the plane interpolation technique is employed (Figure 17). An improvement in the precision of the height component for the network corrected baselines is also evident in Figure 18. However, the cause of the apparent bias in the results for both interpolation methods is still under investigation.

CONCLUSIONS

Interoperability testing of standardized network RTK messages is currently underway within by RTCM SC104. Therefore, an industry-wide network message standard is imminent. A series of tests were undertaken to evaluate the potential of standardized network messages, as described by the Master-Auxiliary concept, for RTK positioning.

Network RTK corrections were used to correct the dispersive and non-dispersive effects for four baselines ranging in length from 49km to 103km. Approximately 60% - 80% of the dispersive effects and 40% - 80% of the non-dispersive effects could be removed. However, the improvement was not as significant as shown in the previous work of Euler and Zebhauser (2003) and Euler et al. (2003). An analysis of uncorrected dispersive and non-dispersive errors shows a smaller impact of atmospheric effects on the test data.

The same four baselines were processed with and without network corrections using 90, 60 and 45 second observation periods. The effectiveness and reliability of ambiguity resolution improved significantly for all solutions when network corrections were applied. The greatest improvements were realized when a plane surface was used to interpolate network corrections. Furthermore, no discernable difference in ambiguity resolution performance could be detected for the corrected baselines when using 45-second or 90-second observation lengths.

Uncorrected dispersive and non-dispersive errors for a short 33km baseline (270 - 271) were not very large. Acceptable RTK performance is perhaps achievable for this baseline without the need for network corrections. Nevertheless, the overall horizontal and vertical position accuracy of the rover increased when network corrections were applied.

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