Advances in ambiguity resolution for RTK applications using the new RTCM V3.0 Master-Auxiliary messages
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ABSTRACT

With the release of RTCM 3.0 there is, for the first time, a standardized way of transmitting GPS corrections from a network of reference stations. The network messages used in RTCM 3.0 are based on the Master-Auxiliary Concept jointly proposed by Leica Geosystems and Geo++. The idea behind the Master-Auxiliary concept is to provide the raw observation data of the network, free of any proprietary modelling, to the rover in a highly compact way so that the rover has full knowledge and control over how the network corrections are applied for its position solution. The distinct advantages of RTCM 3.0 Master-Auxiliary corrections over earlier approaches are the standardized, open and compact nature of the format, the suitability of the format for broadcast communications and the flexibility given to the rover in deciding how best to apply the network corrections. The aim of this paper is to assess how the advantages of the Master-Auxiliary concept translate into benefits for the user. The advances in ambiguity resolution are achieved by combining standard techniques such as stochastic modelling of the ionosphere and repeated validation of independent ambiguity sets with an innovative interpolation of the network corrections.

For the analysis, empirical data are used from a real reference network possessing a number of challenging characteristics, such as large separations between stations in terms of both distance and height. Continuous testing was run over an extended period providing the basis for the first true long-term statistical analysis of rover performance when using Master-Auxiliary corrections. Direct comparisons are made against VRS and FKP and it is clearly shown that Master-Auxiliary concept offers superior performance in terms of time to fix, reliability of ambiguity resolution and accuracy.

INTRODUCTION

The motivation behind using multiple reference stations in a network for GPS corrections is to model and correct for distance-dependent errors that reduce the accuracy of conventional RTK or DGPS positions in proportion to the distance from a rover to its nearest reference station. It is well known that beside multipath, the most significant sources of error affecting precise GPS positioning are the ionosphere, troposphere and satellite orbits. These error sources may be categorized in two groups: dispersive and non-dispersive. The ionosphere is a dispersive error because the magnitude of the resultant error is directly related to the frequency of the ranging signal (L1, L2, L5). The influence of the ionospheric error on different frequencies in the L-band used by satellite navigation systems is well understood. The ionosphere, which is subject to rapid and localised disturbances, is the main restriction on the station density in a reference network. The troposphere and orbit errors are classified as non-dispersive because they are not frequency-dependent and have an equal effect on all ranging signals used by current (and proposed) satellite-based global navigation systems. The aim of a reference network is to model and estimate these error sources and provide this network correction information to rover users so that they may derive positions with a higher accuracy than with conventional RTK. Until the release of RTCM 3.0, there will have been no official internationally accepted standard for network RTK corrections. Prior to the release of RTCM 3.0, two approaches, namely those making use of area correction parameters (FKP) and ‘virtual’ reference stations (VRS), were adopted by the user community as interim measures, both of which have flaws in their concept and methodology, especially with regards to system interoperability. Some of the problems with these approaches are listed below.

Problems Common to VRS and FKP:
1. The modelling performed by the network software, which is proprietary, greatly influences the information that is provided to the rover. The outcome of this is that not all of the relevant error information is provided to the rover prohibiting it from using the optimal processing techniques (algorithms, models, interpolation) for the application. The fact that proprietary information is
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transmitted means that the corrections are not standard and therefore biased towards a particular brand of rovers.

2. The use of RTCM 2.3 as the data format for the existing approaches is inefficient, particularly for area correction parameters. The VRS and FKP approaches do not conform to the philosophy of RTCM's industry standard formats because the messages contain modelled data and not raw data as specified by RTCM. More importantly, proprietary, non-standardised messages are used to transmit part of the information. For area correction parameters (FKP), most of the message is transmitted in proprietary messages.

Problems Unique to VRS:
1. Two-way data links are required between the network computation centre and the user, making access to the correction service costly for both the user and the service provider. Duplex communications also have the downside of limiting the number of simultaneous users who are able to receive the corrections from the network.

2. The rover is forced to re-initialise its position fix once it has travelled more than a certain distance from its initial position because the 'virtual' reference station must be moved to maintain the quality of the network corrections.

3. An arbitrary number of reference stations, typically three, which is determined by the reference station software, are used to calculate the corrections for the rover. This restriction limits the ability of the system to adapt to the prevailing atmospheric conditions by using an appropriate number of reference stations to, for example, model larger scale atmospheric activity. Such a constraint also influences robustness through its impact on the network geometry and the sensitivity to data outages. If even one of the three stations is unable to provide data to the network, the network software must search for another suitable reference station and reset the calculation of correction for the user. During this search process, no network corrections are available to the rovers, causing an impact on the productivity in the field.

4. The virtual reference station approach represents the network to the rover as a single reference station. Thus in the end the rover still has a single baseline solution, albeit with a much shorter baseline length. However, misleading the rover in this way also denies it the opportunity to fully realise the increase in accuracy and reliability possible with a true network solution. It also limits the ability of the rover to perform quality and integrity monitoring.

5. In some jurisdictions, there are legal issues if the GPS correction data is not directly related to a real reference station. Georeferencing GPS corrections (or observations) to virtual reference stations is neither traceable nor repeatable.

In light of these and other limitations of existing approaches to network corrections, Leica Geosystems has driven the development and adoption of the Master-Auxiliary Concept within RTCM Special Committee 104.

THE MASTER-AUXILIARY CONCEPT

In September 2001, Leica Geosystems together with Geo++ presented a paper titled "Study of a Simplified Approach in Utilizing Information from Permanent Reference Station Arrays" (Euler et al., 2001) to the RTCM SC104. This paper contained a proposal for a standard for network correction messages that would overcome the problems of the existing approaches. Since 2001 Leica Geosystems has been a driving force for a standard for network RTK, which would be a benefit to the whole surveying industry. The master-auxiliary proposal put forward by Leica Geosystems and Geo++ has since undergone small refinements based on input from other manufacturers. At the time of writing, the master-auxiliary network messages are the only fully documented non-proprietary proposal for network RTK messages under consideration by RTCM SC104 and have remained in their current form for over one year. Just as NTRIP was in use prior to its formal acceptance by RTCM as a standard, RTCM 3.0 network messages are already available with the Leica GPS Spider reference station software and the Leica System GPS 1200 products. Official acceptance and release of the standard is pending the completion of an interoperability test sanctioned by RTCM and currently in progress between the major manufacturers.

The fundamental concept of the proposed approach is to transmit all relevant correction data from a reference network to the rover in a highly compact form by representing ambiguity levelled observation data as correction differences of dispersive and non-dispersive data. This approach was to become known as the Master-Auxiliary Concept (MAC) and is the basis for the RTCM 3.0 Network RTK messages. A condensed version of this paper was presented at ION GPS 2001. A subsequent paper (Euler et al., 2002) expanded on the concept and demonstrated the superiority of this approach, in terms of throughput, possibility for non-standard data content and the distribution concept, over other proposals and the existing inferior approaches. A significant improvement in the quality of corrections compared to conventional RTK was demonstrated leading to proportional
improvement in ambiguity resolution and positioning accuracy (Euler and Zebhauser, 2003; Euler et al., 2004).

**Basics of the Master-Auxiliary Concept**

A fundamental requirement of Master-Auxiliary Concept is that the phase ranges from the reference stations are reduced to a common ambiguity level. Two reference stations are said to be on a common ambiguity level if the integer ambiguities for each phase range (satellite-receiver pair) have been removed (or adjusted) so that when double differences are formed the integer ambiguities cancel. The main task of the network processing software is to reduce the ambiguities for the phase ranges from all reference stations in the network (or sub-network) to a common level. With this task done, it is then possible to calculate the dispersive and non-dispersive errors for each satellite-receiver pair and for each frequency.

To reduce the volume of data to be transmitted for a network, the Master-Auxiliary Concept sends full raw observation and coordinate information for a single reference station, referred to as the master station. For all other stations in the network (or sub-network), known as auxiliary stations, correction differences and coordinate differences are transmitted. This differenced information, which is calculated between the master and each auxiliary station, is numerically smaller and can thus be represented in the messages by a smaller number of bits. The correction difference information may be used by the rover simply to interpolate the error at the user’s location or to reconstruct the full observation information from all reference stations in the network (or sub-network). Thus the Master-Auxiliary Concept fully supports simplex communication media with no loss of positioning performance noticed at the rover. The bandwidth required to transmit the data is further reduced by splitting the corrections into two parts: dispersive and non-dispersive. As mentioned previously, the dispersive error is directly related to the frequency of the signal and the non-dispersive error is the same for all frequencies. Since the frequency-relationship for the ionospheric error is known, it is possible to represent the full correction for all frequencies (L1, L2, L5) with these two values. Additionally, as the tropospheric and orbit errors are known to change only slowly with time, therefore the non-dispersive component does not need to be transmitted at a high rate as the dispersive error, which can further reduce the bandwidth needed to provide network corrections to the rover.

The Master-Auxiliary Concept gives the rover the flexibility to perform a simple and efficient interpolation of the network corrections or a more rigorous calculation depending on its processing capabilities. The Leica GX1230 RTK rover has a high performance processing unit and is able to maximise the potential of the master-auxiliary network corrections by using sophisticated error modelling techniques.
The master station is always the reference station nearest to the rover, as are the surrounding auxiliary stations. When using Auto-MAX, even the largest reference networks can be fully serviced with a single communication channel. The MAX corrections contain the full information from the cell and therefore provide the maximum level of accuracy and reliability for the rover.

**Individualized Master-Auxiliary Corrections (i-MAX)**

In order to support earlier model rover receivers that are unable to interpret the RTCM 3.0 Network RTK messages, Leica GPS Spider can generate individualized master-auxiliary corrections, known as i-MAX, specific for a rover’s location at every epoch. These corrections require two-way communication and may be transmitted in RTCM format 3.0 and even 2.3 - which is supported by most rovers. Unlike other approaches, i-MAX uses a real reference station as the source for the network corrections so there is always consistency and traceability behind those i-MAX corrections received by the rover. The interpolation performed in Leica GPS Spider for the i-MAX corrections is the same as that used in the Leica GX1230 RTK rovers when positioning using master-auxiliary corrections. As such, rover performance using i-MAX is comparable to that of a rover that fully supports master-auxiliary corrections.

**Common Misunderstandings About the Master-Auxiliary Concept**

It is a drawback that data from only a subset of the network is transmitted.

In a large network, the rover will be too far from many of the stations to benefit from their contribution. Transmitting data from these stations is simply a waste of bandwidth. Intelligent software such as Leica GPS Spider chooses the optimal set of reference station data to send to the rover.

It is a drawback that only a snapshot of the ionospheric and geometric errors are sent.

Since the actual error information is available in the master-auxiliary corrections, the rover can directly calculate the error at its position and, therefore, does not need time for its error models to converge. High accuracy positioning is possible from the moment the first set of corrections is received.

With Master-Auxiliary Concept the master station will be a long way from the rover.

With two-way communications Leica GPS Spider will always choose the closest reference station to be the master. With one-way communications the rover user can choose which correction service to connect to and thereby ensuring that a cell with the nearest master station is used. The RTK performance of Leica GPS 1200 would however be independent of which master station is chosen in the network.

**Accuracy will be compromised because reduced update rates are used.**

Update rates of 1Hz are supported for both the master station observations, and the dispersive and non-dispersive errors. Update rates for the dispersive and non-dispersive errors can be configured to be slower than 1Hz to conserve bandwidth. Having a slower update rate (of say 0.5Hz or 0.2Hz) for these errors will not significantly impact on the accuracy of the rover’s position.

The bandwidth of the network messages is very high.

More data is transmitted with the Master Auxiliary Concept than with the simplified VRS or FKP method, however the format is designed to be very efficient. In actual fact, sending 1Hz master data and 2s dispersive and non-dispersive error in formation, is more efficient than 1Hz VRS with RTCM 2.3 for a typical set of up to 8 stations (7 auxiliary stations plus the master station). Refer to Table 1 for a list of representative bandwidths based on 10 satellites. The individualized version of the master auxiliary corrections, i-MAX, available from Leica GPS Spider is even more efficient than VRS, needing a bandwidth of less than 37% of that bandwidth needed for VRS.

<table>
<thead>
<tr>
<th>Number of Auxiliary Stations</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRS, RTCM 2.3 18/19, 1Hz update rate</td>
<td>3776bps</td>
<td>3776bps</td>
<td>3776bps</td>
</tr>
<tr>
<td>i-MAX, RTCM 3.0 1004, 1Hz update rate</td>
<td>1391bps</td>
<td>1391bps</td>
<td>1391bps</td>
</tr>
<tr>
<td>MAX, RTCM 3.0 1017, 1Hz update rate for master and network corrections</td>
<td>5255bps</td>
<td>6567bps</td>
<td>7879bps</td>
</tr>
<tr>
<td>MAX, RTCM 3.0 1017, 1Hz update rate for master and 0.5Hz for network corrections</td>
<td>3287bps</td>
<td>3943bps</td>
<td>4599bps</td>
</tr>
<tr>
<td>MAX, RTCM 3.0 1017, 1Hz update rate for master and 0.2Hz for network corrections</td>
<td>2106bps</td>
<td>2368bps</td>
<td>2631bps</td>
</tr>
</tbody>
</table>

*This value does not include the variable length type 59 proprietary information message, so the actual bandwidth may be higher.

Table 1: Bandwidths for network corrections

If the network is unable to fix ambiguities, then the rover will not get corrections.

The master-auxiliary corrections contain the full observations for the master station, so a rover is still able to compute a single baseline solution even if the correction differences are not available or not valid. With two-way communications, Leica GPS Spider will always use the closest reference station as the master.
STATIC PERFORMANCE COMPARISON

In order to assess how the advantages of the Master-Auxiliary concept translate into benefits for the user, data was collected from Leica’s RTK testbed. Figure 2 gives an overview of the network setup.

The network consists of 5 stations in the border region between Switzerland, Austria and Germany. Each station is equipped with a dual-frequency GPS receiver and is permanently connected to the Leica office via a broadband internet connection. German, Swiss and Austrian surveying authorities operate the stations. This network does not represent an unrealistic, idealized showcase network, but reflects rather challenging conditions: besides featuring a mix of different receiver and antenna makes and models, the reference station separations are up to almost 100km. Especially challenging is the height separation among the stations: the lowest station (Uznach) is at an elevation of 475m, whereas the station Kops is more than 1900m above sea level.

Leica SpiderNet was used to calculate single site, MAX and i-MAX corrections in RTCM 3.0. The MAX corrections were based on an update rate of 0.2 Hz for the dispersive and non-dispersive components of the network corrections. A third-party network RTK software package was used to generate FKP and VRS corrections. All network corrections were based on the same five stations and were processed simultaneously. The single baseline corrections were taken from station Kops. The rover antenna was located at the Leica office at a height of 474m, where the five receivers in Table 2 were connected to the same rover antenna. The distance from the rover antenna to the closest reference station, Ravensburg, was 43 km. The distance to the master station Kops, which was deliberately chosen to be further away, was approximately 60km with a height difference of 1500m.

Table 2 gives an overview on the type of RTK corrections the different receivers were fed.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>RTK Correction type</th>
<th>RTK Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica GX1230 #1</td>
<td>Single baseline (Kops)</td>
<td>RTCM v.3.0</td>
</tr>
<tr>
<td>Leica GX1230 #2</td>
<td>i-MAX</td>
<td>RTCM v.3.0</td>
</tr>
<tr>
<td>Leica GX1230 #3</td>
<td>MAX</td>
<td>RTCM v.3.0</td>
</tr>
<tr>
<td>Leica GX1230 #4</td>
<td>FKP</td>
<td>RTCM v.2.3</td>
</tr>
<tr>
<td>Third-party receiver</td>
<td>VRS</td>
<td>RTCM v.2.3</td>
</tr>
</tbody>
</table>

This test ran for several months allowing the first true long-term statistical analysis of rover performance when using Master-Auxiliary corrections. The following sections present typical results from a representative 16h time window of these long-term measurements.

**Comparison of accuracy**

One measure of RTK performance is to compare the accuracy of the measured RTK position with the ground truth. For that, all receivers were fed the respective RTK corrections from Table 1 without performing any resets of the receivers. The receivers were configured in kinematic mode and NMEA GGA positions were stored to obtain a record of the position results. These NMEA positions were used to compute height precision and position accuracy for the different network RTK formats. Figure 3 shows the height precision of a MAX solution compared to a single baseline. The results of the MAX data show noticeable benefits. In the 60km single baseline there are a significant number of outliers above 15 cm, but none when using the network solution. The network information for the troposphere and ionosphere also improves the precision of the height results.
However, differences can also be seen between different network RTK formats (Figure 4). As expected, MAX and i-MAX show very similar values. The VRS corrections, which were processed by the third-party receiver, show a significantly lower precision. In addition, a high number of wrong fixes caused a bias in the average height seen as a shift in Figure 4.

Figures 5 and 6 show position scatter plots, again for the different network RTK formats as well as for the single baseline. The values are plotted versus the ground truth of the antenna location.

The RMS is improved from 0.029m to 0.008m when using MAX instead of the single baseline solution. The increased performance of i-MAX and MAX compared to other network RTK approaches is clearly visible in Figure 6. The FKP corrections in this specific test do not precisely model the atmospheric conditions, resulting in noisy positions. In can also be seen that the third party rover receiving VRS corrections cannot reliably resolve the ambiguities resulting in many spurious position solutions. In addition, the advantages of the unique ability of Leica GPS 1200 to repeatedly and independently verify ambiguities can be seen when comparing the RMS of the Leica single baseline solution (0.029m) against the RMS of the third-party rover receiving VRS corrections (0.313m). To provide VRS corrections, software from third-parties were involved, and this detailed analysis of results were not possible. At the time being, we assume that the major differences in positioning results are related to lacking interoperability between network concept and rover solution.

**User benefits - availability and time to fix**

The position and height accuracy is an important indication of RTK performance, the productivity of a GPS field crew however depends mainly on the availability of fixed ambiguities (Richter and Green, 2004).

Figure 7 summarizes the percentage of fixed epochs, i.e. the time span where navigation solutions, differential code solutions and RTK phase fixes were achieved. MAX and i-MAX show very similar values and show a better performance to other network RTK formats. The single baseline with a Leica rover is in terms of productivity on a similar level as MAX and i-MAX, however in this case
the field crew would of course not benefit from the gain in accuracy demonstrated in the previous section.

![Figure 7: Percentage of fixed positions](image)

The test and analysis presented so far simulated a rover occupying a point permanently for 16 hours without interruptions, and thus re-initialisations were only necessary in case of loss-of-locks or interruptions of the correction streams. To achieve results as realistic as possible, a further test was performed which forced the Leica receivers to continuously re-initialise (a full reset of the ambiguity filter) immediately after fixed ambiguities were attained. If no initialisation was achieved after three minutes, a new reset was forced. As the third-party rover did not allow an automated ambiguity reset, it was not included in this test.

Figure 8 includes both the number of RTK fixes within a certain time-to-fix interval, as well as the total number of ambiguities and confirmation of ambiguities. A higher number of restarts indicates a higher availability and reliability and is in fact the most important factor in terms of productivity gain.

![Figure 8: Time-to-fix (TTF) and ambiguity verification (logarithmic scale)](image)

All three network RTK formats have a higher number of fixes within the first 22 seconds than the single baseline. The single baseline is close in this interval, however its overall number of fixes is significantly lower. If the ambiguities of the single baseline cannot be resolved in the first minute, the conditions are not improved by extending the search period due to significant atmospheric biases. In a few cases the network results can be improved by extending the search period which proves that the corrected reference observations are more consistent and may enable ambiguity resolution in conditions where single baseline would not be possible.

Among the network RTK formats, MAX and i-MAX perform at a similarly high level. FKP shows an almost equal percentage of fixes within 22 seconds, but has 15% fewer restarts.

**KINEMATIC PERFORMANCE COMPARISON**

The final test was to make a comparison between a single baseline and i-MAX in a kinematic setup. For this reason, a GX1230 rover was mounted on a model train set which moved on a track of around 14 by 8 meters (Figure 9). The main difference of this test to the static set-up was that due to the kinematic nature of the test and temporary obstruction provided by various obstacles, loss-of-lock could be simulated – providing similar conditions as found in the field.

![Figure 9: Kinematic test setup](image)

Data from this rover and all reference stations was recorded. Based on the same data set, i-MAX and single baseline corrections were then computed in ‘quasi’ real-time replay mode. The percentage of epochs with RTK-fixed solutions (Figure 10), and the number of independent confirmations of the ambiguity set was evaluated.
A gain of 52% fixed epochs can be seen for i-MAX. In general, the kinematic test results were in line with the static restart test. It should again be emphasized that the number of independent ambiguity confirmations is a more suitable factor for performance improvements than a simple fix / no-fix statistic. The number of confirmations increases from 19 to 510, which underlines i-MAX’ significantly higher reliability.

CONCLUSIONS

The Master Auxiliary Concept, the basis for the forthcoming RTCM standard for network RTK corrections, is a revolutionary new approach to network RTK that addresses the limitations of earlier approaches. The RTCM network messages offer a truly open standardized format that enables efficient and accurate network RTK in both broadcast and two-way mode. This paper has shown that the theoretical advantages of the Master-Auxiliary Concept translate into true benefits for the rover user in terms of increased accuracy, performance and reliability. The statistical analysis of all tests clearly showed that the best performance was achieved by combining Leica GPS Spider with Leica GPS 1200 rovers utilizing MAX corrections. The individualized version of the MAX, known as i-MAX, which is also available from the Leica GPS Spider reference station software gives almost similar high level performance as MAX but with the advantage of using a lower bandwidth RTCM 3.0 format that can also be used by older receivers that do not support the new network messages.

ACKNOWLEDGMENTS

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REFERENCES


Whether providing corrections from just a single reference station, or an extensive range of services from a nationwide RTK network – innovative reference station solutions from Leica Geosystems offer tailor-made yet scalable systems, designed for minimum operator interaction whilst providing maximum user benefit. In full compliance with international standards, Leica's proven and reliable solutions are based on the latest technology.

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