# Assessing the Multi-Base Station GPS Solutions

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**Key words**: GPS, Multi-Base Station, Empirical tests.

## ABSTRACT

A permanent network of GPS receivers, the Bravida Network, was established in order to test the Multi-Base Station (MBS) Real Time Kinematic (RTK) system from the German company Trimble Terrasat. The Bravida Network is located in South-East Norway and consists of five stations separated by approximately 70km.

Empirical tests carried out in June 2001 indicate that the MBS approach is well suited for many applications in land surveying. The carrier phase ambiguities are resolved within a reasonable amount of time in all data sets. The accuracy of the computed rover coordinates seems adequate for many applications, as 95% of the true errors lie within approximately 4cm horizontally and 8cm vertically.

There seems to be a stronger autocorrelation present in the MBS solutions than in the standard RTK solutions using one reference station only. Autocorrelation has a serious impact on reliability measures, and this fact raises questions concerning the usual "averaging of coordinates"-approach widely used in geomatics.

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## 1 INTRODUCTION

The use of a Multi-Base Station (MBS) network is a promising technique for fast and efficient GPS RTK data acquisition. The user needs only to operate the rover, reference station data is obtained from the network via a suitable data link, such as e.g. GSM mobile phones.

In the recent years several methods have been proposed to utilize data from a permanent reference receiver network for RTK-positioning, see e.g. Raquet (1998) and Wanninger (2000).

The limitations of differential positioning are mainly due to ionospheric and tropospheric refraction and ephemeris errors. These distance dependent errors are difficult to model when using one reference station only. In addition there are site dependent errors such as multipath.

A reference network software tries to estimate the effect of the distance dependent error sources and parametrize them as functions of position. There is a wide range of methods to utilize information from the network at the location of the roving receiver, as is shown in (Fotopolous & Cannon, 2001).

The corrections from the network are supposed to account for the effects not eliminated in the usual differential approach. With these corrections the user can hopefully compute the differential position with high accuracy.

This investigation looks into; i) the ability to perform ambiguity fixing, ii) accuracy and iii) autocorrelation of the computed coordinates.

Similar investigations have been conducted in e.g. Sweden (see Wiklund (2001)) and Germany (see Vollath et al. (2000a)).

## 2. THE BRAVIDA MBS NETWORK

The Bravida Network consists of 5 reference stations located in the south eastern part of Norway, as shown in Figure 1. The reference stations were established in ETRS89 through classical static surveying in the period of 12-26th of January 2001. The campaign resulted in standard deviations better than 1cm, and external reliability in the 1-2cm range horizontally and 2-5cm vertically for the reference stations. A summary of the ETRS89 realization in Norway ("Stamnettet") with methodology and quality estimates given in Harrson (1998).

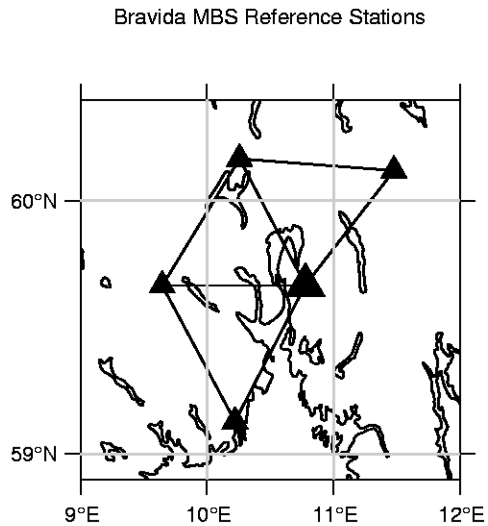

Figure 1: The Bravida MBS reference stations (small triangles) and computation center (large triangle). Inter-receiver distances are approximately 70km.

Topcon Legacy-E geodetic receivers with geodetic antennaes collect dual-frequency carrier and pseudorange observations and transmit these in real-time via permanent telephone lines to the computation center at Ås. The computation center runs Terrasat's GPSNetwork version 1.5 and offers reference station data via mobile telephone link. The rover transmits its approximate coordinates in NMEA format and gets differential corrections in RTCM format in return.

The software GPSNetwork uses bilinear interpolation using the receivers in the bounding triangle of the rover. The software separates the errors in a dispersive and a non-dispersive parameter for each satellite, the latter being a combined tropospheric and ephemeris error parameter.

The computation of the corrections for a rover is a two step process. The network software sends pseudorange corrections in return of the user's single point solution, and then precise carrier phase and pseudorange corrections in return of the user's differential code solution. The latter corrections are incorporated in the computation of a Virtual Reference Station (VRS) close to the rover position. The rover now uses data from the VRS in a regular differential carrier phase computation, aiming at accuracies in the centimeter range. The concept of VRS as implemented in GPSNetwork is described in Vollath et al. (2000b).

When using the VRS concept a two-way communication link is needed. It also means that the computational burden will be on the server side of the network.

## 3. EMPIRICAL TESTS

### 3.1 Collection of test data

A rover station ("A") was established in ETRS89 about 28km from the closest reference receiver. High quality coordinates were obtained through static surveying in the same campaign as the reference stations. Precision and reliability matches the reference stations.

A rover station ("B") was also established 7km from the closest reference station. This station was also tied directly to the "Stamnettet" through classical statical surveying. External reliability reached 1cm horizontally and 2cm vertically. In addition one of the stations in "Stamnettet" was also used as a rover station ("C").

All rover data were collected using identical receiver/antenna setups as the reference receivers. Coordinates using the MBS network were computed in real time, whereas the standard RTK solutions were post-processed using a software from the Topcon Development center in Moscow. In both cases the RTK engine are identical, using identical parameters as specified of Trimble Terrasat (personal correspondance). The models and algorithms in the Topcon RTK engine is described in Rapoport (2001).

### 3.2 Ambiguity Resolution

The critical questions when aiming at subdecimeter accuracy is; i) whether the carrier phase ambiguities can be resolved, ii) the amount of time required and iii) the reliability of the fixed solutions.
Coordinates and data were collected from the rover station "A" at 1Hz for 24 hours the 20-21th of June 2001. A small software was written to monitor the status of the receiver's solution mode. After a fixed solution was obtained, this was kept for 5 epochs, and then the receiver's RTK engine was completely reset. The coordinates were later compared to the known coordinates of the site.
As is seen in table 1 there were very few obviously wrong fixes.

| | |
|---|---|
| **# Fixes** | 5038 |
| **# Correct Fixes** | 5034 |
| **% Correct Fixes** | 99.7% |
| **Mean Time to Fix** | 10.7s |
| **Median Time to Fix** | 1s |
| **Max Time to Fix** | 908s |
| **Min Time to Fix** | 0s |

Table 1: Results from validation of ambiguity fixing. Data set at station "A" was used in conjunction with correction data from the MBS network.

A fix was considered erroneous if the mean position over the 5 epochs deviated more than 10cm horizontally and/or 20cm vertically from the known coordinates of the site.
Figure 2 shows the distributions of the initialization times of the dataset from 20-21th of June 2001.

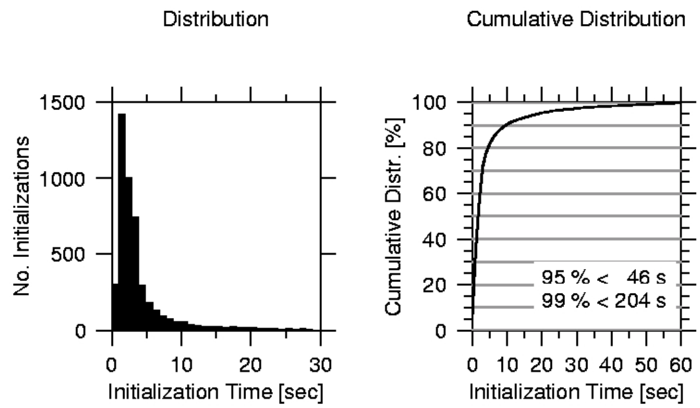


Figure 2: Distribution and cumulative distribution of initialization time for a 24 hour 1Hz data set.

The results should indeed be comparable to the initialization times obtained with a local single reference receiver. It is seen in this data set that 95% of the initializations need less than 46 seconds with float ambiguities before a fixed solution could succesfully be obtained.
A time series of the initialization times, smoothed with a moving average over 100 initializations is shown in Figure 3. It can readily be seen that there are periods where initialization is more difficult.

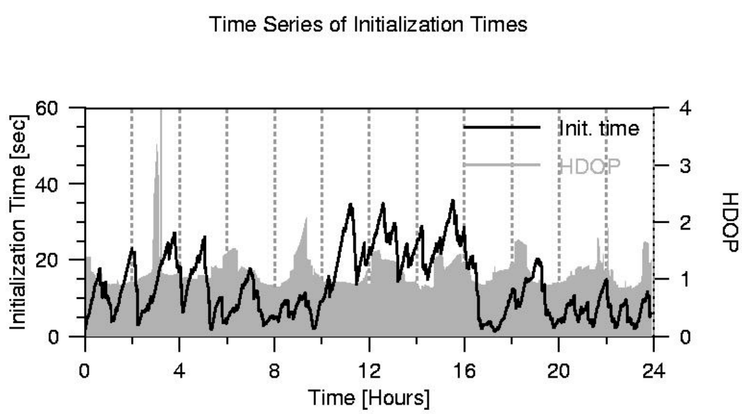


Figure 3: Time series of the initialization times and HDOP. Initialization times are smoothed with a moving average over 100 initializations.

### 3.3 Coordinate Accuracy

A general rule of thumb is that in periods with high iononspheric activity standard RTK positioning will yield poor results for baselines longer than approximately 10km. 24 hour 1Hz data sets were collected at rover stations “A”, “B” and “C” on 20-21th of June. Data sets from stations “B” and “C” were computed both with MBS and a single reference receiver. Data set from station “A” could not be successfully computed using the closest reference receiver, and only the MBS solution is shown here. Figures 4 to 11 show scatter plots and distributions of the “true errors” for these data sets.

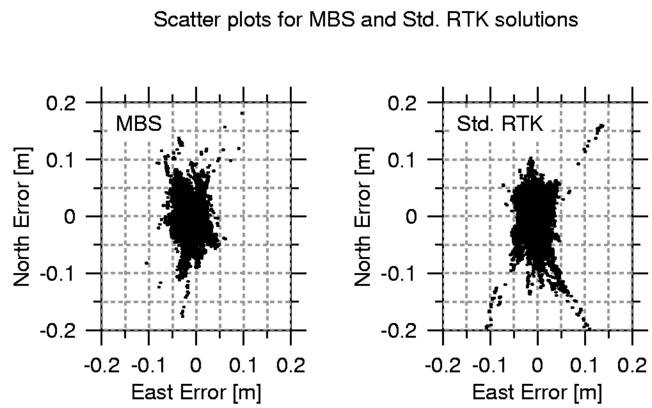


Figure 4: Scatter plots of “true errors” for the MBS solution (left) and the standard RTK solution (right) using a single reference receiver. Data set “B” (baseline length 7km).

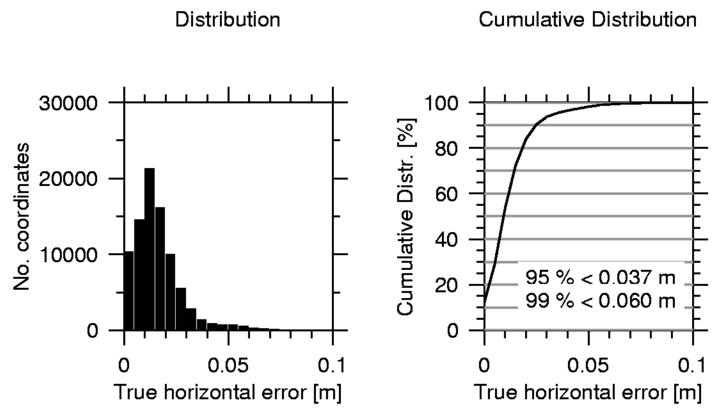


Figure 5: Distribution of “true errors” for the MBS solution. Data set “B” (baseline length 7km).

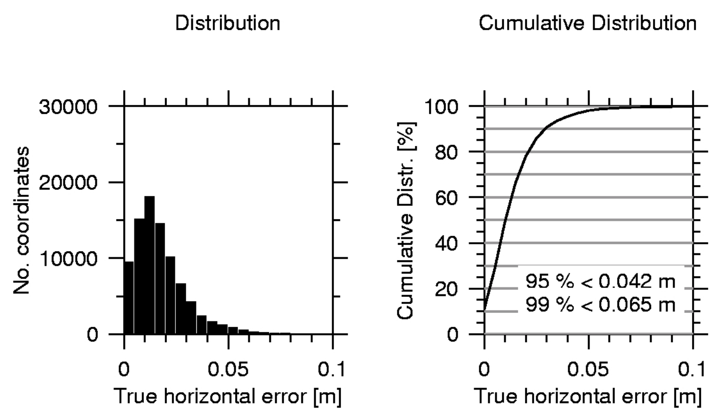


Figure 6: Distribution of “true errors” for the RTK solution. Data set “B” (baseline length 7km).

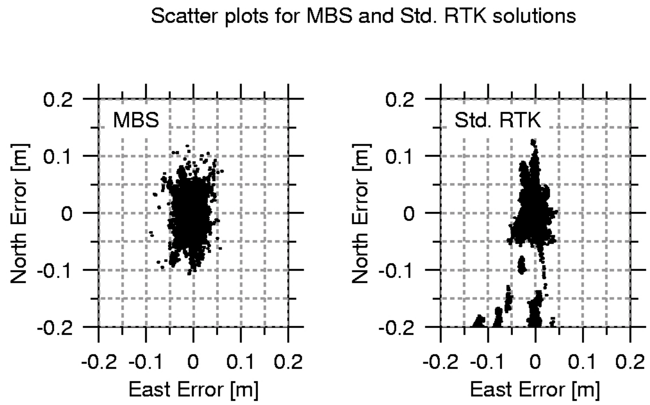


Figure 7: Scatter plots of “true errors” for the MBS solution (left) and the standard RTK solution (right) using a single reference receiver. Data set “C” (baseline length 12km).

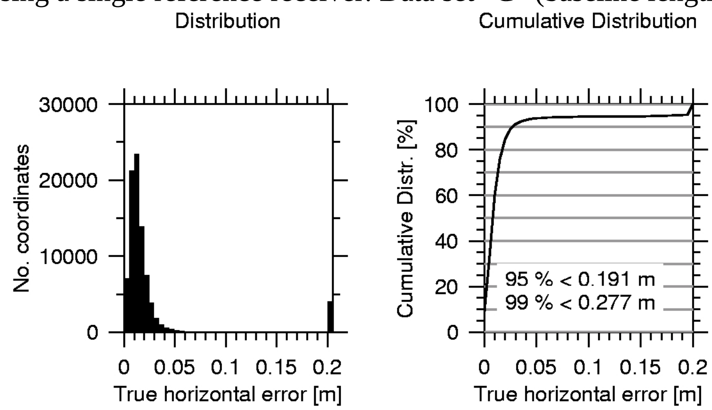


Figure 8: Distribution of “true errors” for the RTK solution. Data set “C” (baseline length 12km).

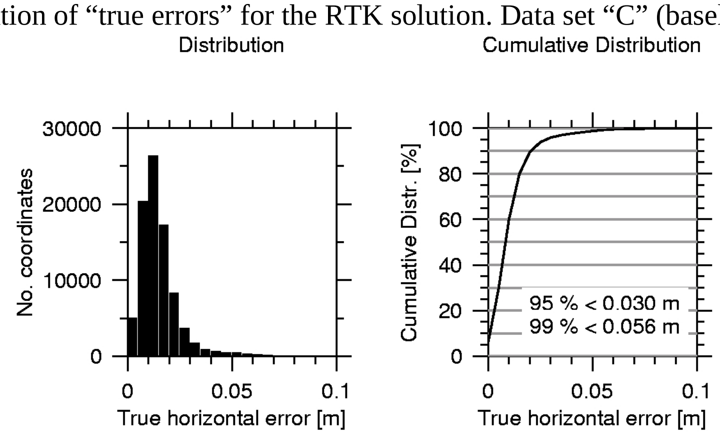


Figure 9: Distribution of “true errors” for the MBS solution. Data set “C” (baseline length 12km).

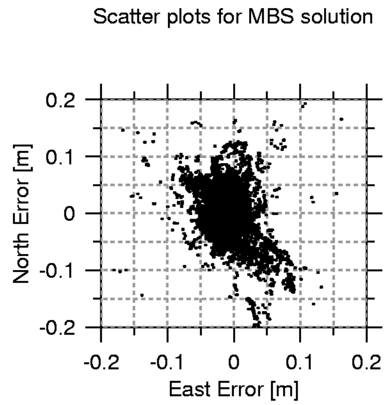

Figure 10: Scatter plot of “true errors” for the MBS solution. Data set “A” (baseline length 28km).

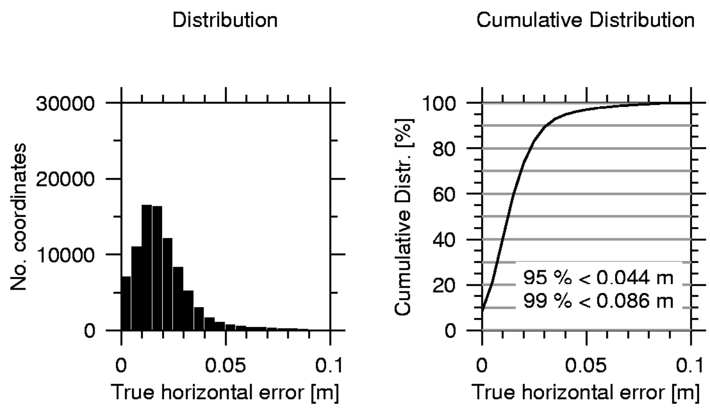

Figure 11: Distribution of “true errors” for the MBS solution. Data set “A” (baseline length 28km).

| **MBS** | **North [m]** | **East [m]** | **Height [m]** |
|---|---|---|---|
| **Mean** | 0.0050 | -0.0070 | 0.0083 |
| **Stddev** | 0.0202 | 0.0132 | 0.0408 |
| **Max** | 0.2743 | 0.1619 | 0.7201 |
| **Min** | -0.2051 | -0.2026 | -0.4921 |

Table 2: Data set at station “A” computed using the MBS approach.

| **MBS** | **North [m]** | **East [m]** | **Height [m]** |
|---|---|---|---|
| **Mean** | 0.0009 | -0.0067 | 0.0062 |
| **Stddev** | 0.0153 | 0.0105 | 0.0301 |
| **Max** | 0.1812 | 0.0961 | 0.4115 |
| **Min** | -0.1756 | -0.1048 | -0.3462 |

| **RTK** | **North [m]** | **East [m]** | **Height [m]** |
|---|---|---|---|
| **Mean** | -0.0035 | -0.0047 | -0.0024 |
| **Stddev** | 0.0180 | 0.0113 | 0.0372 |
| **Max** | 0.1604 | 0.1371 | 0.5574 |
| **Min** | -0.1982 | -0.1079 | -0.3611 |

Table 3: Data set at station “B” computed using MBS and the closest reference receiver only.

| MBS | North [m] | East [m] | Height [m] |
|---|---|---|---|
| **Mean** | -0.0402 | -0.0041 | 0.0024 |
| **Stddev** | 0.0131 | 0.0086 | 0.0262 |
| **Max** | 0.1177 | 0.0600 | 0.3600 |
| **Min** | -0.1067 | -0.0900 | -0.2334 |

| RTK | North [m] | East [m] | Height [m] |
|---|---|---|---|
| **Mean** | -0.0100 | -0.0036 | -0.0574 |
| **Stddev** | 0.0572 | 0.0195 | 0.0776 |
| **Max** | 0.1270 | 0.1036 | 0.2854 |
| **Min** | -0.3757 | -0.1420 | -0.6741 |

Table 4: Data set at station “C” computed using MBS and the closest reference receiver only.

Regarding coordinate accuracy and precision, these solutions seem very comparable.

For a 12km baseline the standard RTK approach experienced some difficulties while fixing the ambiguities. These difficulties were not present in the MBS solution. MBS solutions computed in station “A”. This gave only slightly worse precision than in the 7km and 12km cases.

All data sets computed with MBS correction data had 95% of the true errors within 4cm horizontally and 8cm vertically.

### 3.4 Autocorrelation

Autocorrelation was computed using the well known formula:

$$R(\tau) = \frac{1}{T - \tau} \sum_{k=0}^{T-\tau} x_k x_{k-\tau}$$

Figure 12 shows the one-sided plots of the estimated autocorrelation for the north coordinate of the MBS solution and a standard RTK solution for the same data sets collected at stations “B” and “C”. The MBS solution is seen to decorrelate significantly slower than the standard RTK solution. The same trend is present in the east and vertical components (not shown here).

Insufficient parametrization of the various error sources will introduce biases, and it is belived that these biases decorrelate relatively slowly compared to the differential errors in a single reference receiver approach.

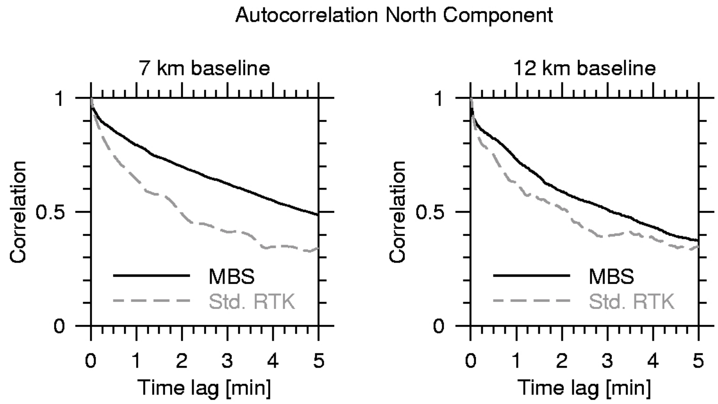

Figure 12: Estimated autocorrelation for the MBS solution and the standard RTK single reference receiver solution for 7km and 12km baselines.

## 4. DISCUSSION

Network solutions will probably be promoted in the geomatics community and might be used for cadastral surveying etc. The end-users will have coordinates, and typically the standard deviations as the only on-line quality measure. Users also tend toward averaging the solutions over say a 1 minute period. If the autocorrleation is not handled properly, this will lead to a serious under-estimation of the reliability measures of the averaged position.

In addition to an under-estimation of the inner reliability due to the unmodelled autocorrelation, the situation is further complicated by the slowly varying biases in the computed coordinates.

In Norway the national standard for cadastral surveying (see Statens Kartverk (2002)) uses external reliability as a measure of coordinate quality. The standard requires that statistical outlier detection shall be carried out, the quality of the outlier detection shall be quatified in terms of internal reliability and the effect of any undetected errors shall be quatified in terms of external reliability.

The applied theory requires the observation’s weight matrix to be known, and for simplicity the observations are often (erroneously) assumed to be independent. A proper handling of strongly correlated data is necessary if external reliability is to be a representative measure of coordinate quality.

## 5. CONCLUSIONS

A bilinear interpolation as implemented in the Trimble Terrasat software seems to give a reasonably good approximation of the errors during quiet ionospheric conditions.
This investigation confirms the results of similar investigations, leaving the MBS RTK as a promising technique for many applications.

Since modelling the autocorrelations may turn out to be quite difficult, special care should be taken in order to minimize the effects of the highly correlated observations.

## 6. FURTHER WORK

The “single outlier”-situation is not appropriate for realistic outlier detection in GPS RTK measured coordinates, as the observations are highly correlated in the time domain. The situation is further worsened in the case of erroneuously fixed ambiguities, where the outliers also will be highly correlated.

## ACKNOWLEDGMENTS

This work was carried out in cooperation with the company Bravida Geomatikk, and their help is much appreciated. The author wish to thank mr. Lev Rapoport at Topcon Moscow for making the RTK engine available for post processing.

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## BIOGRAPHICAL NOTES

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