# Quality of Virtual Data Generated from the GNSS Reference Station Network

**Pasi HÄKLI, Finland**

**Key words**: Network RTK, Virtual Reference Station, virtual data, post-processing GPS

## SUMMARY

VRS (Virtual Reference Station) approach is based on the virtual data and it is the basis for all computation at the user end. Since the quality of virtual data is the backbone to the results, FGI decided to investigate the quality of virtual data.

Study was implemented by computing zero-baselines between virtual and "real" GPS data at the locations of stations of the Finnish permanent GPS network, FinnRef®. Both long-term and short-term variations of the virtual data were studied. Long-term quality was studied by computing time series of daily static solutions. Computed time series show that the quality of virtual data is quite homogeneous. With daily static solutions standard deviations are in the range of few millimetres for all stations and coordinate components. From daily time series we can also conclude that the accuracy is highly dependent on the coordinates of the VRS network since a clear change in trends was seen after the update of the coordinates.

Short-term quality was studied by computing short static and kinematic sessions with virtual data. Hourly and kinematic time series show more details than daily solutions and some daily periods are seen. Periodicity may indicate either to remaining biases in the network parameter estimation or unsuccessful baseline processing. Latter may be caused by poor satellite constellation or bad data quality. Kinematic solutions give a picture of the accuracy that could be expected in real-time surveys.

Spatial quality of virtual data was studied both regionally and locally. The study showed that the reference station coordinates are in a key role to good results. However, e.g. land uplift causes problems and time series show a good correlation between land uplift rates computed from the national permanent GPS network and from the virtual data. Hence it is evident that biases in the reference coordinates (or frames) explicitly affect the virtual data quality. Also increasing interpolation distance i.e. distance from the master station contributes the error budget.

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## 1. BACKGROUND

Nowadays permanent GNSS reference station networks are widely used also for real-time GNSS positioning. Reference stations are integrated at the computing centre and the data is processed in real-time i.e. stations are networked. Networking gives possibility to estimate biases within the network baselines and to transmit bias information to the rover receiver in real-time. This technique is referred to network RTK.

There are different approaches to generate and transmit the information to the rover. One approach is VRS (Virtual Reference Station) in which so-called virtual data is transmitted to the rover receiver. Virtual data is generated from the master reference station data by displacing it geometrically to VRS (~ rover) position and adding associated biases, interpolated from the network, into it. In this approach the rover receiver considers virtual data as a reference station data and computation at the rover end is performed relative to that. In VRS approach virtual data is the basis for all computation at the rover end. Therefore all results are dependent on the quality of virtual data. Thus all biases in the virtual data will also prejudice the results. The purpose of this study was to determine the quality of virtual data i.e. the success of bias estimation.

Finnish Geodetic Institute (FGI) has studied VRS approach since 2002 and main interest has been in real-time applications. Results from real-time studies has been published e.g. in (Häkli, 2004) and (Häkli and Koivula, 2004). During the last few years the spectrum of network RTK applications has spread from conventional mapping to various specific applications. Since the quality of virtual data is the backbone to the results and eagerness to use virtual data has increased also for post-processing applications, FGI decided to investigate the quality of virtual data. Network RTK and virtual data have blurred the traditional hierarchical networks (Häkli and Koivula, 2005) (Häkli et al., 2006) and brought new challenges for computing and qualifying the results. Traceability of the results and the knowledge of the error budget may be missing. Break of the mathematical link between user and computation centre or point-to-point kind of measurements (one vector) disable the possibility to estimate error accumulation. This along with inadequate or strict regulations may prevent the use of such techniques. For example recommendations or regulations in Finland do not recognize network RTK at the moment and therefore many applications are not possible to use. Therefore studies are required if new techniques are desired to mobilise.

## 2. TEST PROCEDURE

Virtual data was investigated by computing zero-baselines between virtual and “real” GPS data at the known locations. Virtual data was generated from the data of the VRS network, GPSNet.fi. It consists of 86 permanent GPS stations covering the whole Finland. The virtual data was generated to the coordinates of the Finnish permanent GPS network, FinnRef®. FinnRef network consists of 13 permanent GPS stations and serves as the basis of the EUREF-FIN, national realization of ETRS89 in Finland (Ollikainen et al., 2000). One IGS and four EPN stations in the network also connects Finland to the international reference frames. Official EUREF-FIN coordinates of the FinnRef stations were used as a reference in virtual data generation. GPSNet.fi network coordinates were computed with respect to FinnRef but otherwise the networks are totally detached to each other. This ensures independent zero-baseline results.

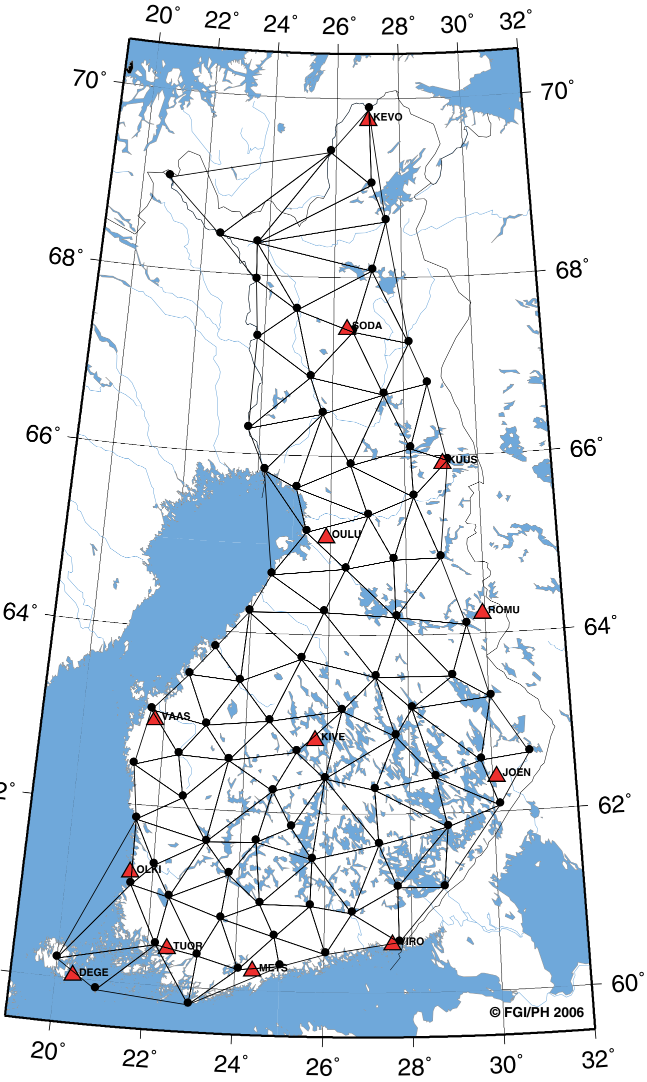

**Figure 1.** GPSNet.fi (VRS) network and zero-baseline stations at the locations of FinnRef stations. GPSNet.fi stations drawn with circles and FinnRef stations with triangles.

Zero-baselines were processed with Trimble Total Control (version 2.73) with ordinary processing parameters. Reference coordinates were fixed to the official EUREF-FIN coordinates of the FinnRef stations. Results were then converted into ETRS-TM35FIN coordinates on the UTM projection plane according to the national recommendations (JHS 154). All the values presented here are in ETRS-TM35FIN.

Both long-term and short-term variations of the virtual data were studied. Long-term quality was studied by computing time series of daily static solutions over a period of three months. It illustrates the reliability of the virtual data generation and attainable (optimum) accuracy e.g. for post-processing applications. Short-term quality was studied by computing short static and kinematic sessions with virtual data. This depicts e.g. temporal variations of results that can be expected in real-time positioning. Spatial quality of virtual data was studied both regionally and locally. Regional quality was studied by choosing zero-baseline stations nationwide and local variations with the distances to master station.

## 3. TIME SERIES OF VIRTUAL DATA

### 3.1 Daily solutions

Since there is no indication of quality of virtual data transmitted to user it is necessary to investigate the quality empirically. From long-term daily results we can get statistical analysis and compute e.g. probabilities for accuracy measures. This enables more realistic estimation of the error budget of the final results. For example in post-processing applications where virtual data is used as a reference station we have an additional error compared to conventional static surveying. This is caused by the virtual data itself i.e. biases in the virtual data generation. These biases include atmospheric variations and residuals in the coordinates of the VRS network. From probabilities we can consider to get the constant part of the additional error in the final results. The rest of the error budget comes from the post-processing.

In this study we computed time series of zero-baselines for the period of three months (March-May 2006). Zero-baselines were computed as daily static solutions for all 13 FinnRef stations. Many short-term GPS biases are absorbed or averaged out from the daily solutions hence giving a good picture about the quality of virtual data. Results are shown in North, East and up components and also as baseline distance.

During the time series period happened some major occurrences that have to be taken into account in the analysis of the results. Coordinates of GPSNet.fi were updated during the study period. GPSNet.fi network was finalized in the autumn of 2005 and network coordinates were computed in the beginning of 2006. Two computations were performed with the same basic strategy but slightly different processing and adjustment parameters and methods were applied. Also different data sets were used. In both computations FinnRef network served as a reference. It was decided after some discussions to force the VRS network to the official EUREF-FIN coordinates of the FinnRef stations even though their epoch is in 1997.0. This would cause residuals e.g. due to postglacial rebound (see e.g. Mäkinen et al., 2003) in the final coordinates but this way they would be as close as possible to the EUREF-FIN frame. Another cogent reason to use EUREF-FIN coordinates instead of ITRF was that the geodynamical model needed for the backward transformation to EUREF-FIN was not available. Geodynamical model would take into account e.g. the effects of the land uplift. Such a model should be available for Fennoscandia in the near future. At that time the computation strategy can be reconsidered.

Coordinates from the first computation were in use until DOY 89 (March 30, 2006). However, new coordinates were introduced after the completion of the second computation and they have been valid since DOY 90 (March 31, 2006). Changes in coordinates were relatively small (approximately 5 mm) but even though the update of coordinates is clearly seen in time series at some stations. Consequences of the update for the time series are twofold. On one hand the accuracy has improved but on the other hand the precision has deteriorated. By accuracy we mean absolute or external accuracy while precision describes internal accuracy. However, changes in time series can be seen only at some stations and positive effects of the coordinate update overbalance the negative ones. Figures 2 and 3 show examples of both cases. At the station OULU accuracy has improved whereas precision (also accuracy in this case) in time series of KEVO has deteriorated. Anyhow, it seems that the quality of virtual data is quite sensitive to the precision of the VRS network.

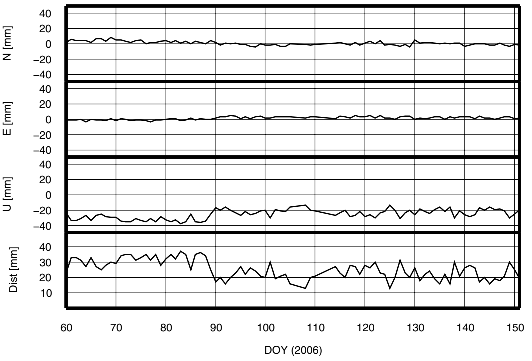

**Figure 2.** Zero-baseline time series of the station OULU. Accuracy is improved after coordinate update at DOY 90.

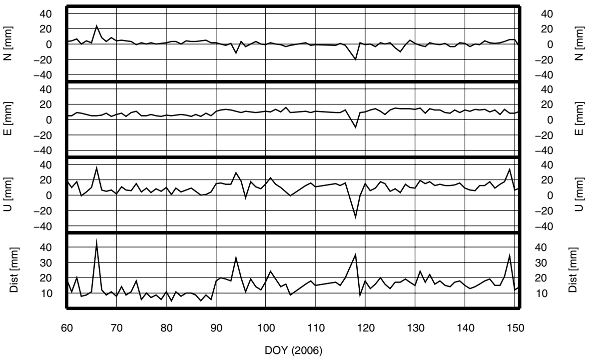

**Figure 3.** Zero-baseline time series of the station KEVO. Precision has deteriorated since the coordinate update at DOY 90.

A change in time series trend can be seen also at METS station. It is related to the coordinate update albeit it fixes a bug in the GPS processing software. Misinterpretation of the antenna caused a systematic error of 11 mm in up component. The bug causes a jump in time series at DOY 90 (Figure 4). Other phenomena related to update of coordinates are yet unanalyzed. Also seasonal effects in time series are visible. The bigger jumps at the stations ROMU (Figure 5) and SODA (Figure 13) shortly after DOY 70 are most likely caused by snow dropping from the top of the antenna radome. The phenomenon was discussed by Mäkinen et al., 2003. This is an annual effect at some stations with adequate conditions for snow accumulation.

Because of the coordinate update and seasonal phenomena we will concentrate only on the data since DOY 90. Time series show good repeatability at all stations (Table 1). Daily solutions deviate on an average of 2.0 mm, 1.7 mm and 4.4 mm for north, east and up components, respectively. Accuracies (by means of rms) are worse, especially in up component. Part of this is explained by the residuals in the reference station coordinates and part is due to interpolation errors during the virtual data generation. Both influence mainly on the up component. The average rms of the time series is 3.1 mm for north, 4.4 mm for east and 15.3 mm for up component.

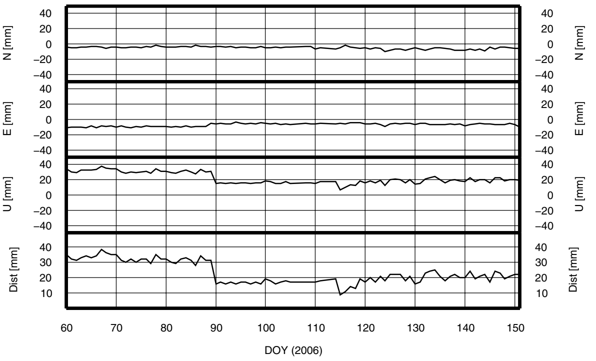

**Figure 4.** A jump in METS time series at DOY 90 is caused by a misinterpretation of the antenna in data processing.

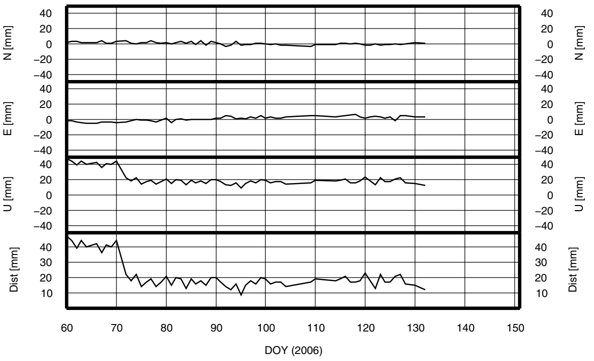

**Figure 5.** Seasonal effect on time series at ROMU station. Accumulated snow drops off from top of the antenna radome shortly after DOY 70.

**Table 1.** Accuracies and deviations of the time series of the daily static solutions.

| Station | rms (mm) | | | std (mm) | | |
|---|---|---|---|---|---|---|
| | N | E | U | N | E | U |
| DEGE | 2.4 | 4.0 | 14.0 | 2.4 | 1.7 | 6.8 |
| JOEN | 3.3 | 1.7 | 11.6 | 2.8 | 1.7 | 5.8 |
| KEVO | 4.2 | 11.3 | 14.2 | 4.2 | 3.5 | 8.2 |
| KIVE | 1.9 | 4.9 | 7.9 | 2.0 | 2.2 | 4.3 |
| KUUS | 3.8 | 6.4 | 2.9 | 2.9 | 3.1 | 2.9 |
| METS | 5.8 | 6.1 | 17.4 | 1.8 | 1.2 | 3.1 |
| OLKI | 3.8 | 1.8 | 21.7 | 1.2 | 1.3 | 4.9 |
| OULU | 2.0 | 2.8 | 22.5 | 1.9 | 1.2 | 4.5 |
| ROMU | 1.5 | 3.5 | 17.3 | 1.5 | 1.6 | 3.1 |
| SODA | 1.8 | 4.7 | 9.6 | 0.7 | 0.9 | 2.7 |
| TUOR | 2.7 | 2.6 | 3.2 | 1.4 | 1.6 | 3.1 |
| VAAS | 5.2 | 3.6 | 35.9 | 1.7 | 1.6 | 4.4 |
| VIRO | 2.3 | 4.2 | 20.6 | 1.3 | 1.1 | 2.7 |
| **average** | **3.1** | **4.4** | **15.3** | **2.0** | **1.7** | **4.4** |

Small deviation reflects to successful estimation of station parameters (e.g. atmosphere) at the network stations since the virtual data seems to be homogeneous of quality. However, the deviation has increased at some stations since the update of the network coordinates. It is thus evident that precision of the network has an explicit influence on repeatability.

Large rms of the results indicates to remaining systematic errors that are most likely composed of the imprecise reference coordinates and interpolation errors. Additionally, the results may include other systematically ill-modelled effects e.g. ionosphere, troposphere, etc. Influences of separate factors are difficult to estimate without further studies and information. However, already a short time series illustrate that the network coordinates are in a key role. As the time series are still short, no further analysis is done yet. Also probabilities and other statistical parameters of virtual data are too early to comprise.

### 3.2 Hourly and kinematic solutions

Short-term quality of virtual data was studied by computing zero-baselines from short static and kinematic sessions at FinnRef stations. One week of data (GPS week 1373, DOY 120-126/2006) was processed with 30-second interval for both tests. Hourly static solutions were to give information about sub-daily variations while kinematic solutions were to reflect instantaneous quality to be expected in real-time surveying. Sub-daily variations are caused by e.g. changing tropospheric and ionospheric activity and satellite constellation. Thus they reflect the success of network parameter estimation. If variation has daily or semi-daily cycles they may arise from either changing constellation or tidal related effects though also ionospheric activity have a cyclic nature.

Periodicity of time series was not yet analyzed by any mathematical method. However, some stations show nice and apparent periodicity in time series. Even hourly solutions show periodicity at some stations though the signal is much weaker than in the time series of kinematic solutions. Periodicity is stronger and more detailed seen in kinematic solutions even if the noise is bigger. Figures 6 and 7 introduce the time series of hourly and kinematic solutions at KIVE station, respectively.

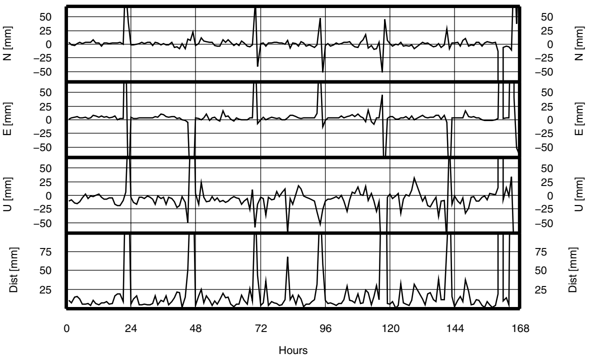

**Figure 6.** Time series of the hourly solutions at KIVE station. Periodicity as peaks is visible at the end of each day.

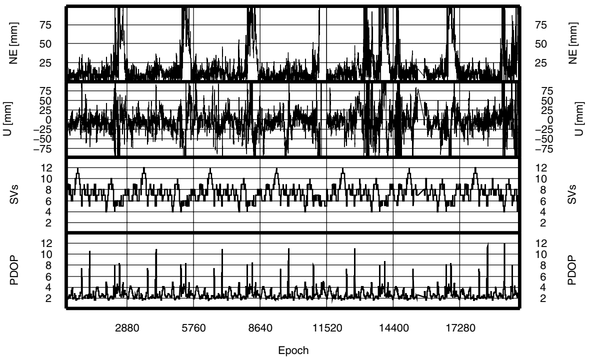

**Figure 7.** Time series of the kinematic solutions at KIVE station. Same periodicity as in hourly solutions is seen but with more details.

With hourly solutions periodicity seems to be a matter of satellite constellation since the peaks are clear when constellation is poor for a longer while. It is obvious and seen also from the standard deviations of the solutions that during such periods baseline solution is also weaker even if hourly data should be sufficient enough for reliable baseline solutions (since our baselines are very short). Time series of KEVO has many unsuccessful hourly solutions (see Figure 8) while daily solutions show no significant deviation (cf. DOYs 120-126 in Figure 3). However, also many kinematic solutions are deteriorated (Figure 9). Weak solutions may be caused either by unsuccessful processing or bad data quality or both. However, it is difficult to distinct the cause. Further analysis for the data and e.g. atmospheric factors are to be done later. Also periodicity of the kinematic solutions will be studied in more details later. Tables 2 and 3 summarize the time series of the hourly and kinematic solutions.

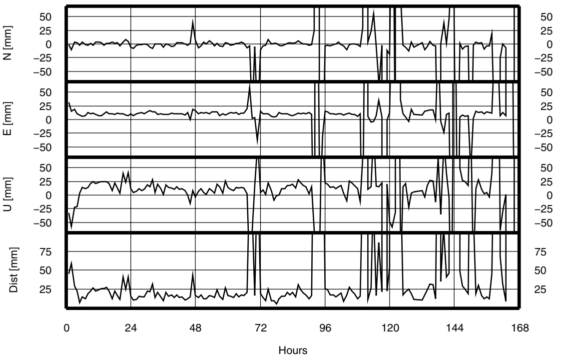

**Figure 8.** Time series of the hourly solutions at KEVO station with many unsuccessful solutions.

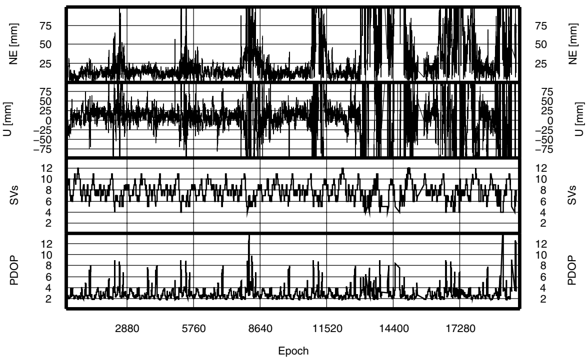

**Figure 9.** Time series of the kinematic solutions at KEVO station. Similar solutions of bad quality as in hourly time series are seen.

**Table 2.** Accuracies and standard deviations (gross errors excluded) of the time series of the hourly solutions.

| Station | rms (mm) | | | std (mm) | | |
|---|---|---|---|---|---|---|
| | N | E | U | N | E | U |
| DEGE | 7.0 | 6.2 | 22.0 | 7.0 | 4.8 | 14.2 |
| JOEN | 8.0 | 4.4 | 20.0 | 7.9 | 4.3 | 16.4 |
| KEVO | 26.1 | 24.0 | 32.7 | 26.1 | 21.3 | 31.2 |
| KIVE | 10.8 | 8.2 | 21.8 | 10.8 | 7.4 | 20.6 |
| KUUS | 3.4 | 5.1 | 7.0 | 2.7 | 2.4 | 6.9 |
| METS | 7.7 | 6.0 | 19.5 | 4.8 | 2.6 | 9.1 |
| OLKI | 4.6 | 2.6 | 24.0 | 2.9 | 1.6 | 6.5 |
| OULU | 4.1 | 4.7 | 24.1 | 4.1 | 4.0 | 10.7 |
| ROMU | 4.5 | 5.1 | 20.3 | 4.5 | 3.6 | 11.5 |
| SODA | 2.5 | 4.8 | 10.4 | 1.8 | 1.6 | 5.2 |
| TUOR | 3.7 | 2.7 | 7.5 | 3.0 | 1.8 | 7.3 |
| VAAS | 6.5 | 4.0 | 37.2 | 4.2 | 2.8 | 8.9 |
| VIRO | 3.8 | 4.3 | 20.6 | 2.9 | 2.1 | 5.4 |
| **average** | **7.1** | **6.3** | **20.5** | **6.4** | **4.6** | **11.8** |

**Table 3.** Accuracies and standard deviations (gross errors excluded) of the time series of the kinematic solutions.

| Station | rms (mm) | | | std (mm) | | |
|---|---|---|---|---|---|---|
| | N | E | U | N | E | U |
| DEGE | 15.0 | 10.1 | 31.4 | 15.0 | 8.8 | 27.6 |
| JOEN | 20.7 | 11.5 | 34.9 | 20.7 | 11.4 | 33.1 |
| KEVO | 22.2 | 21.5 | 57.1 | 22.2 | 19.1 | 56.4 |
| KIVE | 19.2 | 12.5 | 32.0 | 19.2 | 11.7 | 31.5 |
| KUUS | 8.6 | 7.2 | 19.2 | 8.5 | 5.5 | 19.2 |
| METS | 11.6 | 8.4 | 23.0 | 9.6 | 5.1 | 17.6 |
| OLKI | 9.4 | 5.4 | 30.0 | 8.9 | 4.8 | 17.2 |
| OULU | 13.5 | 9.1 | 38.8 | 13.5 | 8.6 | 30.9 |
| ROMU | 13.4 | 8.8 | 33.7 | 13.4 | 8.3 | 29.0 |
| SODA | 8.7 | 7.3 | 19.5 | 8.4 | 5.3 | 17.7 |
| TUOR | 9.3 | 5.5 | 17.4 | 9.0 | 5.1 | 17.4 |
| VAAS | 10.9 | 6.8 | 40.8 | 9.6 | 6.1 | 20.5 |
| VIRO | 7.8 | 5.7 | 23.9 | 7.3 | 3.8 | 12.1 |
| **average** | **13.1** | **9.2** | **30.9** | **12.7** | **8.0** | **25.4** |

## 4. SPATIAL QUALITY OF VIRTUAL DATA

Spatial quality of virtual data was studied on a regional and local scale. Regional quality was to qualify the results nationwide while local quality studies interpolation errors.

### 4.1 Regional quality

The need for a study of regional quality came up with the analysis of the daily time series where a clear effect was seen after the update of GPSNet.fi network coordinates. The coordinates were forced to EUREF-FIN frame even if a well-known land uplift phenomenon has deformed the crust in Finland since the reference epoch (1997.0) of EUREF-FIN. Seeing that the effect of land uplift and interpolation of network parameters is mainly going to up component we concentrate in heights.

As a first stage we took average of time series for up component at each station. Mean values are drawn and contoured in Figure 10. Mean values were first computed related to METS station and then converted into absolute land uplift values. They were compared to the latest uplift rates published in Koivula, 2006. Figure 11 show the land uplift map corresponding to those rates and Table 4 gives the absolute land uplift rates determined with both methods. As we can see the isobars fit quite nicely with an exception at VIRO station. VIRO seem to differ from all the other stations significantly. Further analysis on this is required. However, by excluding VIRO station from the results at this stage and fitting a regression line through the uplift rates computed from FinnRef and virtual data, we get a nice correlated data set (see figure 12). R-squared for this line (0.794) is surprisingly high. Hence it is obvious that virtual data describes explicitly possible deformations in reference frames or accurateness of VRS network via network coordinates. In Finland biased adjustment method in the computation of GPSNet.fi network coordinates was a compromise that require further discussion in the future. The dilemma of land uplift is well known in Fennoscandia and it is at high priority e.g. within NKG (Nordic Geodetic Commission) community. In the near future there should be the first geodynamical model available that should produce better results.

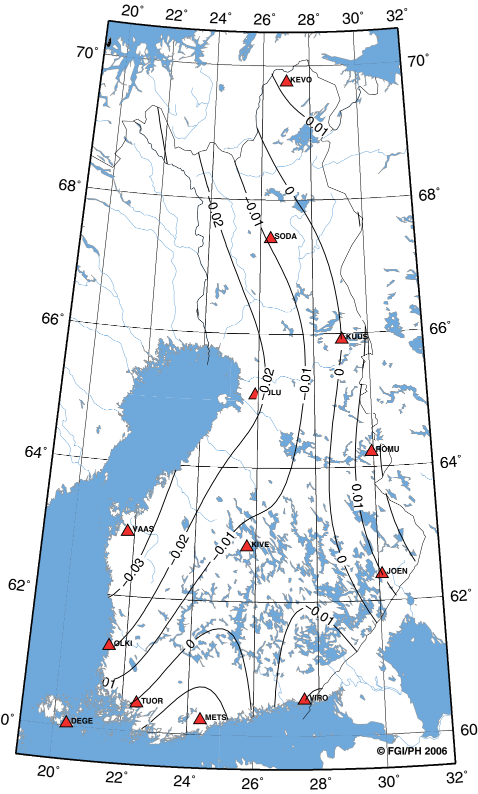

**Figure 10.** Regional accuracy of virtual data for up component.

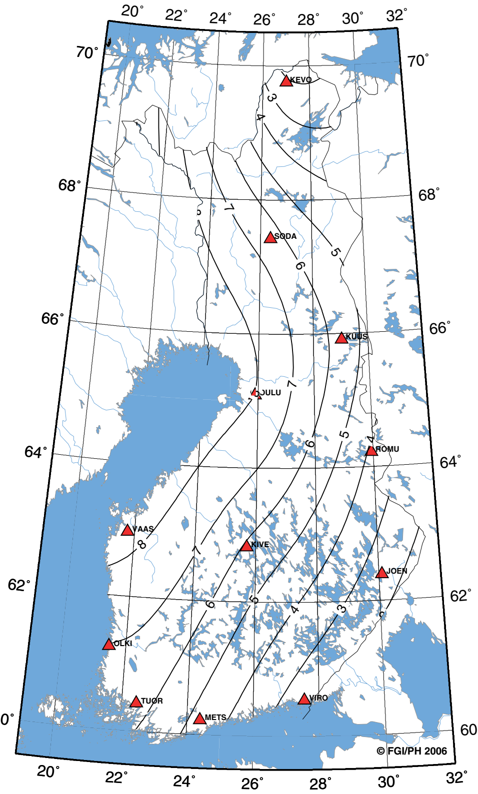

**Figure 11.** Land uplift computed from FinnRef time series. Contours drawn according to uplift rates published in Koivula, 2006.

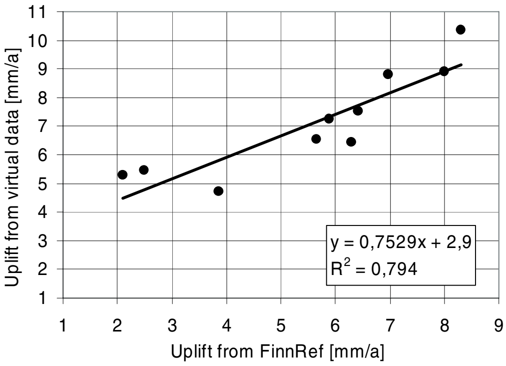

**Figure 12.** Correlation between land uplift rates computed from FinnRef (Koivula, 2006) and virtual data. VIRO station excluded from the fit.

**Table 4.** Absolute land uplift (AL) rates computed from FinnRef and virtual data. Table gives also mean up component (ΔU) of the zero-baseline time series.

| Station | FinnRef | Virtual data | |
|---|---|---|---|
| | AL (mm/a) | ΔU (mm) | AL (mm/a) |
| DEGE | n/a | 12.30 | 5.21 |
| JOEN | 2.49 | 10.09 | 5.45 |
| KEVO | 2.11 | 11.57 | 5.29 |
| KIVE | 5.89 | -6.62 | 7.24 |
| KUUS | 5.66 | 0.02 | 6.53 |
| METS | 4.69 | 17.14 | 4.69 |
| OLKI | 6.97 | -21.17 | 8.80 |
| OULU | 8.00 | -22.11 | 8.90 |
| ROMU | 3.86 | 17.00 | 4.71 |
| SODA | 6.43 | -9.19 | 7.52 |
| TUOR | 6.30 | 0.74 | 6.45 |
| VAAS | 8.30 | -35.61 | 10.35 |
| VIRO | 2.46 | -20.40 | 8.72 |

### 4.2 Local quality

As we saw the time series results differed quite much between the stations. Standard deviations of daily solutions for up component varied from 2.7 mm to 8.2 mm between stations. The scatter in accuracy was even bigger. Part of the accuracy obviously results from the coordinates of the VRS network but some part could be allocated to the interpolation biases. Since we found clear evidence that the network coordinates influence on the accuracy we came to a conclusion that standard deviation (=precision) could better reflect the success of virtual data generation. Surely the coordinates will affect precision too but mainly its effect is systematic of nature. Another problem with accuracies is that it is very difficult to distinct which part comes from the precision of the VRS network and which part from the interpolation during the virtual data generation. Hence we concentrate on standard deviations.

If we look at the standard deviations and distances to master station we find a connection. If a station is close to the master station the deviation seems to be smaller than at those stations further away. The effect is seen both in daily and hourly solutions. Figures 13-16 illustrate the daily and hourly time series at the closest and furthermost stations from the master station. Figure 17 shows the connection for all stations but KEVO. KEVO is the northernmost station and at the edge of the network. Daily solutions show that there was a clear change in trend after coordinate update of the VRS network that has to be studied further. Also hourly solutions indicate that there might be poor data or some other problems. Therefore we excluded KEVO from the study. We fitted a regression line through the rest of the data and got a correlation of R=0.745 which clearly shows some connection between the standard deviation and distance to the master station. The correlation is however not so evident than influence of land uplift. Anyhow with the results we can conclude that also interpolation distance has a role in the quality of virtual data.

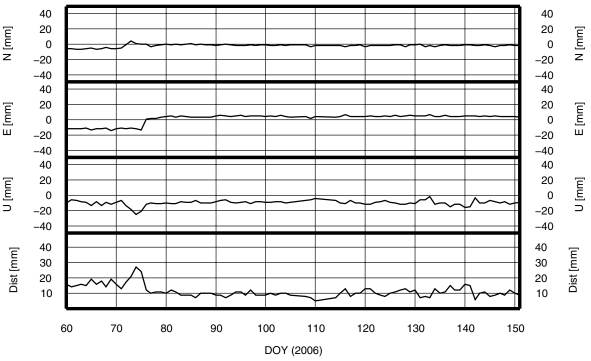

**Figure 13.** Daily solution time series at SODA. SODA is the closest station to master station (8km).

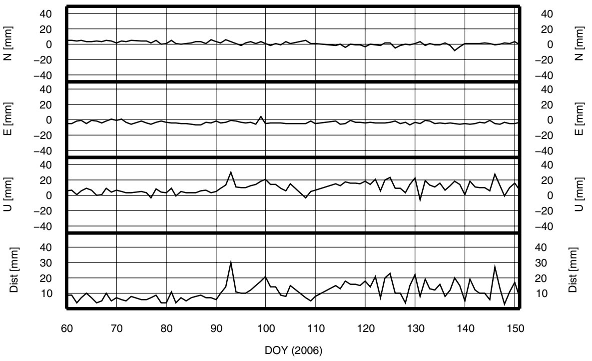

**Figure 14.** Daily solution time series at DEGE. DEGE is the furthermost station from the master station (31km).

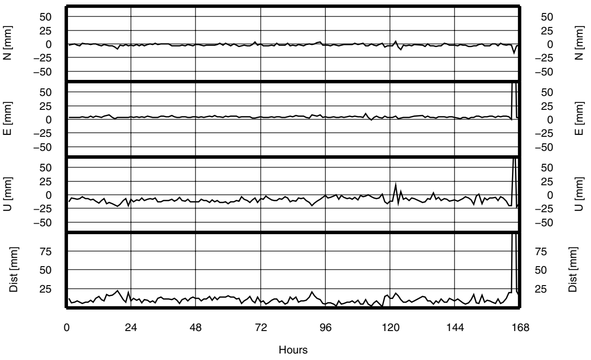

**Figure 15.** Hourly solution time series at SODA. SODA is the closest station to master station (8km).

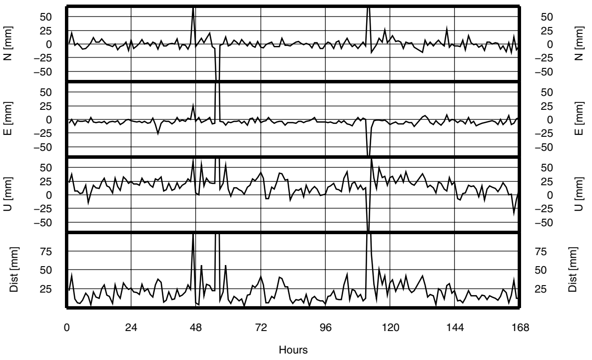

**Figure 16.** Hourly solution time series at DEGE. DEGE is the furthermost station from the master station (31km).

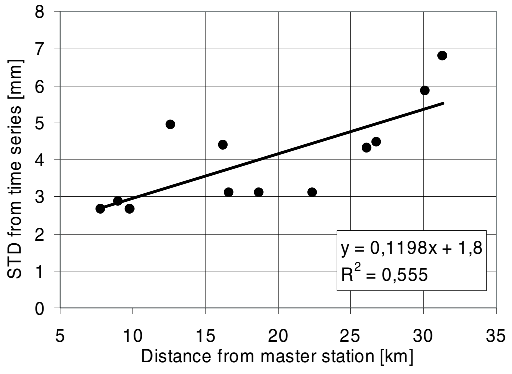

**Figure 17.** Spatial correlation of virtual data. A dependency of standard deviation and distance to master station was found. This indicates to increasing interpolation bias further away from master station.

## 5. CONCLUSIONS AND DISCUSSION

Time series of the zero-baselines show that quality of virtual data is quite homogeneous. With daily static solutions standard deviations are in the range of few millimetres for all stations and coordinate components. From daily solutions we can conclude that the accuracy is highly dependent on the coordinates of the VRS network. Also increasing interpolation distance i.e. distance from the master station contributes the error budget.

Hourly and kinematic solutions show more details in time series. Some daily periods are seen even without any mathematical analysis. These may indicate either to remaining biases in the network parameter estimation or unsuccessful baseline processing. Latter may be caused by poor satellite constellation or bad data quality. Kinematic solutions give a picture of the accuracy that could be expected in real-time surveys.

The study showed that the reference station coordinates are in a key role to good results. However, e.g. land uplift causes problems and time series show a good correlation between land uplift rates computed from the national permanent GPS network and from the virtual data. Hence it is evident that biases in the reference coordinates (or frames) explicitly affect the virtual data quality.

Even a short time series proves the potential of the virtual data. However, more data, further studies and analysis are required on many subjects. Problems in reference frames also require further discussion.

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## CONTACTS

Pasi Häkli
Finnish Geodetic Institute
Department of Geodesy and Geodynamics
PL 15 (Geodeetinrinne 2)
FI-02431 Masala
FINLAND
Tel. +358 9 295550
Fax +358 9 29555200
Email: pasi.hakli@fgi.fi
Web site: http://www.fgi.fi/