GALILEO/Modernized GPS: A New Challenge to Network RTK

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BIOGRAPHY

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Herbert Landau received a Ph.D. in Satellite Geodesy from the University FAF Munich, Germany in 1988. At Trimble he is acting as Managing Director of Trimble Terrasat GmbH, Germany and as Director of the Trimble GPS Algorithms and Infrastructure Software group. He has many years of experience in GPS and has been involved in a large variety of GPS and GLONASS developments. His professional interest is focused on high-precision real-time kinematic positioning and reference station network processing.

Timo Allison graduated from Leeds University with B.Sc. and Ph.D. degrees in Electrical & Electronic Engineering. He has been involved in GPS survey receiver development at Trimble Navigation since 1986, and with RTK systems since 1994. Currently, he works for the Trimble GPS Algorithms and Infrastructure Software group on precise positioning systems.

ABSTRACT

Network RTK in local or regional reference networks has been proven as an efficient technology for high accuracy GPS positioning over the last few years. Comparing with single base RTK, the advantage of network RTK is that large portions of ionospheric and geometric errors are removed through network corrections. Hence network solutions increase the reliability and productivity of ambiguity resolution and the positioning accuracy of rovers working in the system.

Several preliminary studies have demonstrated that with the third/fourth frequency available from GALILEO and modernized GPS, the reliability and productivity of single base OTF (on the fly) initializations at the rover increase dramatically when comparing with a dual frequency RTK system. So, the question arises: will network RTK become obsolete when GALILEO and modernized GPS are operational because of the high performance of single base RTK? What can network RTK benefit from GALILEO and modernized GPS?

It is a well-known fact that the initialization performance of an RTK system decreases significantly with higher ionospheric activity. Furthermore, the geometric errors (including troposphere and orbit), which are not frequency-dependent, will not be removed by adding more frequencies. In other words, positioning accuracy will be improved only marginally by mitigating multipath

due to the availability of more observables. This paper demonstrates two and three carrier RTK performance in various single-base and network scenarios. Simulation studies show that in the presence of a reference station network, RTK initialization and positioning accuracy are improved considerably.

INTRODUCTION

GPS is currently experiencing a major modernization step. The first satellites with a civil code on L2 are scheduled to be launched in 2005 and the first satellites supporting the third frequency L5 will be in orbit after 2006. While the US is working on the modernization of GPS the European Union together with the European Space Agency ESA are working with partnering countries on the development of a new satellite system GALILEO. GALILEO is scheduled to be in orbit after 2008. With the availability of a third frequency L5 for GPS and additional GALILEO satellites we can expect considerable improvements in centimeter accurate RTK positioning. A number of authors have published simulation results to verify the benefit of the availability of a third frequency and GALILEO satellites, e.g. *Werner, Winkel (2003), Zhang et al. (2003), Julien et al. (2004), Sauer et al. (2004).* Rather than concentrating on single base line performance only, this paper will focus on the question of whether Network RTK is still required in times of modernized GPS and GALILEO.

DATA SIMULATION

In contrast to earlier publications in which we had used data from a hardware simulator (*Vollath & Roy, 2001, Vollath et al. 2003*, *Sauer et al., 2004 and Chen et al., 2004*) we used a software simulator to generate the code and carrier data for a 28 satellite GPS configuration and a 27 satellite GALILEO constellation for this paper. Based on these constellations 1 Hz raw pseudorange and carrier phase data were generated for a time period of 6 hours during daytime to ensure high ionospheric effects in L1, L2, L5 for a GPS and a GALILEO constellation. The impact of the different frequencies GALILEO uses is not studied here. Error sources like noise, multipath, tropospheric, ionospheric and orbital effects were simulated in a way that the generated data should be as realistic as possible.

SOFTWARE SIMULATOR

A software simulator was developed at Trimble to support a variety of developmental and QA testing roles. It is particularly valuable for both RTK receiver firmware and Network processing development in which the ambiguity resolution process is critical to system performance. The data from an entire network is simulated simultaneously to provide data files for post processing. For this study, the noise parameters given below are of key interest, and care was taken to provide a realistic simulation by comparison with GPS data from a variety of short baselines that can be assumed free of significant ionospheric errors. These provided an indication of typical multipath (correlated) error while GPS zero-baseline data was used to set the Gaussian (uncorrelated) noise levels. Independent noise streams are generated for each station, satellite and frequency. Noise seeds are set to ensure repeatability between test runs.

SIMULATION NETWORKS

Data was generated for stations in three different networks with different inter-station distances varying from 50 km to 120 km (Figure 1). For the network stations a subset of the German BLVA network stations was chosen. Each of the three different networks used in this study comprises one central network station and 5 or 6 surrounding network stations. The surrounding network stations were chosen such that the distance to the central network station and between neighboring stations is close to 50km, 90km and 120km. The corresponding networks will be denoted VRS 50km, VRS 90km and VRS 120km. These three different network sizes can be considered as normal (i.e. at present widely in use), large and very large. Rover data was generated at distances from the central reference station from 2.5 to 65 km, spaced at 2.5km.

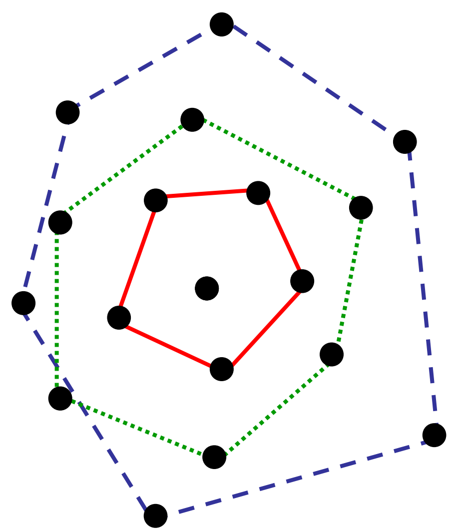

Figure 1: Simulation networks.

NOISE

For the network stations as well as for the rovers a constant Gaussian noise for code and carrier data was simulated. No elevation dependent Gaussian noise was included (Table 1).

MULTIPATH

Multipath on code and carrier was simulated using a first order Gauss-Markov process elevation dependent model (multipath noise proportional to 1/sin(elevation)). The model is switched to a linear model below an elevation of 5°. The noise values at 90° elevation and the respective time correlation coefficients for code and carrier are shown in Table 1.

	code	carrier
Gaussian noise	0.125m	0.003 cycles
multipath noise	0.1m	0.00425 cycles
time correlation	20s	50s

Table 1: Noise values and time correlation coefficients.

TROPOSPHERIC EFFECTS

Tropospheric effects were simulated by applying a zenith effect scale, which is typical for network areas as the one used for the simulation. The values used for the scale effect are given in

Table 2 . We find these kind of variations on the tropospheric scale routinely in the networks we operate with the Trimble GPSNet™ software. The tropospheric model used was the modified Hopfield model with standard meteorological conditions (20°C, 50% relative humidity, 1013 mb).

Ansbach	1.031	Aschau	1.040
Auerbach	1.052	Augsburg	1.040
Eichstaett	1.047	Freilassing	1.038
Garmisch	1.038	Guenzburg	1.035
Kelheim	1.040	Landshut	1.049
Mindelheim	1.030	Muenchen	1.031
Neumarkt	1.039	Noerdlingen	1.036
Pfaffenhofen	1.041	Straubing	1.045
Toelz	1.030	Wettzell	1.054

Table 2: Tropospheric scaling.

IONOSPHERIC EFFECTS

Ionospheric effects were simulated by using an IONEX file for day 349, GPS-week 1197 (15. dec. 2002), which showed exceptionally high ionospheric effects. A day with strong ionospheric activity was chosen to test the RTK performance under a factor of 2-3 higher than average ionosphere. This was done to be able to derive performance data for difficult ionospheric conditions. Since the IONEX file has a resolution of only 2.5° x 5° we added local ionospheric disturbances on top of the IONEX files to generate realistic differential ionospheric effects as we expect them on the baseline distances we analyzed. Typical generated ionospheric differential effects can be seen from Figure 2-Figure 7.

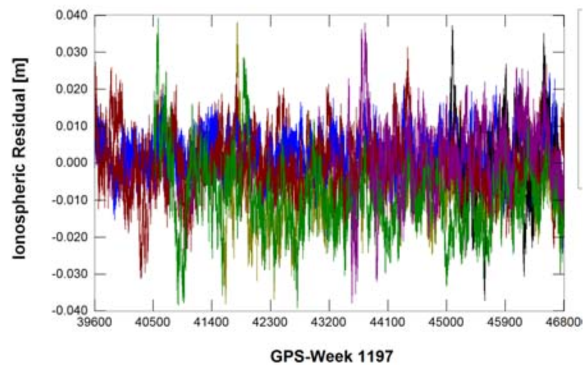

Figure 2: Double differenced ionospheric residual, NO ionosphere, baseline 10km.

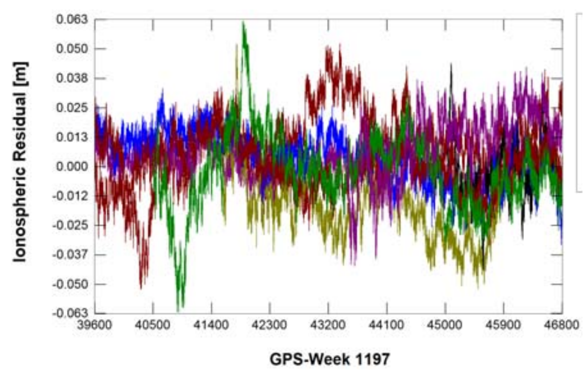

Figure 3: Double differenced ionospheric residual, with ionosphere, baseline 10km.

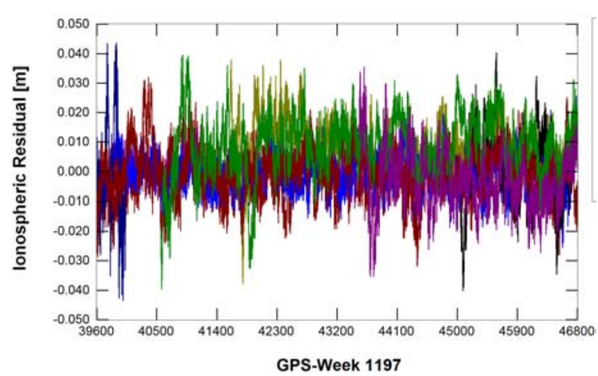

Figure 4: Double differenced ionospheric residual, with ionosphere, after application of VRS, baseline 10km.

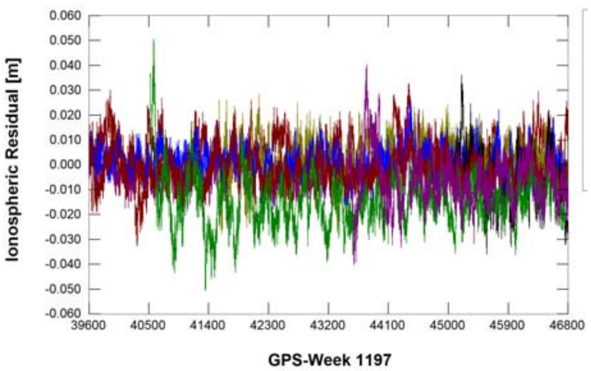

Figure 5: Double differenced ionospheric residual, NO ionosphere, baseline 50km.

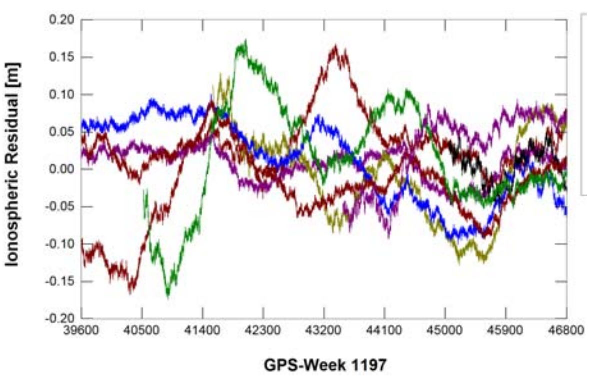

Figure 6: Double differenced ionospheric residual, with ionosphere, baseline 50km.

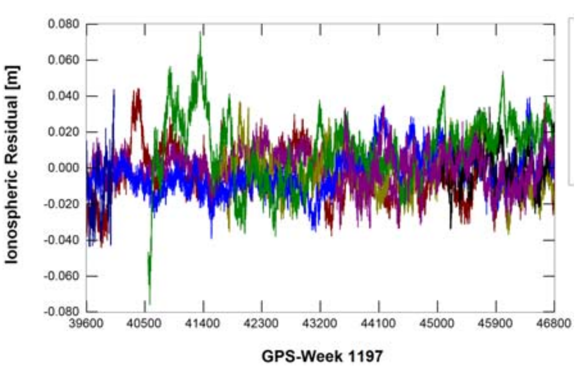

Figure 7: Double differenced ionospheric residual, with ionosphere after application of VRS, baseline 50km.

ORBITAL EFFECTS

Orbit errors were simulated by introducing an artificial satellite clock error of up to 1 msec. The clock error was satellite dependent. This leads to a simulated orbit error of up to a few meters.

PERFORMANCE ANALYSIS

As mentioned above the simulated data was used to analyze RTK performance in the three network configurations and compared with a standard single base RTK solution on various baseline lengths. In the three network solutions we are generating Virtual Reference Station (VRS™) data from the network to serve as a local reference station using our GPSNet™ processor. By generating the VRS data from the three different networks, using a single base as a fourth case and using the identical rover files for the performance analysis we are able to generate four different performance runs (three network solutions plus one single base for each mode). The performance analysis was done for various experiment configurations (

Table 3). This was done to provide insight on the influence of the different network sizes, different satellite constellations and the different number of frequencies.

Satellite Systems	Single Base	VRS 50km	VRS 90 km	VRS 120 km
GPS	2/3	2/3	2/3	2/3
G&G	2/3	2/3	2/3	2/3

Table 3: Experiment configurations.

Each analysis mode included a run with two frequencies and for comparison a second one with three frequencies. For ease of RTK performance analysis a post-processing version of our kinematic processor was used in a special mode. The processor uses the FAMCAR method, which is described by *U. Vollath & K. Sauer (2004).* The software was run through the complete dataset of 6 hours while the start time was increased by 1 second after each successful initialization. After starting at the predefined start time the processor runs until an initial ambiguity fix or an upper runtime threshold is exceeded, then the start time is increased and the processor again runs until it has successfully fixed the ambiguities or exceeded the upper runtime threshold. In that way more than 20.000 runs were generated for each experimental configuration providing a sufficient number of samples for statistical analysis. The focus of the analysis was to derive performance numbers on the following parameters:

- Reliability of the initialization (correctness of the ambiguity fix)

- Time to first fix (TTF)

- Position accuracy (horizontal and vertical RMS)

STATISTICAL SIGNIFICANCE

This section addresses the question of statistical significance of the experiments carried out in this study. Each experiment configuration carried out consists of a series of more than $n = 20000$ sample experiments (which are assumed here as independent of each other although this is not strictly true due to the presence of time correlated influences such as multipath, ionosphere,…).

Although the error probabilities for two different experiment configurations may be different, the estimators may give the same value. On the other hand the error probability for two different experiment configurations may be the same, but the estimators give different values. Nevertheless if the difference between the two estimators is sufficiently large, i.e. the difference is significant, the error probabilities are not likely to be the same.

We want to determine the probability that for two given independent experiments the differences in the determined failure rates are not created by chance, but are statistically significant.

To quantify this we consider here two different experiment configurations with error probabilities p_1 and p_2 and the corresponding error estimators P_1 and P_2:

$$P_i = \frac{F_i}{n_i}$$

with F_i denoting the number of false initializations for trial i with n_i fixing trials as sample size. These can be interpreted as discrete random variables with a Bernoulli (Binomial) distribution. According to ([Spiegel 1975]) the variance of the estimates is:

$$\sigma_{P_i}^2 = \frac{P_i(1-P_i)}{n_i}$$

We have the expectation value and variance for the difference of the estimators $P_1 - P_2$:

$$\mu_{P_1-P_2} = 0$$

$$\sigma_{P_1-P_2}{}^2 = \sigma_{P_i}^2 + \sigma_{P_2}^2 \text{ .}$$

This allows us to define a normalized stochastic variable

$$Z = \frac{P_1-P_2}{\sigma_{P_1-P_2}}$$

with an expectation value of 0 and a standard deviation of 1. The probability density function for Z can be approximated by the standard normal distribution.

For a given confidence interval, a maximum value of Z can be given by inspecting the normal distribution probabilities (Table 4).

Confidence Level	99.73%	95.45%	95%	68.27%
Z_{max}	3.00	2.00	1.96	1.00

Table 4: Confidence Levels and maximum Z

Table 5 gives some numerical examples for a sample size of 20000 used in this study. The first three columns specify the number of wrong fixes and the associated failure and probabilities respectively. The next three columns give the minimum number of wrong fixes F_2 needed for a Z statistics greater than 1.96, i.e. for a probability of at least 95 % that the two experiments differ significantly.

F_1	P_1 [%]	Reliability [%]	F_2	P_2 [%]	Reliability [%]
0	0.0	100	4	0.02	99.98
1	0.005	99.995	7	0.035	99.965
2	0.01	99.99	9	0.045	99.955
3	0.015	99.985	11	0.055	99.945
4	0.02	99.98	12	0.06	99.94
5	0.025	99.975	14	0.07	99.93
6	0.03	99.97	15	0.075	99.925
7	0.035	99.965	17	0.085	99.915

Table 5: Significance limits.

Now we can answer questions like: if an experiment returns a reliability of 100%, what is the minimum true reliability with a confidence level of 95 %? The first row of the table provides the answer that the true reliability is at least better than 99.98 %.

Also, if another experiment has at least 4 wrong fixes, the differences are significant. This allows drawing the conclusion that the first processing option is better in terms of reliability than the other if these criteria are met.

RELIABILITY

The use of a third frequency and of a GPS&GALILEO satellite constellation shows an increase in reliability for single baselines as well as for VRS solutions. However the enhancements differ significantly between VRS and single baseline. For the single baseline solution there is a minor improvement when using the third frequency. The number of incorrect fixes is reduced by less than 40% on baselines longer than 10km so this still does not render previously intractable baseline lengths tractable (Figure 8). A similar behavior was observed in *Sauer et al. (2004), their Figure 9.* We want to point out that the early reliability breakdown is due to the extremely high (factor 2-3 higher than usual) ionospheric activity in the experiments carried out here. The reliability of RTK systems under normal ionospheric conditions is much better.

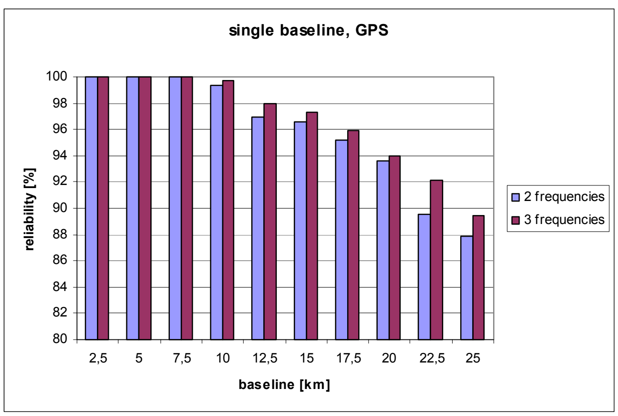

Figure 8: Reliability, single baseline, GPS.

When using a GPS&GALILEO satellite constellation (Figure 9) there is a considerable improvement of reliability such that baselines of up to 20km can be processed successfully. The effect of the third frequency in the GPS&GALILEO constellation is a minor one. Therefore baselines longer than 20km are not tractable even with a combination of 3 frequencies and a GPS&GALILEO constellation.

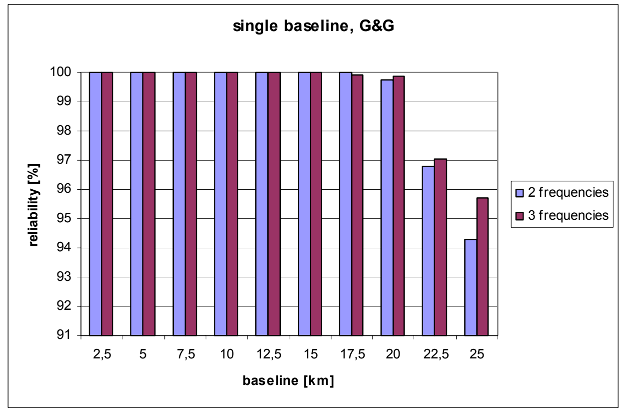

Figure 9: Reliability, single baseline, GPS&GALILEO.

In the case of VRS the situation is different. The applicability range of VRS is considerably enlarged when the third frequency is used (Figure 10), which had only a small impact on the performance of the single baseline solution. The third frequency makes the ambiguity resolution more robust in the difficult ionospheric conditions which arise from interpolation errors in larger networks. While for the medium sized VRS network (VRS 90km) an acceptable reliability cannot be guaranteed using current technology (GPS, 2 frequencies), the use of the third frequency significantly reduces the number of false fixes. The resulting configuration meets the reliability requirements. For VRS there is only a minor enhancement of the reliability when a GPS&GALILEO satellite constellation is used (Figure 11). Adding more satellites does not make the ambiguity resolution much more robust in this case since with every new satellite also a further unknown containing the ionospheric influence for that satellite is added. Indeed when using only 2 frequencies reliability breakdowns (e.g. at 42.5km) can occur even in a GPS&GALILEO satellite constellation.

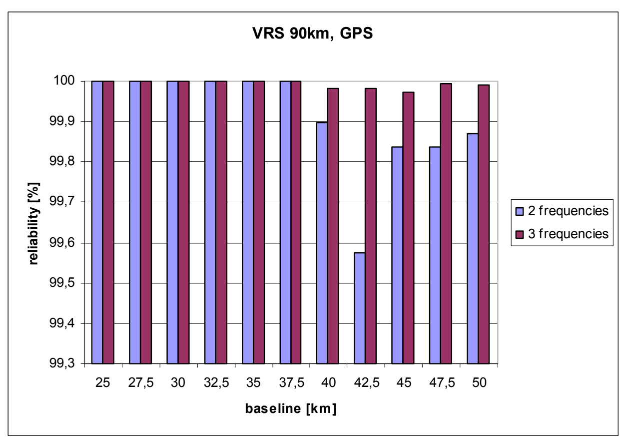

Figure 10: Reliability, VRS 90km, GPS.

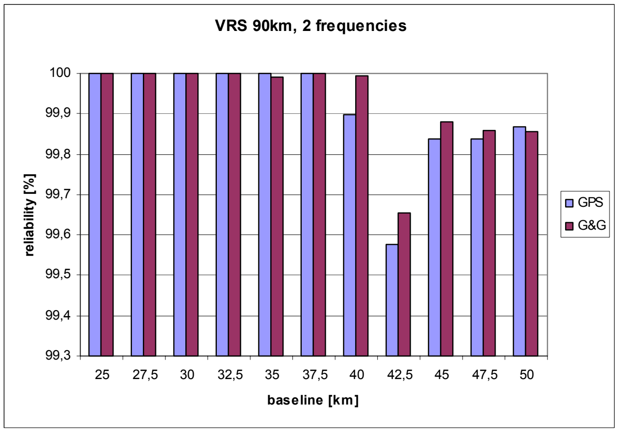

Figure 11: Reliability, VRS 90km, 2 frequencies.

Table 6 shows that with the currently available 2 frequencies of the GPS an inter-station distance of 50km is possible and guarantees full reliability. This is also well known from operating networks. However a network size of 90km cannot be operated with acceptable reliability using the current technology. The addition of the third frequency increases the reliability of the 90km network to an acceptable level of 99.9%. When using a GPS&GALILEO satellite constellation in addition to the third frequency, a reliability in the significance level of 99.99% is possible. This level of reliability can no longer be significantly distinguished from full (100%) reliability. The maximum achievable reliability for very large networks (with inter-station distances of 120km and more) was 99.8%.

VRS	GPS 2f	GPS 3f	G&G 2f	G&G 3f
50 km	100	100	100	100
90 km	99,58	99,97	99,65	99,99
120 km	98,73	99,75	98,96	99,76

Table 6: Overview of reliability results in %.

TIME TO FIRST FIX (TTF)

The fixing time for single baselines does not significantly depend on the number of frequencies used, but there is a slight dependency on the satellite constellation (Figure 12). However even when using a GPS&GALILEO satellite constellation the fixing times for single baseline remain two orders of magnitude larger than for the VRS solutions.

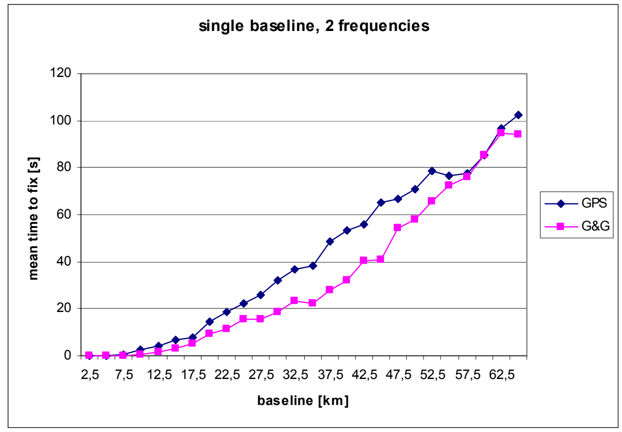

Figure 12: TTF, single baseline, 2 frequencies.

For the VRS solutions the fixing times do not significantly depend on the number of frequencies used or the satellite constellation. In Figure 13 only a slight dependency on the size of the VRS network is visible. This is due to growing interpolation errors for the ionosphere.

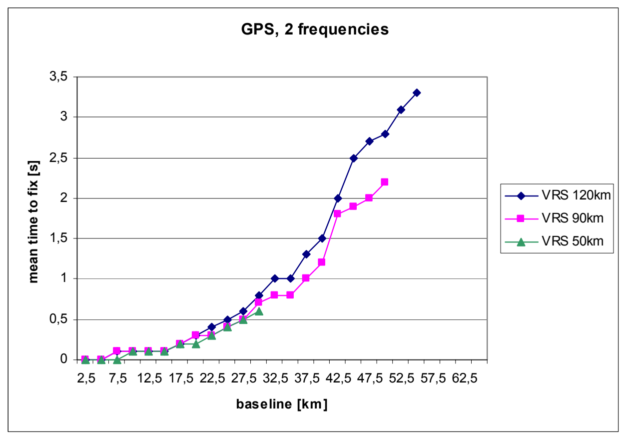

Figure 13: TTF, GPS, 2 frequencies.

The changes in fixing time will not significantly impact the applicability of the different solutions discussed. In particular the fixing time for VRS will not increase significantly when the network size is increased.

POSITION ACCURACY

The vertical RMS is almost independent of the satellite constellation and the number of frequencies used (not shown). The vertical RMS is smaller for smaller inter-station distances in the VRS (Figure 14, Figure 15). Accordingly the single baseline solution always shows a considerably larger vertical RMS than the VRS solution since tropospheric corrections are better for VRS and the interpolation in the VRS case gets better the smaller the size of the VRS network.

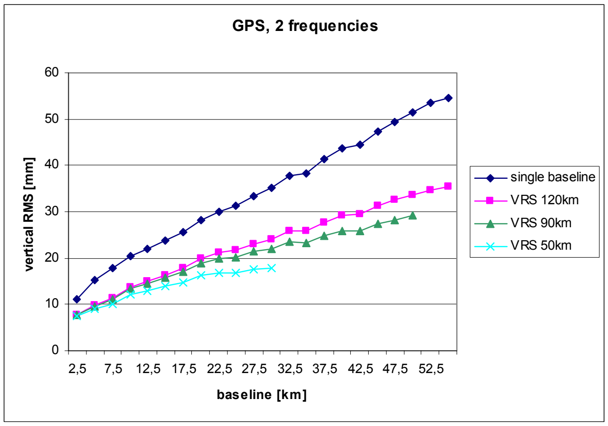

Figure 14: Vertical RMS, GPS, 2 frequencies.

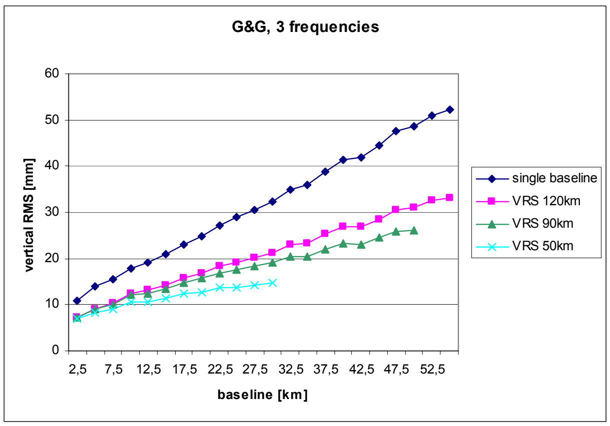

Figure 15: Vertical RMS, GPS, 3 frequencies.

As shown in Figure 16 and Figure 17 the horizontal RMS depends on the satellite constellation and the number of frequencies used. This is true for single baselines as well as for VRS solutions. With more satellites geometry errors can be more properly removed. The horizontal RMS in contrast to the vertical RMS also depends on the ionosphere. The ionospheric influence can be better eliminated the more frequencies are available. The choice of the satellite constellation has more impact on the horizontal RMS than the number of frequencies.

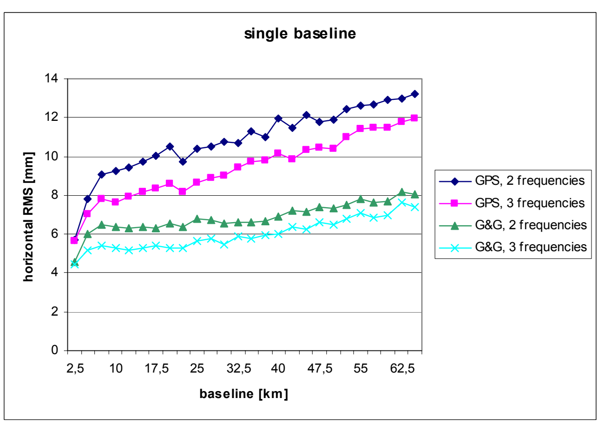

Figure 16: Horizontal RMS, single baseline.

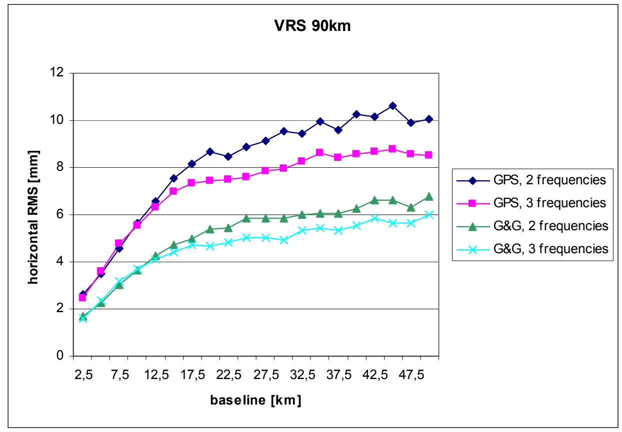

Figure 17: Horizontal RMS, VRS 90km.

There is almost no dependency of the horizontal RMS on VRS size (Figure 18) and thus increasing the inter-station distance in the VRS does not lead to a larger horizontal RMS. The single baseline solution always shows a larger horizontal RMS than the corresponding VRS solutions.

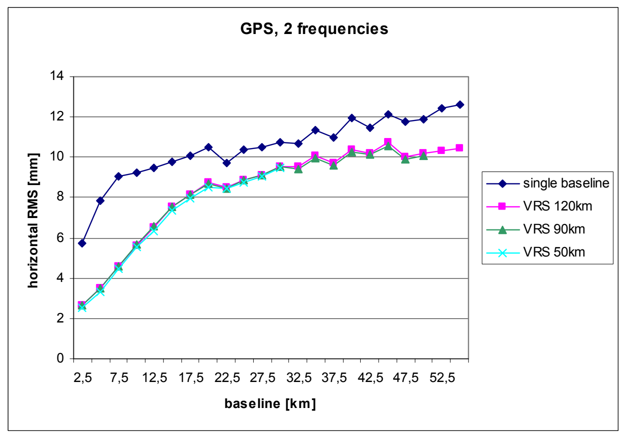

Figure 18: Horizontal RMS, GPS, 2 frequencies.

VRS	GPS 2f	GPS 3f	G&G 2f	G&G 3f
50 km	9,5	7,9	5,8	4,9
90 km	10,5	8,7	6,7	5,9
120 km	10,7	9,0	6,9	6,1

Table 7: Maximum horizontal RMS in mm.

CONCLUSIONS

It has been shown that the impact of the new capabilities introduced by GALILEO/Modernized GPS on the performance of single baseline and VRS solutions will be considerable. For single baseline processing the effect of a GPS&GALILEO satellite constellation on the reliability is much stronger than the effect of the third frequency. For VRS processing the situation is reverse: the use of the third frequency increases the reliability to a much larger extent than using a GPS&GALILEO constellation. Therefore it will only be possible to benefit from the third frequency when VRS is used.

The third frequency will allow an increase of the inter-station distance for VRS networks to 90km. For such networks the time to fix will not change significantly compared to smaller VRS configurations so a VRS configuration with larger inter-station distances will have the same usability.

The horizontal RMS does not depend on the size of the VRS network so it is not expected that it will increase. Indeed the horizontal RMS may even decrease when the third frequency is used (Table 7). The only drawback with increasing the inter-station distance is that the vertical RMS increases. However this increased vertical RMS will still be far beyond the vertical RMS of all single baseline solutions. The horizontal RMS can be further reduced by using a GPS&GALILEO satellite constellation.

Single baseline processing will benefit most from the GPS&GALILEO satellite constellation. However the single baseline solution achieves full reliability only on baselines up to 20km. Therefore an increase in the applicability range for single baseline processing is not expected. The addition of the third frequency improves single baseline processing results only marginally in accordance with previous studies. This analysis demonstrates that VRS and the modernization of satellite systems will complement but not substitute each other.

REFERENCES

Chen, X., U. Vollath, H. Landau, K. Sauer (2004): *Will Galileo/Modernized GPS Obsolete Network RTK?*, Paper presented at the European GNSS 2004 Conference, May 16-19, 2004, Rotterdam, The Netherlands

Julien, O. M. E. Cannon, P. Alves, G. Lachapelle (2004): *Triple Frequency Ambiguity Resolution Using GPS/Galileo*, European Journal of Navigation, Volume 2, Number 2, May 2004

Sauer, K., U. Vollath, F. Amarillo (2004): *Three and Four Carriers for Reliable Ambiguity Resolution*, Paper presented at the European GNSS 2004 Conference, May 16-19, 2004, Rotterdam, The Netherlands

Spiegel, M. (1975): *Theory and Problems of Probability and Statistics,* Schaum's Outline Series in Mathematics, McGraw-Hill, Inc.

Vollath, U., Roy. E. (2001): *Ambiguity Resolution using Three Carriers, Performance Analysis using "Real" Data*, Proceedings of the GNSS-2001 conference, May 9-11, 2001, Sevilla, Spain

Vollath, U., Sauer, K., Amarillo, F., Pereira, J. (2003): *Three or Four Carrier- How Many are Enough?*, Proceedings of the ION GPS/GNSS Satellite meeting, September 9-12, 2003, pages 1470-1477, Portland, Oregon, USA

Vollath, U., K. Sauer (2004): *FAMCAR Approach for Efficient Multi-Carrier Ambiguity Estimation*, Paper presented at the European GNSS 2004 Conference, May 16-19, 2004, Rotterdam, The Netherlands

Werner, W., J. Winkel (2003): *TCAR and MCAR Options with Galileo and GPS*, Proceedings of the ION GPS/GNSS Satellite meeting, September 9-12, 2003, pages 790-800, Portland, Oregon, USA

Zhang, W., M. E. Cannon, O. Julien, P. Alves (2003): *Investigation of Combined GPS/Galileo Cascading Ambiguity Resolution Techniques*, Proceedings of the ION GPS/GNSS Satellite meeting, September 9-12, 2003, pages 2599-2610, Portland, Oregon, USA