Will GALILEO/Modernized GPS Obsolete Network RTK?

Xiaoming Chen, Ulrich Vollath, Herbert Landau, Knut Sauer

Trimble Terrasat GmbH

BIOGRAPHY

Dr. Xiaoming Chen is a software development engineer at Trimble Terrasat. He holds a Ph.D. in Geodesy from Wuhan (China) Technical University of Surveying and Mapping.

Dr. Ulrich Vollath received a Ph.D. in Computer Science from the Munich (Germany) University of Technology (TUM) in 1993. At Trimble Terrasat, where he is working on GPS algorithms since more than eleven years, he is responsible for the algorithm development team. His professional interest is focused on high-precision real-time kinematic positioning and reference station network processing.

Dr. Herbert Landau is Managing Director of Trimble Terrasat. He has many years of experience in GPS and has been involved in a large variety of GPS and GLONASS developments for high precision positioning systems and applications.

Dr. Knut Sauer received a Ph.D. in Satellite Navigation from the Imperial College of Science, Medicine and Technology, London, UK. In 2003 he joined Trimble Terrasat as software development engineer where he is working on high precision kinematic positioning using the future Galileo system.

ABSTRACT

Network RTK in a local or regional reference network has been proven as an efficient technology for high accuracy GPS positioning over the last few years. Currently, Network RTK is implemented based on dual frequency GPS. With the third/fourth frequencies available from GALILEO and modernized GPS, will network RTK become obsolete?

Comparing with current dual-frequency GPS RTK performance, one of the main advantages of the third/fourth frequencies is that the reliability and productivity of OTF initializations at the rover increase dramatically. However, theoretical analyses and simulations show that the initialization performance decreases significantly with higher ionospheric activity (These results are available in another paper submitted). On the other hand, the geometric errors which are not frequency-dependent (e.g. troposphere and orbit) 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.

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.

Theoretical analyses and simulations show that with the presence of a reference station network, RTK initialization and positioning accuracy are improved considerably. In conclusion, a network solution will enhance the performance of high precision positioning using GALILEO and modernized GPS.

INTRODUCTION

Network RTK technology is one of the most interesting research topics in high precision GPS real time positioning in last few years (Landau et al., 2001, 2002, 2003; Vollath et al., 2000, 2001a, 2002a, 2000b; Chen et al., 2003; Lachapelle et al., 2002, Rizos, 2002). Many countries have implemented this technology to provide nation-wide or region-wide RTK services (Landau et al., 2002). Comparing with traditional single base RTK technology, network RTK removes significant amount of spatially correlated errors due to the troposphere, ionosphere and satellite orbit, and thus allow performing RTK positioning in reference station networks with distances of up to 40 km or more from the next reference station while providing the performance of short baseline positioning.

The benefits of using more than two carriers with the planned modernized GPS and Galileo satellite navigation systems have been proven by several authors. In principle, instantaneous ambiguity resolution becomes feasible for a broad range of applications. A boost of system availability and reliability is recognized as well (Vollath et al., 2003). 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? These questions will be addressed by analyzing the main error sources which affect ambiguity fixing and positioning performance and what can be reduced by a reference station network.

OBSERVATION MODEL

Double difference code and carrier phase observation can be expressed as:

$$\nabla\Delta P_i = \nabla\Delta\rho + (\nabla\Delta T + \nabla\Delta dR) + \frac{\nabla\Delta I}{f_i^2} + \nabla\Delta\varepsilon_{i,p} \qquad (1)$$

$$\nabla\Delta\Phi_i = \nabla\Delta\rho + (\nabla\Delta T + \nabla\Delta dR) - \frac{\nabla\Delta I}{f_i^2} + \lambda_i\nabla\Delta N_i + \nabla\Delta\varepsilon_{i,\Phi} \qquad (2)$$

Where, $\nabla\Delta$ is double difference operator, $\nabla\Delta P_i$ and $\nabla\Delta\Phi_i$ are double difference pseudorange and carrier phase observations in meter; *i* is frequency index, f_i and λ_i are the correspondent frequency and wavelength (for Galileo, i: 1-4, for GPS, i: 1-3), ρ is geometric range between Satellite and receiver, *T* is tropospheric effect, *dR* is orbit error, *I* is ionospheric effect, *N* is the ambiguity. $\varepsilon_{i,p}$ and $\varepsilon_{i,\Phi}$ are code and phase noise.

AMBIGUITY FIXING PERFORMANCE

Three/four carrier ambiguity resolution for single base RTK has been discussed in various literature (Vollath et al., 1998, 2001, 2003a; Teunissen, 2002; Tiberius, 2002; Zhang, 2003). Vollath (2003) employed ADOP analyses to predict the fixing performance for three carrier GPS, three and four carrier Galileo under different ionospheric, multipath condition.

The Ambiguity Dilution of Precision ADOP is defined as:

$$ADOP(C) = \sqrt{\det C}^{\frac{1}{n}} \qquad (3)$$

where *C* is the covariance matrix of ambiguities and n is the number of ambiguities.

The success rate for a given ADOP can be computed as:

$$P(ADOP) = \left(2\cdot\Phi\left(\frac{1}{2\cdot ADOP}\right)-1\right)^n \qquad (4)$$

where *Φ(x)* is the probability density function of the normal distribution.

The ADOP is a measure for the average accuracy of the ambiguities computed in a floating solution to be determined for a fixed solution. Although the success rate derived from ADOP is neither an upper nor a lower bound for the probability of successful ambiguity resolution, it has been proven to give realistic predictions and can be used for relative comparisons of different signal scenarios.

Fig. 1 and Fig. 2 give the success rate of instantaneous ambiguity resolution based on geometry-free model in terms of “Nines” for two and three carrier GPS, Galileo (Vollath et al, 2003a). The x-axes of Fig. 1 and Fig. 2 labeled as cm of ionosphere standard deviation, which can be interpreted as baseline length in km at 10 ppm of differential ionosphere. The results presented are based on the assumption that at least 4 double differences have to be fixed to allow useful positioning. For that reason, the fourth power of the ADOP probability has been used.

For a given success rate P, the “Nines” are computed as:

$$Nines(p) = -\log_{10}(1-p) \qquad (5)$$

A standard error of 0.01 cycles is assumed for carrier phase measurements. The code error specification is given in Table 1.

Table 1 Code error specification

System	Code 1 Mpath [m] Noise [m]	Code 2 Mpath [m] Noise [m]	Code 3 Mpath [m] Noise [m]
GPS	0.21 0.15	0.21 0.05	0.21 0.05
Galileo	0.21 0.05	0.21 0. 05	0.21 0.05

The improvements by using three instead of two frequencies are obvious. For example, in case of Galileo, with an ionospheric influence of 5 cm the two carrier solution results in a probability of 4.9% (0.02 NINES) whereas the three carrier solution provides 94.8% (1.28 NINES) reliability. However, with the increase of ionospheric influence, the performance decreases significantly in both cases.

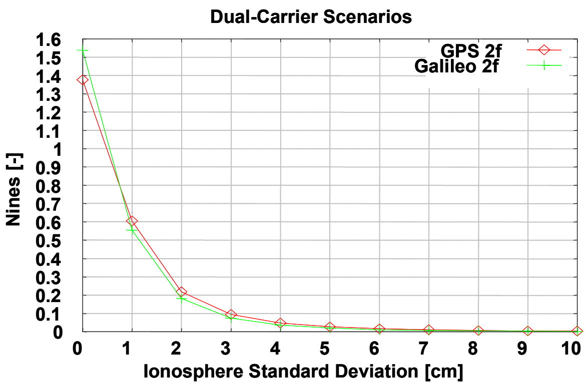

Fig. 1 Two carrier success rate

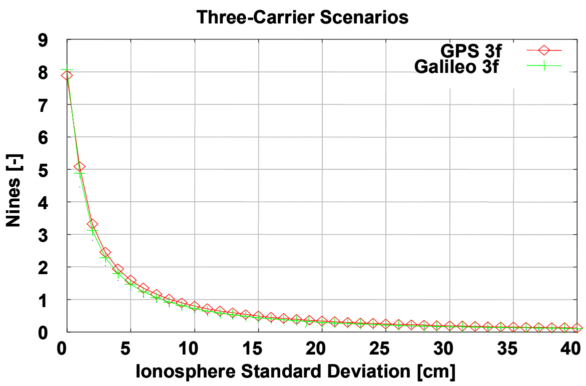

Fig. 2 Three carrier success rate

In order to improve the ambiguity resolution performance, it is necessary to reduce the ionospheric error. One method to accomplish this, which has been proven to be very efficient, is to use a reference station network.

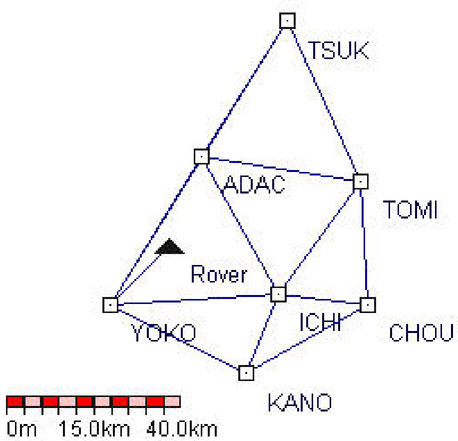

Fig. 3 GSI sub-network (Japan)

Fig. 3 – Fig. 5 give an example from the Japan Geographical Survey Institute (GSI) sub-network showing how much ionospheric error can be reduced by a reference station network. Fig. 4 shows ionospheric PPMs (scale error in part per million) from all satellites and the correspondent hourly I95 index. From GPS time 8:00 to 12:00, the ionospheric PPM from low elevation satellites is higher than 30 PPM, which means 60 cm ionosphere for a 20 km baseline. Fig. 5 shows ionospheric residuals from a generated VRS station to Rover (distance from rover to nearest reference station is 24km) after applying the network corrections. It shows that ionospheric residuals have been reduced to less than 10 cms. Though it is obtained from a dual-frequency GPS network, it should apply to multiple frequencies as well.

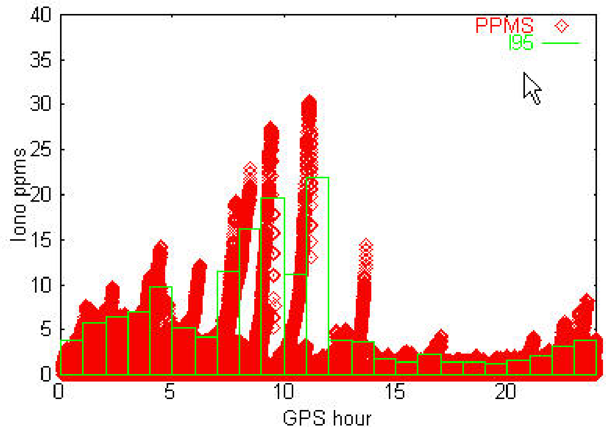

Fig. 4 Linear ionospheric influence in part per million (PPMS) and Hourly I95 index from GSI network (Japan).

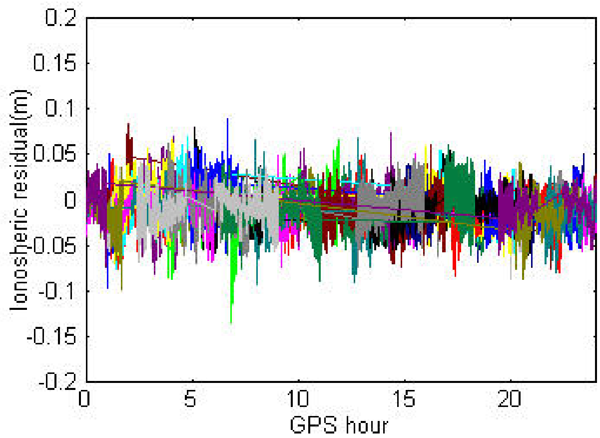

Fig. 5 Ionospheric residuals of VRS to Rover from GSI network (Japan)

If we compare figure 2 with figure 1 we find that the ambiguity resolution is more robust against ionosphere with more frequencies. This will benefit Network RTK in terms of network spacing. Due to the inability to perfectly model the ionosphere, the interpolation errors grow with the distance between rover and nearest reference station and the inter-station distance between reference stations. Fig. 6 shows interpolation errors at the rover for different network sizes (small: nearest reference station 31km;

medium: nearest reference station 46km; large: nearest reference station 88km; extreme large: nearest reference station 126km). With third/fourth frequency available, the tolerance of the RTK positioning with respect to the ionospheric influence is larger, i.e. the RTK system using three carriers will tolerate a larger network interpolation error. For example, if a dual-frequency solution can tolerate 8 cm of error, 87 % of the network interpolation errors will conform to that in the “large” network case. If we assume that a three carrier system is tolerating a larger error, e.g. 16 cm, 97 % of the errors will be within these bounds for the large network resulting in a much better reliability. In other words less reference stations will be needed to maintain the same performance as a dual-frequency GPS system resulting in a considerable cost reduction.

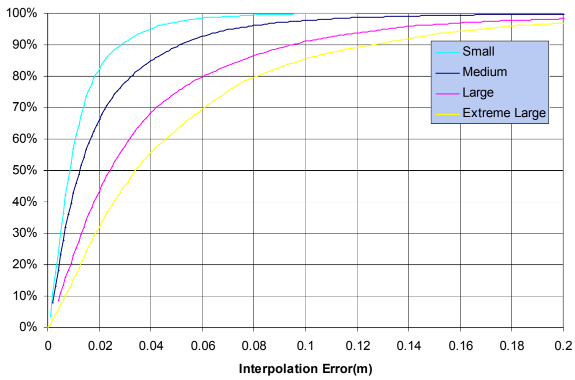

Fig. 6 Cumulative probability of interpolation error

POSITIONING ACCURACY

Successful ambiguity resolution converts carrier phase observables to high precision pseudoranges which enables cm level positioning. However, as shown in eq. (2), besides the ambiguity, there are still other factors affecting the positioning accuracy: carrier phase multipath and the non-dispersive errors such as tropospheric effect, orbit errors. The ionospheric effect is not considered since it can be removed by ionospheric-free carrier phase combination.

Multipath

Carrier phase multipath has a great influence on the positioning accuracy as well as ambiguity fixing performance. Sauer et al. (2004) studied the impact of carrier phase multipath on multiple frequency ambiguity resolution performance based on hardware simulated data. The same dataset is used in this paper to assess the positioning performance. In the simulated dataset, carrier phase multipath was implemented as a first order Gauss-Markov process. The correlation time assumed was 50 seconds and the a priori variance was 0.003 $cycle^2$. Technical details of how to generate carrier phase multipath can be founded in Sauer et al.(2004).

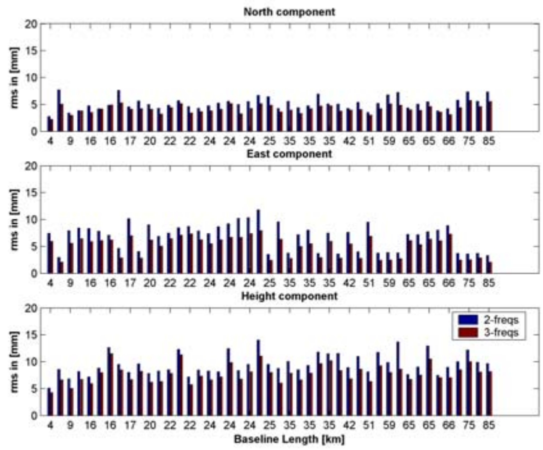

Figure 7: Positioning Accuracy [RMS] – GPS

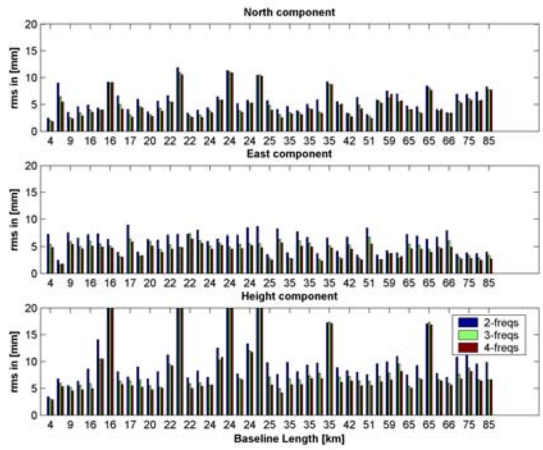

Figure 8: Positioning Accuracy [RMS] – Galileo

Fig. 7 and Fig. 8 show the positioning accuracy for GPS and Galileo respectively. The computed positions and trajectories have been compared against their *true* counterparts. For the kinematic scenarios the comparison was done on an epoch-by-epoch basis. No obvious dependency to the baseline length could be observed. Comparing the accuracy of dual frequency processing, a gain of up to 20% better accuracy was observed on three and four carrier processing.

Using a reference station network, multipath on the reference station data could be further mitigated, however, due to the main influence of multipath in a RTK system is on the rover side, a significant gain of positioning accuracy is not expected.

Orbit error

The effect of orbit error on differential positioning can be roughly expressed as:

$$db = \frac{dr}{\rho} b \qquad (6)$$

where, dr is the orbit error, ρ is the satellite range and b is the baseline length.

The impact of orbit error (along-cross track and radial) to a single difference observation at difference elevation angle is illustrated in Fig. 9 and Fig. 10. If there is 10m of long-cross track error the impact on single difference observation of a 100km baseline will reach the maximum value of 5cm on zenith direction, and if there is 10m of radial error, the effect is much smaller, it has a maximum of 6mm at around 45 degree elevation. So, with longer baseline length and higher satellite elevation angle, orbit errors could significantly degrade the positioning accuracy.

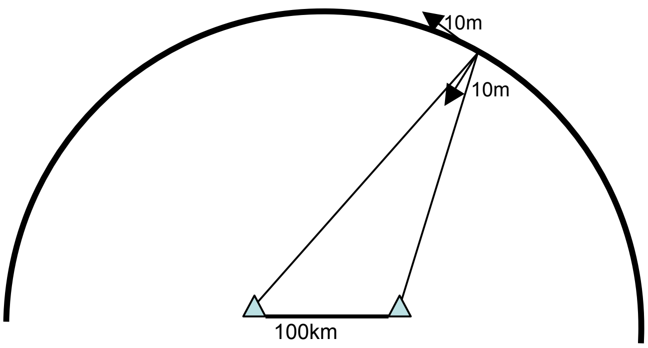

Fig. 9 Orbit and baseline geometry

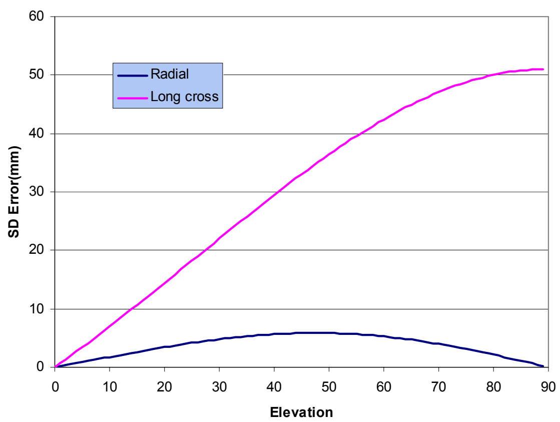

Fig. 10 Orbit error vs elevation

Fig. 10 shows clearly how the orbit error affects differential positioning. The question to be asked is: how good will it be in Galileo and Modernized GPS? First, let's have a look at the orbit accuracy of current GPS system. Fig. 11 shows the RMS and maximum difference between precise and broadcast orbits of all GPS satellites in GPS week 1226, RMS of all satellites are below 6 m, and the maximum error is about 20m for SV 24. Since the RTK system normally uses broadcast orbit, under the accuracy of current GPS broadcast orbit, positioning accuracy of single base RTK for long baseline is compromised.

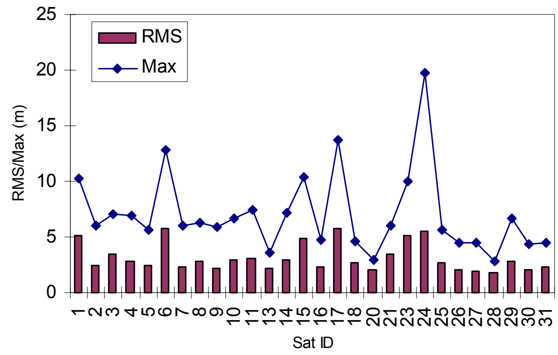

Fig. 11 GPS broadcast orbit error

Hopefully, GPS modernization will reduce the clock and orbit error from 2.3m to 1.25m (Sheridan et al., 2001). Similar accuracy is expected from Galileo. Furthermore, Galileo will broadcast an a priori estimation of the clock and ephemeris errors: SISA (Signal In Space Accuracy). The SISA is a quantitative estimation of the orbit and clock prediction of satellites, clocks, signal, navigation message or in the processing itself (Blomenhofer et al., 2003). The improvement of orbit accuracy and integrity of modernized GPS and Galileo will help to improve the positioning accuracy at longer baseline.

For network RTK, the orbit error is not really a problem even for longer baseline since ultra-rapid orbits are accessible in the computing center via the internet. Additionally, the orbit error can be fully eliminated through appropriate interpolation techniques (Han, 1997).

Tropospheric effect

Troposphere is a non-dispersive media. The effect can not be eliminated by adding more frequencies. The tropospheric delay mainly affects the height component. Uncorrected tropospheric residuals will cause systematic biases in the height component of the position. This kind of effect can be easily seen from the long-term height variation when processing a static baseline using kinematic post-processing. Fig. 12 shows the rover height error versus time for a 32 km static baseline (Germany, Hoehenkirchen to Neufahrn, Nov. 22, 2001 0:00-6:00). The dataset was processed by the Trimble Total Control (TTC) kinematic processor using the ionosphere free observable with default tropospheric model (modified

Hopfield, standard met. conditions). It can be seen clearly that the height is biased up to 10 cm from 3 to 6 o'clock. However, if tropospheric scaling (it is a measure equivalent to ZTD estimation, it equals to estimated ZTD divided by ZTD from tropospheric model) is applied to the rover (Table. 2) in the processing, the height is almost flat as shown in Fig. 13.

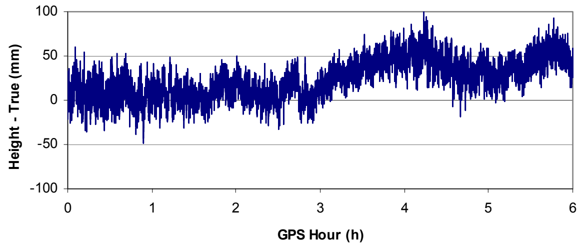

Fig. 12 Height – True height for Neufahrn (No Scaling)

Table 2. Tropospheric scaling

Time (hour)	Tropospheric scaling (%)
0	0
3	0
3.5	-0.7
4	-0.6
4.5	-0.6
5	-0.5
6	-0.4

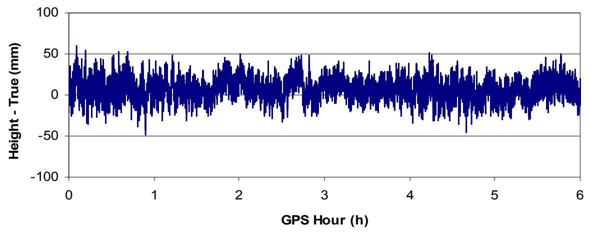

Fig. 13 Height – True Height for Neufahrn (scaling applied)

Although the estimation of the zenith total delay in a RTK system is possible, it needs considerable time to converge and increase the time of ambiguity initialization consequently. With a reference station network, the tropospheric zenith delay can be estimated for all reference stations with an accuracy of 10 mm absolute ZTD and 7 mm relative ZTD by using dual frequency GPS receivers (Vollath et al., 2003). With more observables and less noisy data available from Galileo and modernized GPS, the accuracy of ZTD estimation could be even higher, accordingly, more improvement on RTK positioning could be expected.

CONCLUDING REMARKS

This paper addressed several constraint factors (ionosphere, troposphere, orbit error and multipath) of three/four carrier ambiguity resolution and positioning performance. Theoretic analysis and simulation show that:

- Although three/four frequency ambiguity resolution with a single base is better than dual frequency systems, the activity of ionosphere still constrains ambiguity fixing performance. With the presence of a reference station network, the ionospheric effect will be greatly reduced and hence improve the performance of ambiguity resolution.
- Network RTK will benefit from more frequencies in terms of network spacing due to the fact that ambiguity resolution is more robust against ionosphere with more carriers.
- Multipath mitigation due to the availability of more observables will improve positioning accuracy only marginally. Further multipath mitigation by a reference station network is not expected to improve the accuracy significantly.
- Modernized GPS/Galileo is expected to provide higher orbit and satellite clock accuracy. This will reduce the positioning error for single-base long baseline RTK systems. Nevertheless, network RTK will not benefit too much from the improved orbit because the availability of ultra-rapid orbit and the elimination of orbit errors by the interpolation.
- The tropospheric effect will not be removed by adding more frequencies. Like current dual frequency GPS system, this effect can be reduced by a reference station network.

In conclusion, a network solution will still enhance the performance of high precision positioning using GALILEO and modernized GPS.

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