Virtual Reference Stations versus Broadcast Solutions in Network RTK -

Advantages and Limitations

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1 ABSTRACT

In the last few years it has been shown by several authors and in a variety of tests and applications that Network RTK solutions are superior to classical single baseline RTK solutions. Today Network RTK is a widely accepted technique and therefore an increasing number of organizations are establishing networks providing real-time corrections from a reference station network. Basically two different techniques are currently used and discussed for these applications: the generation of Virtual Reference Station (VRS) data or the transmission of broadcast formats. Besides the dependency on the data transmission link between network server and the field user (dial-in versus broadcast) a major difference of the two techniques is the following: In VRS mode the corrections are applied in the network server whereas in broadcast mode the corrections are applied in the field. Both methods have advantages and limitations. The authors try to quantify and qualify all the arguments by doing some analyses of different scenarios.

2 Introduction

While the RTCM committee is working on a new standard for a broadcast network solution, basically two different methods are currently used in GPS network: FKP (network area corrections) and VRS. Within the scope of this paper we will focus on the following topics:

- The modelling of the troposphere in VRS and broadcast solutions.
- The basic differences in ionospheric modelling in VRS, FKP and other broadcast solutions.

3 Tropospheric modeling in VRS and FKP mode

Today's operating reference station networks are creating either Virtual Reference Station (VRS) data or network area corrections (FKP parameters) as in the German SAPOS network. It is sometimes claimed by other authors that the FKP method of transmitting network corrections only induces negligible errors whereas VRS may introduce quite significant errors (Wübbena et al., 2001) due to assumptions on the tropospheric model. In the following we will analyze the possible remaining errors of the two methods by doing some numerical analysis.

FKP parameters are computed from the residual difference between reference stations. In order to compute these residuals we need to apply orbital information and a tropospheric model. Without the use of a tropospheric model it would not be possible to fix the ambiguities in the network. Since we often do not have actual meteorological data on the reference stations we are forced to work with standard atmospheric parameters in the network server software. The uncertainty of the tropospheric model will influence the computed correction stream not in an absolute sense. Since we are looking only at differences between the reference stations the network corrections only include the relative offsets between the truth and the used tropospheric model. However, this is the same effect for FKP and VRS if they are computed in the same way and by the same model.

3.1 Influence of the applied tropospheric model on the rover solution

In the VRS case the network solution generates an "optimal" observation set for a virtual reference station (VRS) nearby the rover. Depending on the distance from the next reference station the rover might observe the satellite signal under a different elevation angle and azimuth than the reference stations. The rover also might be at a different height than the reference station. Therefore it is necessary to correct not only for geometric displacements during the generation of the VRS data but also for the tropospheric differences between the reference station(s) and the VRS.

A geometric range observed at the rover is corrected via the following relationship.

$$\rho^{s}{}_{Rover} = \rho^{s}{}_{Reference} + \Delta\rho^{s} + T^{s}{}_{Rover} - T^{s}{}_{Reference}$$

where

ρ^s is the geometric range from the satellite s to the reference station and rover, respectively.

$\Delta\rho^s$ is the geometric range difference between reference station and VRS to satellite s

T is the tropospheric model correction for the satellite s to the reference station and VRS, respectively.

The term T is computed from a tropospheric model used in the VRS system. In the Trimble product GPSNet™ we are using a modified Hopfield model as described in Goad&Goodman (1983) with standard atmospheric parameters, i.e. we assume an atmospheric pressure of 1013 hPa, a temperature of 20°C and a relative humidity of 50% at sea level. A rover system might use a different model and therefore experience a difference in the ranges to the satellites depending if working in VRS or in FKP mode. This difference can be estimated by comparing the tropospheric corrections from different models on different baseline lengths. The difference can be easily computed from the equation

$$\delta T = T^{VRS}{}_{Rover} - T^{VRS}{}_{Reference} - (T^{Rov}{}_{Rover} - T^{Rov}{}_{Reference})$$

where

T^{VRS} is the tropospheric correction computed from the VRS internal model (e.g. modified Hopfield in the GPSNet case)

T^{Rov} is the tropospheric correction computed from the Rover internal model.

3.2 The influence of the tropospheric differences in FKP and VRS mode

We would like to have a closer look at the influence of the tropospheric model differences in the FKP and VRS modes now. In order to do that, let us assume that we have a very simple three-station network, which forms a triangle with equal lengths of 200 km (Figure 1). In the center of the triangle we have the rover position. The rover is approximately 115 km from the reference stations. The line C-Rover is orthogonal to the line A-B and the distance from C to A-B is approximately 173 km. A satellite is tracked under an elevation angle of 10° and in the direction from C to the rover. The rover and stations A and B are all at sea level, while the station C is varying in height. We now simulate a tropospheric model error in the network by using the modified Hopfield model (Goad&Goodman, 1974) to compute truth and use the Davis (Davis et al., 1984,1985) model as the network server model. Due to the inconsistencies between both models we will find differences. Please note that we are using identical pressure and humidity parameters for all the models but we are using a 15°C temperature for the Davis model while the modified Hopfield model is working with 20°C. The results of this simulation are summarized in table 1 at the end of this paper. Due to the set-up of the network and the independence of the models from azimuth the baselines C-A and C-B will show identical tropospheric model differences and thus occur only once in the table. Column 2 of table 1 represents the modified Hopfield differences for the baselines C-A and C-B, which we assume as truth. Column 3 represents the same value for the Davis model and column 4 is the difference between columns 2 and 3, i.e. the “error” residual in the baseline. Columns 5-7 are representing the same values for the baseline from station C to the Rover.

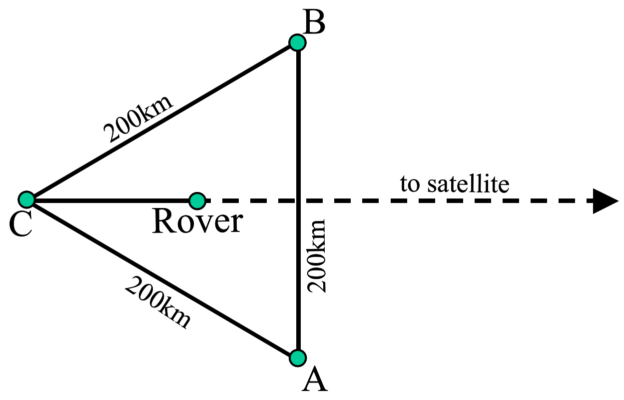

Figure 1: Network sketch for three station network and rover location

Let us also assume that the other modeling for orbits and ionosphere is perfect, thus no additional effect from other error sources is going to be visible in the network corrections. From the computed inconsistencies between the “truth” (modified Hopfield) model and the Davis model (column 4) we can generate FKP parameters and the network corrections at the rover position. These network corrections in our case would just represent the inconsistencies between the truth (Hopfield) and the Davis model.

Now, in the VRS case we would transfer the data from the nearest reference station to the rover by applying a geometric displacement, the tropospheric correction from the model used in the network server (Davis), plus the network corrections.

If we apply a linear correction model we end up with the corrections in column 8 of table 1. The simple structure of the network allows us to compute the network corrections easily via the following relationship:

$$\delta\rho \approx \delta T \cdot 115km/173km$$

The linear network correction terms $\delta\rho$ are represented by column 8 in table 1. Due to the non-linearity of the tropospheric model we end up with some induced errors, which are caused by the fact that we are using linear network corrections. These errors are summarized in column 9. They are derived as the difference between the real model errors in VRS mode (column 7) and the network corrections (column 8). The table shows that the actual errors are practically zero for small height differences and become up to 14 mm on a 900 m height difference.

However, in FKP mode we correct the data for tropospheric effects at the rover without any knowledge of the tropospheric model used in the server software. It can be shown that this may induce errors. In our simulation we were using the Lanyi (Lanyi, 1984) model to simulate the influence of a different model, use identical standard pressure and humidity but a temperature of 25°C. We used the above described network set-up and came up with the errors of up to 68 mm on a 115 km baseline and a height difference of 900 meters (see table 1).

In summary we can state that due to the consistency of the tropospheric models between the actual network processing and the generation of the VRS data we find errors of less than 14 mm in VRS mode. In FKP mode the user might see (depending on the tropospheric model used in the rover) much larger errors, which were in our case up to 68 mm (more than four times higher than in VRS case).

3.3 Residual errors due to tropospheric model differences in FKP mode

3.3.1 Identical standard atmospheric parameters for server and rover model

The following graph shows the difference δT between the modified tropospheric model in GPSNet™ and an assumed Lanyi model in the Rover. It is representing the typically induced error in case of a FKP solution under the ideal situation of identical meteorological conditions in both models. The difference is given for different baseline lengths up to 200 km and for various height differences between the reference and the rover. The difference in the graph below is just caused by the difference in height and baseline length. The values were computed for an elevation angle of 10° above the horizon and under the assumption that the baseline is located in the direction to the satellite, i.e. resulting in the maximum possible difference.

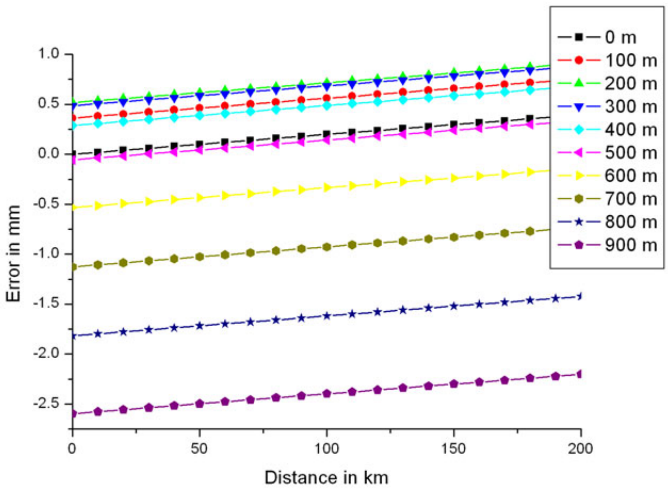

Figure 2: Model differences due to height difference and baseline length

As we can see from the figure the influence of the different models is marginal for typical distances. Only for baselines of 200 km and height differences between the reference and the rover of 900 meters the difference in the models is larger than 2 mm.

3.3.2 Different standard atmospheric parameters and no height difference

While the height difference between the reference station and the rover might cause a difference in the observed residuals in the rover solution, a difference in the assumed standard meteorological conditions might also cause a difference. In the following we analyzed the model differences assuming that the server uses again a modified Hopfield model and the rover a Lanyi model. We also assume that rover and reference are at the same height, but we assume differences in the met conditions. We modify one parameter at the time; the graph below shows the effect of a temperature difference of 10°C, a pressure difference of 20 hPa and a relative humidity difference of 50 %.

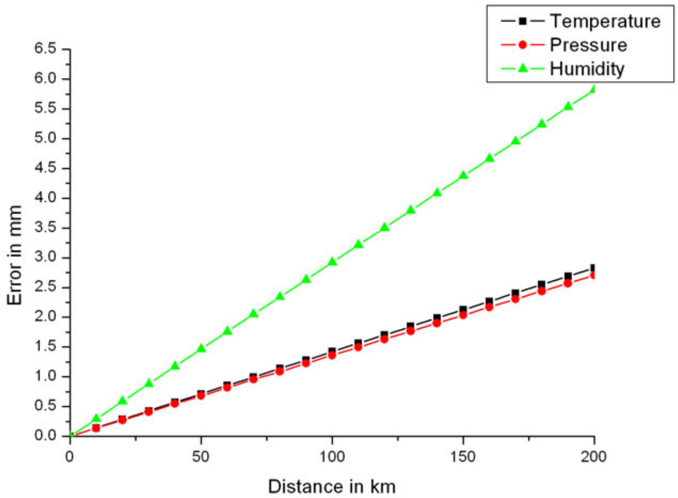

Figure 3: Model difference due to differences in the standard met parameters

The computed difference from the assumed extreme model differences are of the order of 5 mm on long distances. On normal RTK distances of 50 km or less we will find that the difference is around 1 mm or less.

3.3.3 Different standard atmospheric parameters with height differences between reference and rover

However, we could also think of some extreme case with a large height difference and a difference in standard meteorological parameters in network server and rover. If we use similar standard parameters like for the analysis above and run threedifferent cases, i.e. a 10°C, 20 mbar and 10% relative humidity difference, we come up with the errors shown in the following figure.

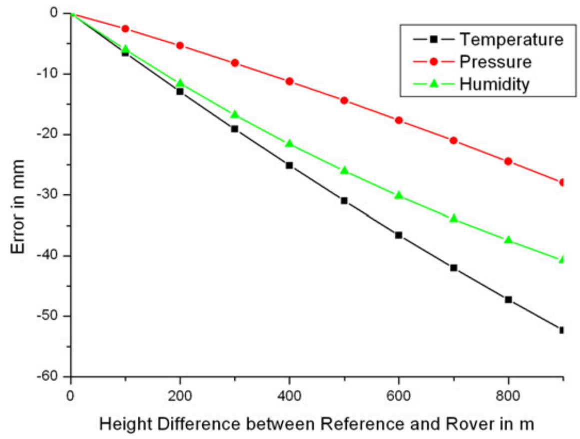

Figure 4: Error induced by the use of different standard met parameters versus height difference between reference and rover

Once again, as we can see different standard meteorological parameters may cause considerable errors in the rover when working in FKP mode due to the inconsistency between the tropospheric models in server and rover.

3.4 Residual errors due to tropospheric model differences in VRS mode

If the virtual reference station and the rover position are identical no error is introduced at all. However, in the normal VRS operation the first DGPS position computed by the rover is used as the VRS position.

This DGPS position is transmitted from the rover to the VRS server using a standard NMEA string via GSM or GPRS. It is typically good to a few meters. This “inaccuracy” in the VRS position actually causes the residuals at the rover to experience an additional effect. This is caused by the fact that the rover might use a different tropospheric model from the VRS server. The server computes a tropospheric correction from the reference station to the VRS position, while the rover is computing a tropospheric correction between VRS position and the rover. This might induce an error. The effect was analyzed and is shown below:

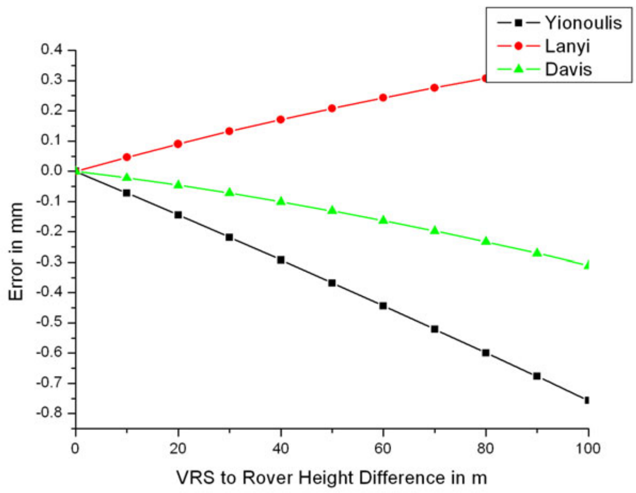

Figure 5: Difference induced due to the offset between VRS and rover position

The above figure shows the difference caused by three different tropospheric models (Davis et al. (1984), Lanyi (1984), Yionoulis (1970)) when compared with the modified Hopfield model results. The effect is dependent on the error in height of the DGPS position. However, as we can see from the graph the induced difference will usually not be larger than 0.2 mm for typical DGPS position errors of a less than 10 meters. The effect is therefore negligible. Please note that we did this analysis only for a possible height error since this effect is much less sensitive to horizontal errors.

4 Ionospheric Modeling

In network RTK the most critical error component is the differential ionospheric residual error between the reference station network and the rover, i.e. the level of differential ionosphere the rover “sees” in the data. If this effect is too large the rover may extend the time taken to perform reliable ambiguity resolution.

In the following we will try to look into the possibilities and limitations of VRS and FKP mode for ionospheric modelling.

4.1 FKP limitation on ionospheric residual interpolation

Ionospheric FKP parameters represent the linear part of ionospheric residuals by scaling parameters in north and east direction. It provides quite a good interpolation of ionospheric residual under stable ionospheric condition. However, under disturbed ionospheric condition, ionospheric residuals can no longer be considered as linear, and interpolation error increases dramatically as the inter-station distance increases. This would lead to bad rover performance in terms of reliability and availability.

Here we give an example showing the FKP interpolation accuracy of ionosphere with different inter-station distances and under different ionospheric conditions. The data used here is collected from the BLVA (Bavarian Land Survey Department) network on Dec. 5, 2002. Four network configurations are presented here. One is the standard configuration of the BLVA network (small network) as shown in Figure 6. Station Hoehenkirchen was used as the rover, the nearest reference station is Bad Toelz, which is 31.2km from the station. Station Augsburg was selected as rover in three additional configurations. Reference stations around Augsburg are about 50 km apart (medium network, nearest station: Guenzburg, 46.2km), 100km (large network, nearest station: Biberach, 86.8km), and 150 km (extremely large network, nearest station: Lindau, 126km) were used to simulate different network size configurations. The network configurations are shown in Figure 7. In Figure 6 and 7, stations belonging to one network configuration are connected by line. Rover and nearest reference station are marked by triangle.

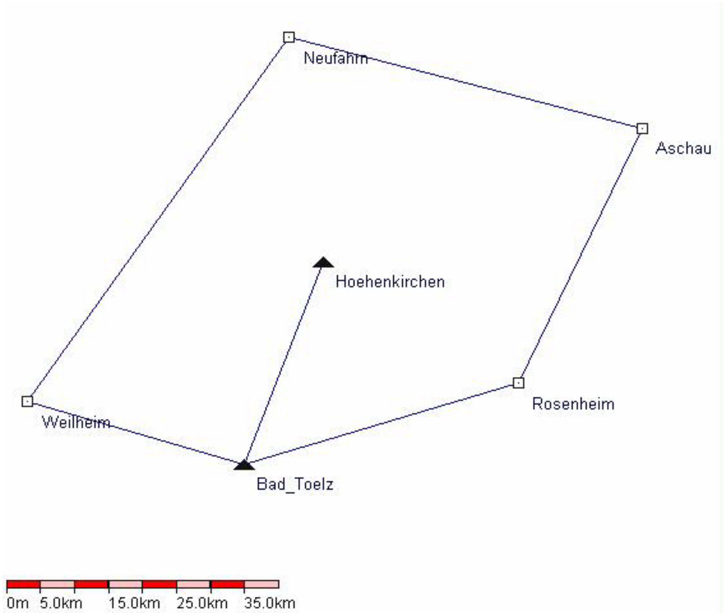

Fig. 6 Network configuration (small)

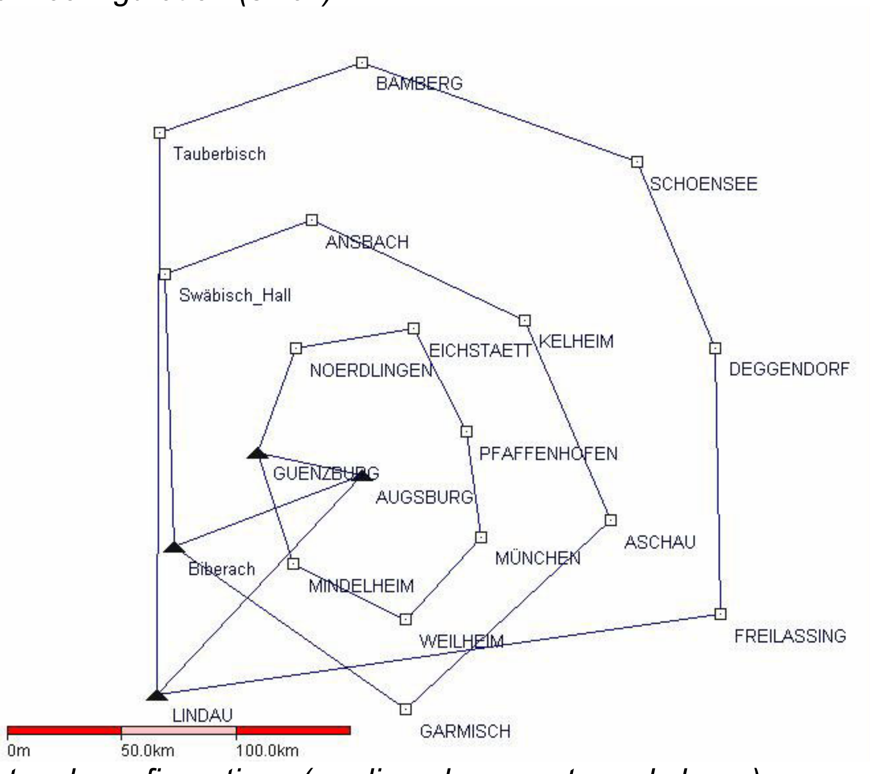

Figure. 7 Network configurations (medium, large, extremely large)

Fig 8 shows hourly 95% interpolation errors at the rover for different network sizes. Among these four configurations, the small network gives the best interpolation and the large network gives the worst interpolation. The worst time period is around local noon, when there is some local ionospheric disturbance. Even for the small network the interpolation errors at Augsburg exceed 6 cm at 13:00h.

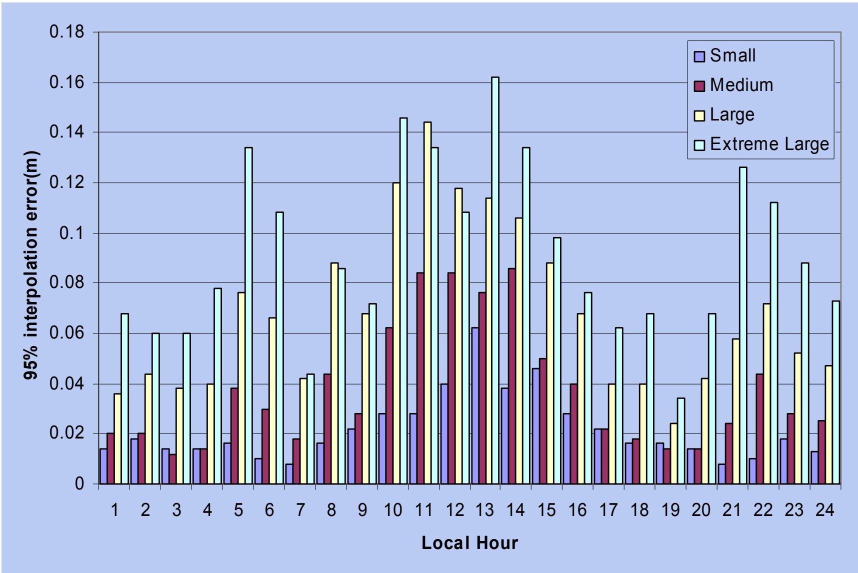

Fig. 8 Hourly 95% interpolation error for difference network configurations

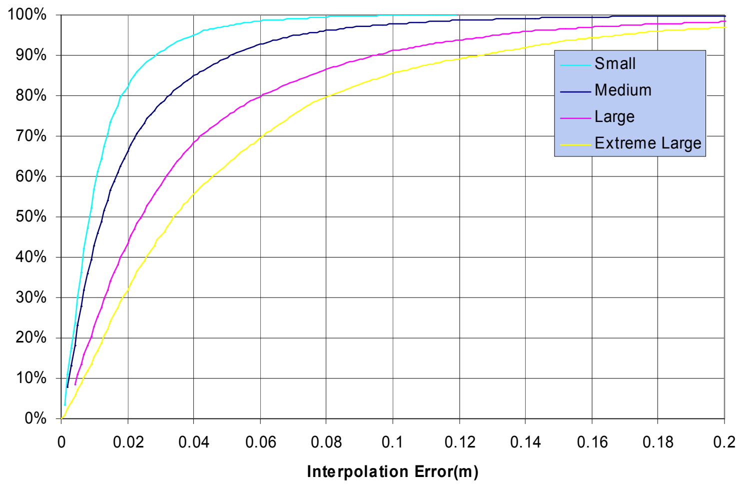

Fig. 9 Cumulative probability of interpolation error

Fig. 9 shows the cumulative probability of interpolation error over one day for the different network configurations. Two thresholds of interpolation error are of primary interest: 2 cm and 8 cm.

The 8 cm threshold is of special importance since a dual-frequency RTK solution will tend to optimal performance if the remaining ionospheric differential effects are less than 8 cm. If the errors are larger than this threshold the availability of a RTK solution will take significantly longer than for smaller values. In a standard (non-network) RTK solution the ionospheric effects grow with baseline length. In a network solution we would ideally like to see no dependence on the baseline length between the rover and the next reference station. However, in practice this is limited due to the inability of the models to perfectly model the ionosphere. This is especially true if a linear FKP model is used. As we can see in Fig.9, about 99.5% of interpolation errors are less than 8 cm for small network, 95.1% for medium network, 86.5% for large network and 79.8% for extremely large network. Consequently we can assume optimal RTK performance in almost all situations in the small RTK network while in the larger networks we will find much more often situations with long initialisation times.

Another threshold of importance is the differential ionospheric error of approx. 2 cm. Besides the ambiguity resolution performance, the positioning accuracy is also affected by the magnitude of ionosphere left in the rover data. This is also true for L1/L2 receivers, which is shown in the following figure.

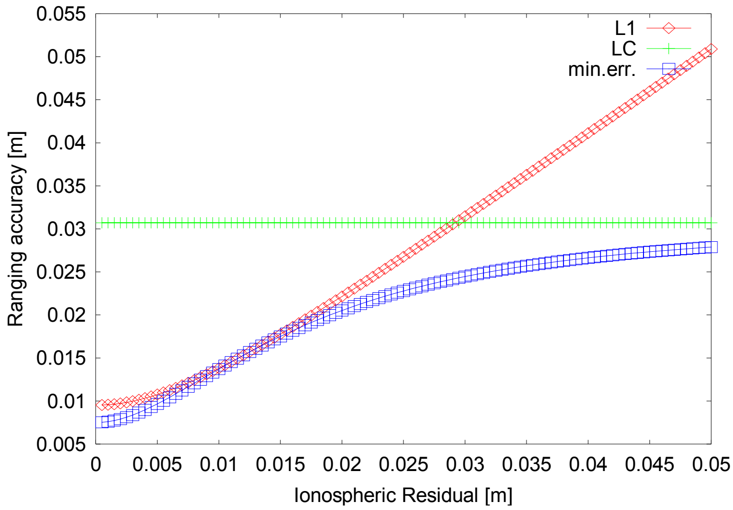

Fig. 10 Ranging accuracy versus ionospheric residual

For an assumed carrier phase multipath of 0.05 cycles, three possible carrier phase combinations available for positioning are rendered. The graph shows the effective ranging error for L1 carrier phase only (L1), the iono-free carrier phase combination (LC) and the minimum error (min.err.) carrier phase combination [Sjoberg (1990)].
The error in the iono-free combination is not ionosphere-dependent by definition. The disadvantage is that the error propagation for the multipath results in an elevated error level. The L1 combination is better for low ionosphere residuals while getting worse for higher values. The optimum carrier phase combination is of course better than both combinations for any ionosphere value. It can be seen, that below 2 cm of ionosphere, the L1 solution is approximating the optimal solution. Here, L1 and the minimum error combination are significantly more precise than the iono-free solution.

In our case (see Fig. 9) about 82.3% of interpolation errors are less than 2 cm for small network, 66.1% for medium network, 43.3% for large network and 32% for extremely large network.

In summary we have shown clearly that the FKP interpolation accuracy degrades with the sparseness of the network. To guarantee good rover performance while using FKP parameters, the inter-station distances should be carefully designed.

4.2 Modelling the residual ionospheric error in the rover RTK system

In the VRS case the model computation and the full correction of the data is done in the server. For the broadcast format solution the computations are done in the rover. The rover will still have to compute its internal model for atmospheric effects. A complex ionospheric model requires processor power and a considerable convergence time. This limits the ability of the rover to perform perfectly after a cold start – especially when using a broadcast format solution. On the other hand, a VRS solution will always provide optimal rover performance after cold start because the VRS server is continuously updating it's complex atmospheric models using not only a subset of the network but the complete network

A GPS reference station network allows modeling tropospheric and ionospheric conditions within its coverage area and providing network corrections for both error contributions in FKP or VRS mode. It is sometimes stated in the literature (Wübbena et al. 2001) that in the VRS case the stochastic properties of the differential atmosphere between the rover and the reference stations is destroyed by the VRS computation. This is true, the stochastic properties of the ionospheric signal in the VRS to rover are totally different from the ionospheric signal of the original baseline [Vollath et. al. (2002)]. However, FKP implementations currently running in production in Germany are using tools like the Smartgate or the SAPOS Decoder box to convert the FKP information to a standard RTCM stream. Therefore the RTK engine also "sees" in the FKP case only the modified observational data and therefore the situation is not different from the VRS case. The argument that the original reference station is missing in the VRS data stream and thus limits the rovers capability to model the atmospheric effects is invalid since it is currently transmitted in a published RTCM 59 message in the GPSNet™ case, which has been adopted by all the major receiver manufacturers.

5 Advantages and Disadvantages of VRS versus FKP

Let us summarize the advantages and disadvantages of the VRS and FKP modes.

The Virtual reference station (VRS) method has the advantage that it allows complex modelling of ionospheric and tropospheric effects in the server using the full network information. In contrast, the FKP method has very limited possibilities to model the residual ionospheric effect, the model for the correction is very simple (in most case just linear as in the SAPOS case) and the rover has only access to data from two stations in the FKP case to compute an atmospheric model. In the broadcast format currently under discussion by the RTCM committee, the rover will have access to a larger number of stations, but it will still be limited and the complete computational burden is on the rover processor.

While the VRS case requires two-way communication links, the broadcast modes do not. However, the use of two-way communication links like GSM and GPRS is often preferred due to the availability of the cell phone infrastructure and the ability to transmit additional information to (e.g. dedicated warnings) and from (e.g. positions, feature codes) the field rovers. With the use of GSM and GPRS the invoicing for the service is also much easier than in a broadcast solution.

Another advantage of the VRS method is the elimination of tropospheric errors due to consistent tropospheric modelling throughout the complete VRS generation step as we have shown above. In the FKP mode we have the danger of inconsistent tropospheric modelling between server and rover.

One disadvantage of VRS, which is often argued about, is it's limitation in support of kinematic applications with rovers moving over large network areas with one dial-in period. In VRS the corrections are optimised for the initial rover position at the time of dial-in. If the rover then moves considerably after the dial-in the corrections might not be appropriate for the new rover location. Although this effect is only influencing rovers that are moving large distances (several kilometres), the rover can work around this problem by using additional information. The Trimble GPSNet™ server VRS solution provides additional information (FKPs) in a specially designed RTCM message 59. This message 59 is publicly known. The FKPs are optimised for the VRS rover position and are derived from the network solution. Thus a rover receiving a VRS data stream from GPSNet™ will have the advantages of both worlds. It will receive an optimised data stream for the initially provided rover position. In addition, with extended rover operation it can correct local effects by a linear FKP model around the initial position

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Table 1: Influence of different tropospheric models in VRS and FKP mode with respect to the station height difference

Height of Station C [m] 1	Truth [mm] (C-A/B) 2	Davis [mm] (C-A/B) 3	Delta[mm] (C-A/B) 4 (2-3)	Truth[mm] (C-Rover) 5	Davis[mm] (C-Rover) 6	Delta[mm] (C-Rover) 7 (5-6)	Linear Network Corrections [mm] 8	Errors induced in VRS mode [mm] 9	Lanyi (C-Rover) [mm] 10	Errors induced in FKP mode [mm] 11
0	108.2	105.9	2.3	0.0	0.0	0.0	1.5	-1.5	0.0	-1.5
100	-69.4	-67.1	-2.3	-177.6	-173.0	-4.6	-1.5	-3.1	-184.1	8.0
200	-244.6	-237.8	-6.8	-352.8	-343.7	-9.1	-4.5	-4.6	-365.4	17.1
300	-417.5	-406.3	-11.2	-525.7	-512.2	-13.5	-7.4	-6.1	-543.9	25.6
400	-588.2	-572.5	-15.7	-696.4	-678.5	-17.9	-10.4	-7.5	-719.7	33.7
500	-756.6	-736.6	-20.0	-864.8	-842.5	-22.3	-13.3	-9.0	-892.9	41.4
600	-922.8	-898.6	-24.2	-1031.0	-1004.5	-26.5	-16.1	-10.4	-1063.5	48.6
700	-1086.9	-1058.4	-28.5	-1195.1	-1164.3	-30.8	-18.9	-11.9	-1231.6	55.4
800	-1248.8	-1216.2	-32.6	-1357.0	-1322.2	-34.8	-21.7	-13.1	-1397.2	61.9
900	-1408.6	-1372.0	-36.6	-1516.8	-1478.0	-38.8	-24.3	-14.5	-1560.4	67.9