New Tools for Network RTK Integrity Monitoring

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BIOGRAPHY

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ABSTRACT

Over the last few years Network RTK has been proven to be an efficient technology for high accuracy positioning. The principle of Network RTK is that a significant portion of ionospheric, tropospheric and ephemeris errors are estimated over a region and this information is provided to rovers in the field. Among spatially correlated errors, ionosphere is most difficult to model and contributes the largest error for network RTK users in terms of reliability and availability. The ionospheric index I95, which was proposed by Wanninger (2002), is a good measure to predict the linear ionospheric effect for single baseline RTK users. However, in Network RTK this effect is actually modeled in the network server and taken out by the software, since the model in the server is at least linear (if not more complex). Therefore Network RTK requires different measures to describe potential residual errors in the generated data stream transmitted to the user. The authors propose to use two different ionospheric linearity indicators (IRIM and IRIU) to predict Network RTK performance. Similar indicators can be used for the non-dispersive part too.

This paper proposes two indicators of ionospheric linearity:

- Ionospheric Residual Integrity Monitoring (IRIM): Omitting one reference station from interpolation and then comparing the interpolation results at that station with the real measurements. Compute a weighted RMS over all satellites. This can also be considered as integrity monitoring for residual interpolation and ambiguity resolution in the network.
- Ionospheric Residual Interpolation Uncertainty (IRIU): With sufficient surrounding reference stations, an interpolation method such as Weighted Linear Interpolation Method (WLIM) produces standard deviation of interpolation. The standard deviation represents the ionospheric linearity over the interpolation region for the field user.

Two network scenarios are presented in this paper. One is in Japan, with a very high ionospheric gradient (maximum 40 ppm for low elevation satellites), another one is in Bavaria, Germany, with medium ionospheric gradients but very disturbed around local noon. Test results show that both ionospheric linearity indicators highly correlate with the differential ionospheric residuals “seen” by a real rover in the field.

In conclusion, ionospheric linearity indicators (IRIM and IRIU) are very useful tools to predict the rover performance. Such measures can improve the RTK reliability and productivity of rovers working in a networking system.

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, 2003; Vollath et al, 2000, 2001,2002a, 2000b; Wanniger, 1999; Talbot et al, 2002; Raquet, 1998; Lachapelle et al, 2002, Rizos, 2002). Many countries have implemented this technology to provide nation-wide or region-wide RTK service (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.

Network RTK is composed of three main processes: network correction computation, correction interpolation, and correction transmission (Lachapelle et al, 2002). Based on network error correction transmission mode, network RTK can be classified into two principle modes (Landau et al, 2002):

- Virtual Reference Station mode: This mode requires bi-directional communication. The basic advantage of this mode is that it makes use of existing RTCM and CMR standards implemented in all major geodetic rover receivers and thus is compatible with existing hardware.
- Broadcast mode, in which the error corrections due to atmospheric and orbit effects are transmitted in a special format, which requires changes of rover receiver hardware or additional hardware to convert the non-standard format to a standard RTCM data stream before used by the rover.

Both modes have some advantages and limitations (Landau et al, 2003). In general, they provide quite good RTK performance in normal ionospheric conditions. However, under disturbed ionosphere, sometimes the rover fails to initialize due to high ionospheric residuals.

Though most post of ionosphere effects have been taken out by the interpolation, nevertheless, if the remaining ionospheric differential effects are less than 8 cm, a dual-frequency RTK solution will tend to optimal performance. If the errors are larger than this threshold the availability of a RTK solution will take significantly longer than for small values (Landau et al, 2003). 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 to perfectly model the ionosphere. Integrity monitoring for network RTK is therefore a necessity.

NETWORK RTK INTEGRITY MONITORING

Integrity monitoring is an integral part of network RTK. One possible way is to use one reference station as a "rover" and carry out continuous RTK to monitoring the rover RTK performance. However, this method requires an additional station, which means more cost is added to the network operation. Another disadvantage is that it can only monitor the integrity of certain part of the network which is near the "rover".

The rover receives network corrections calculated (interpolated) from residuals of reference stations. Therefore, information derived from the network residuals could serve as a network integrity monitoring with no more additional cost and full coverage of the network.

Wanninger (2002) proposed the ionospheric index I95, which gives 95% margin of ionospheric PPMs over one hour, indicates the ionospheric activity in the hour over the network area. This information is a good measure to predict linear ionospheric effects for single baseline RTK users. However, in Network RTK this effect is actually modeled in the network server and taken out by the software, since the model in the server is at least linear (if not more complex).

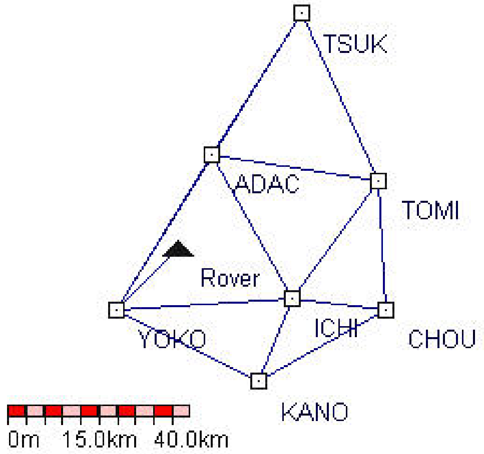

Fig. 1 GSI sub-network (Japan)

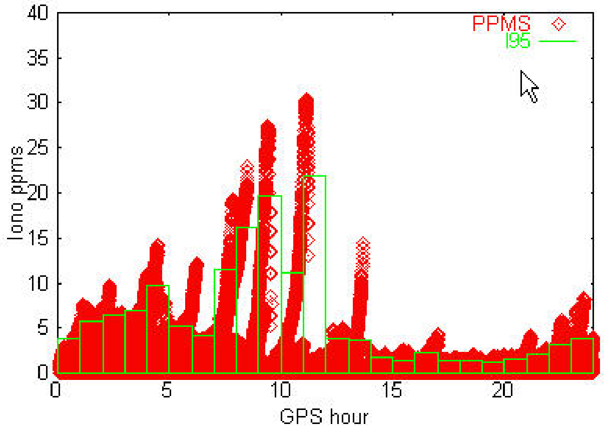

Fig. 2 Ionospheric PPMs and Hourly I95 index from GSI network (Japan)

We would like to give one example from the Japan Geographical Survey Institute (GSI) network on Jan. 19, 2002 (Fig.1, triangle mark in the figure represents rover position). Fig.2 shows ionospheric PPMs from stations and all satellites and correspondent hourly I95 index. From GPS time 8:00 to 12:00, the I95 value is quite high due to high ionospheric PPM from low elevation satellites. Fig. 3 shows ionospheric residuals from a generated VRS station to Rover (distance from rover to nearest reference station is 24km). It shows that there is no significant residual increase from 8:00 to 12:00 compare to other time periods.

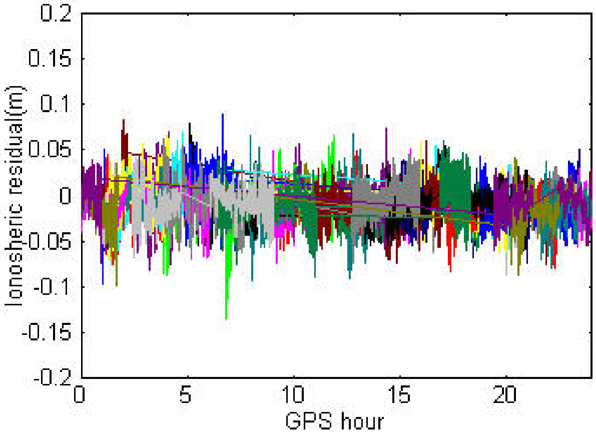

Fig. 3 Ionospheric residuals of VRS to Rover from GSI network (Japan)

Another example is from the BLVA network in Germany on Dec. 5, 2001 (Fig. 4). Fig. 5 shows ionospheric PPMs from all stations and all satellites and correspondent hourly I95 index, though the I95 index is not as high as in GSI network, but there are some high ionospheric disturbance at around local noon time, which results high ionospheric residuals from the generated VRS station to Hoehenkirchen at around noon time (Fig. 6).

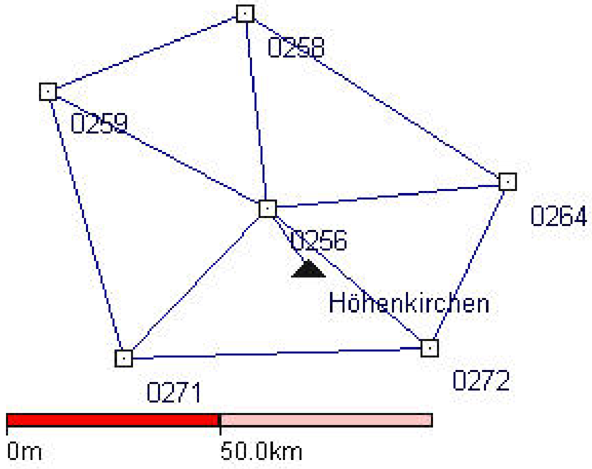

Fig. 4 BLVA sub-network (Germany)

Above examples show that I95 can be used to represent the ionospheric activity over the network region, but it cannot represent the disturbance of the remaining ionospheric residual in a network RTK solution.

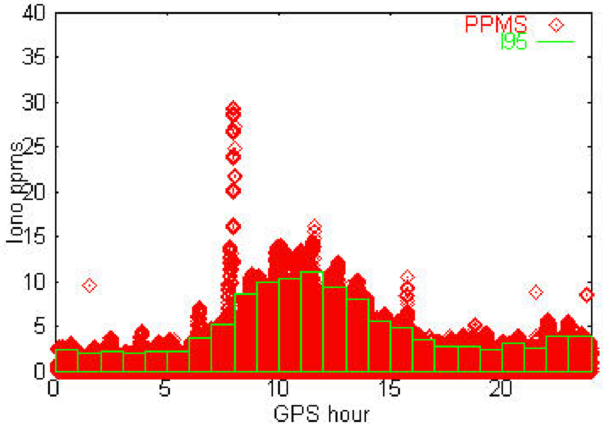

Fig.5 Ionospheric residuals of VRS to Rover from BLVA network

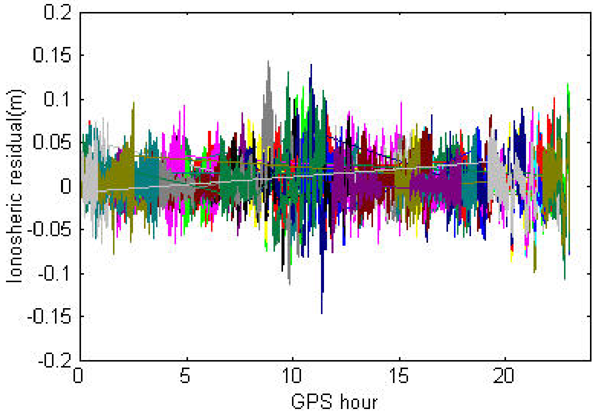

Fig. 6 Ionospheric residuals of VRS to Rover from BLVA network (Germany)

Therefore Network RTK requires different measures to describe potential residual errors in the generated data stream transmitted to the user.

IONOSPHERIC RESIDUAL INTEGRITY MONITORING (IRIM)

As the linear part of ionospheric residual is normally taken out by the interpolation, the nonlinear part, which is not modeled by the interpolation, will remain in the network correction sent to the rover. In another words, the more linear the ionosphere, the better accuracy of the interpolation and less error "seen" by the rover. Thus, the ionospheric linearity could provide network operator a better idea of the residual errors within the network. Furthermore, it can provide a good estimate of the interpolation error for a possible field user.

One possible ionospheric linearity indicator is Ionospheric Residual Integrity Monitoring (IRIM), which is calculated by omitting one reference station from interpolation and comparing the interpolation results for all satellites at that station with the real measurements, then compute a weighted RMS over all satellites at one epoch, and accumulate the weighted RMS over one hour to get 95% distribution. This can also be considered as integrity monitoring for residual interpolation and ambiguity resolution in the network.

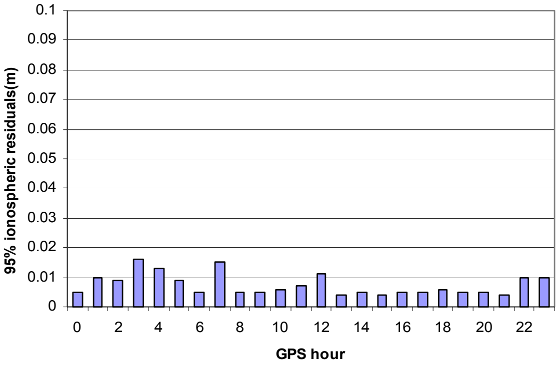

Fig. 7 IRIM for GSI network (Japan)

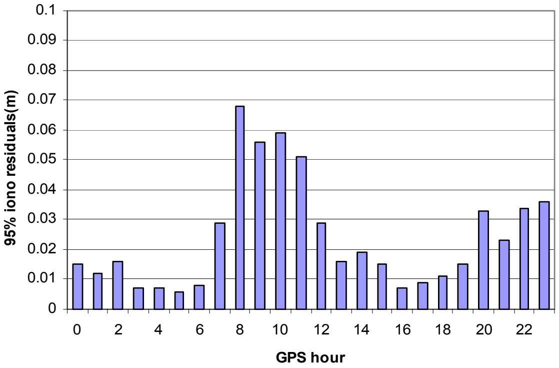

Fig. 8 IRIM for BLVA network (Germany)

Fig. 7 shows IRIM for GSI network and Fig. 8 shows IRIM for BLVA network respectively (calculated from the same dataset used in Fig. 1-3 and Fig. 4-6). For GSI network, IRIM is almost flat over the day as the residual of VRS to rover; for BLVA network, IRIM peaks at around noon time and it has another small peak around 20 – 24 h, which is highly correlated with the residual of VRS to rover. Comparing with I95, IRIM is more appropriate to describe the residual remained in the baseline from VRS to rover, especially for GSI network.

IONOSPHERIC RESIDUAL INTERPOLATION UNCERTAINTY (IRIU)

Although IRIM gives an overall picture of ionospheric disturbance over the network, however, for the individual rover within the network, uncertainty of the interpolation for the specific rover in the network at a certain epoch should also be addressed. This should be very useful to provide network operator indications of rover performance anywhere in the network. On the other hand, this information could feed into the rover RTK engine to improve network RTK performance.

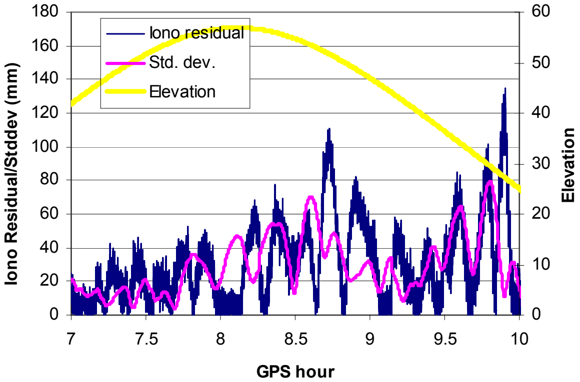

Fig. 9 Ionospheric residual and WLIM standard deviation of SV 02

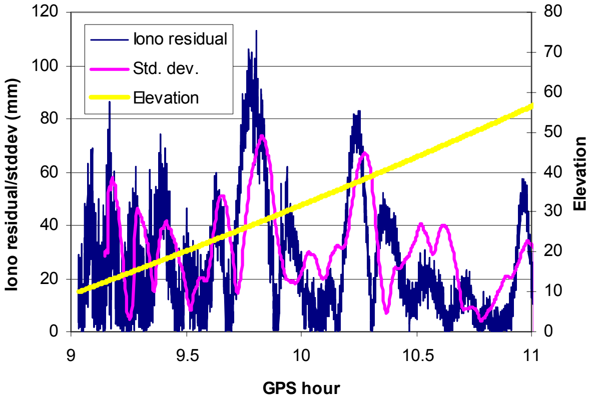

Fig. 10 Ionospheric residual and WLIM standard deviation of SV 09

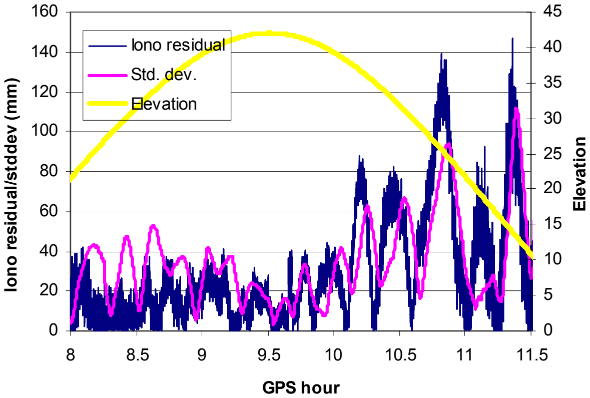

Fig. 11 Ionospheric residual and WLIM standard deviation of SV 24

One statistic could serve this purpose is the standard deviation of weighted linear interpolation (WLIM), which is a standard interpolation method of Trimble infrastructure software - GPSNet^{TM}. WLIM uses residuals from reference stations surrounding the rover to calculate network corrections for the rover weighted by the distance to rover. To compute the standard deviation, at least 4 reference stations are needed.

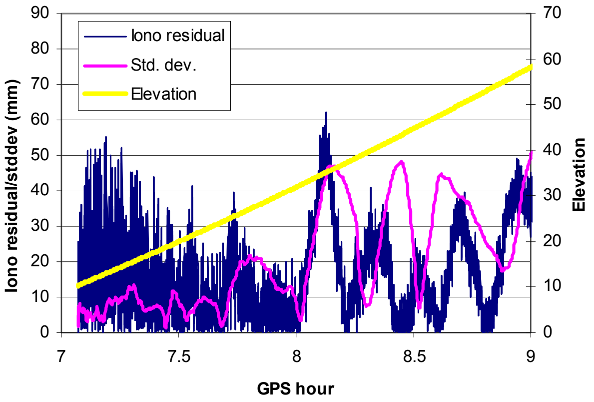

Fig. 12 Ionospheric residual and WLIM standard deviation of SV 26

WLIM can be described by following formulas:

$$\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix} = \begin{bmatrix} 1 & \Delta N_1 & \Delta E_1 \\ 1 & \Delta N_2 & \Delta E_2 \\ \vdots & \vdots & \vdots \\ 1 & \Delta N_n & \Delta E_n \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad or \quad R = AX$$

Where, r_i (i=1,2…n) represents residuals at reference stations. $\Delta N_i, \Delta E_i$ are the north and east coordinate difference from VRS to reference stations. a, b, c are estimates for constant part, north and east gradient.

By using least square adjustment, we can get estimation:

$$X = (A^T PA)^{-1} A^T PR$$

Where P is a distance dependent weighting matrix. And correspondent variance of unit weight:

$$\sigma_0^2 = \frac{V^T PV}{n-3}$$

and covariance matrix for X:

$$Q = \sigma_0^2 \cdot (A^T PA)^{-1}$$

Then, we can get the network correction and correspondent variance:

$$r_{vrs} = BX \text{ and } \sigma_{vrs}^2 = BQB^T$$

where, $B = \begin{bmatrix} 0 & \Delta N & \Delta E \end{bmatrix}$, $\Delta N, \Delta E$ is the north and east coordinate difference between the rover and reference station which used to generate the VRS station

Fig. 9 to Fig. 12 show the ionospheric residuals of VRS to rover (absolute value) and the standard deviation of WLIM for SV 02, 09, 23 and 26. The dataset used in these figures is from the BLVA network, same as used in Fig 5, 6 and 8. These figures show that the standard deviation of WLIM fit the real residual from VRS to rover very well, and thus provide a good indication of how good the interpolation is, or in another word, how uncertain the interpolation is.

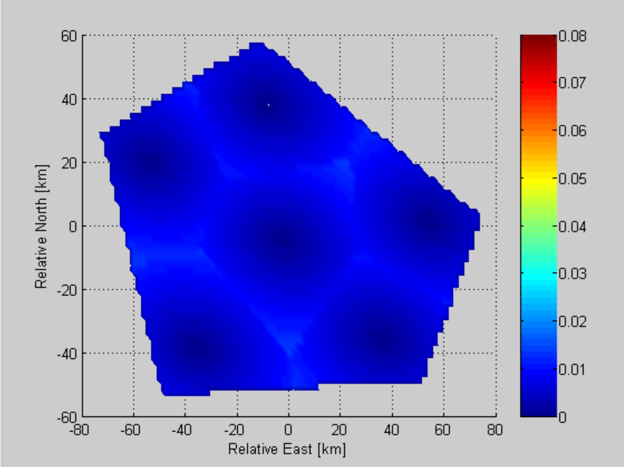

Fig. 13 IRIU at GPS time 07:00 of BLVA network

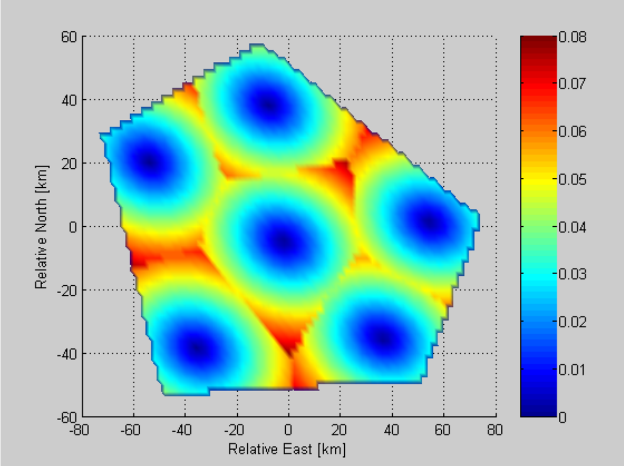

Fig. 14 IRIU at GPS time 08:45 of BLVA network

Since the calculation of the standard deviation of WLIM only depends on the position of rover, residuals and positions of reference stations used in the computation, the weighted mean standard deviation of all satellites can be given in a grid and display in a colored map, named as ionospheric residual interpolation uncertainty (IRIU). Fig. 13 and Fig. 14 show IRIU for BLVA network at GPS time 07:00 and 08:45 respectively. They give snapshots of expected remaining ionospheric residuals over the network at a certain time. If there are some big values somewhere in the network, performances of RTK might be disturbed.

CONCLUSIONS

Two ionospheric linearity indicators (IRIM and IRIU) were presented in this paper. Comparing with I95 index, they are more appropriate to describe the disturbance of the ionosphere. IRIM provides the overall view of network RTK integrity over a time period. On the other hand, IRIU provides more detail information over the network. Two network (BLVA and GSI) scenarios presented in the paper demonstrate both ionospheric linearity indicators are useful tools to predict network RTK rover performance. Furthermore, if the information transmitted to the rover, such measures can improve the RTK reliability and productivity of rovers working in a networking system. Similar indicators could be used for the non-dispersive part too.

Trimble Terrasat has implemented both indicators in their infrastructure software GPSNet version 2.1.

ACKNOWLEDGEMENTS

The authors thank GSI and BLVA for their kindly providing data used in this paper.

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