On Testing of RTK-Network Virtual Concept

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Key words GPS positioning, RTK GPS Positioning, RTK-Network, Virtual Reference Stations (VRS) RTK GPS.

ABSTRACT

This paper deals with testing and calibrating a Real Time Kinematic (RTK) GPS network system (Trimble Terrasat). In the test net three reference stations were used situated in Southern Finland, in the cities of Lahti, Hämeenlinna and Vantaa. The distances between the reference stations are about 82 km, 84 km and 64 km. As the test net for determining the reliability, the uncertainty and the accuracy of the RTK-Network virtual concept GPS-test net of Southern Finland and the Klaukkala testfield of the Institute of Geodesy (IG) of Helsinki University of Technology (HUT) were used. The testing measurements were made together with the firm GeoTrim Oy and IG/HUT. The adjustment of the test net was made in the global coordinate system EUREF-FIN by using the three reference stations as the fixed points; the final testing and calibration results were calculated and analyzed in IG/HUT. The coordinates of the test net have been calculated by using the Bernese software and the precise ephemeris.

In the classical RTK GPS measurements one reference station is used. The effects of atmospheric refraction on the GPS radio signal restrict the use of the RTK measurements up to distances of 15 km (20 km) from the reference station to the rover. The solution for decreasing essentially the RTK relative positioining error depending on the distance of the rover from the reference station is the technique of the virtual reference station (VRS) by linking together several original reference stations for forming the RTK network. In the network a distance between the reference stations may be about 80 km. The calculation takes place in the network center: GPS data recording, the real time modeling of GPS errors among other things atmospheric errors and orbit errors of the satellites, the calculation of the virtual reference stations, the transmission of virtual data to the users, monitoring of the system and controlling the quality. It is possible to make RTK measurements rabidly and with good accuracy at the whole area of the network - even at the distance of 40 ... 45 km from the nearest physical reference station.

At the plane, in the regression analysis the value of the constant term of *(a)* varied between 17 mm ... 28 mm and the value of the relative term of *(a)* depending on the distance varied between 0.2 ppm ... 4.2 ppm. Considering also the discrepancies of the ortometric height *dH*, the corresponding values in the regression analysis of *(b)* were 25 mm ... 45 mm and 3.2 ppm 17.6 ppm. In the classical RTK GPS the distance between reference station and the rover weakens significantly the accuracy of coordinates.

For investigating the accuracy of the classical RTK GPS in detail measurements of the mapping, the RTK GPS -equipments of four different manufacturers were tested in the Otaniemi test field of IG/HUT. For transmitting the corrections to the rover the radio modem and also the GSM modem were used. Five reference stations were used; the distances between the reference points and the rover were 350 m, 2200 m, 4800 m, 12500 m and 21000 m. For determining the accuracy of the RTK mapping the discrepancies *dx*, *dy* and *dH* between the measured coordinates, the plane coordinates *x*, *y* and the ortometric height *H*, and the corresponding reference coordinates of the test field were calculated. For analyzing the accuracy, a total discrepancy of the plane coordinates, *(a)*, and a 3D-total discrepancy, *(b)*, were calculated using Pythagoras.

The Virtual Reference Stations (VRS) RTK GPS test measurements were made during September and October 2000. The test measurements included nine test points (known points) at the distance of 15 km …40 km from the nearest physical reference station, both inside and outside of their triangle. The measurements were made by Trimble/Spectra Precision Geotracer 3220 RTK system. In every test point was measured 10 independent VRS OTF fixed solutions. Always when system got fix solution then point was measured using stop&go VRS RTK mode, two 2 sec. and one 10 sec. measurements.

In the following are the means of the mean values of the coordinate discrepancies and of the total discrepancies (in millimeters) at the interpolation area and at the extrapolation area of the reference stations, i.e. the areal accuracy of the VRS RTK-Network: at the interpolation area

	MMdx	*MMdy*	*MMdH*	*MM(a)*	*MM(b)*
2 sec.	14	11	53	19	58
2 sec.	13	11	53	19	58
10 sec	. 14	12	54	19	59,

and at the extrapolation area:

	MMdx	*MMdy*	*MMdH*	*MM(a)*	*MM(b)*
2 sec.	15	7	30	15	34
2 sec.	15	9	36	19	43
10 sec	15	9	37	19	43.

The results of the regression analysis of the *(a)* values depending on the distances from the nearest reference station at the interpolation area and at the extrapolation area are as follows: *(â)* = a + b*s, were a is the constant term (in millimeter) and b is the relative term (in ppm):

at the interpolation area

2 sec.	a = 16.9 mm	+/- 8.6 mm,	b = 0.10 ppm	+/- 0.34 ppm
2 sec.	a = 17.3 mm	+/- 8.3 mm	b = 0.09 ppm	+/- 0.33 ppm
10 sec	a = 17.4 mm	+/- 8.4 mm,	b = 0.06 ppm	+/- 0.33 ppm

at the extrapolation area

2 sec.	a = 20.6 mm	+/- 2.3 mm	b = -0.06 ppm	+/- 0.08 ppm
2 sec.	a = 22.1 mm	+/- 2.4 mm	b = -0.10 ppm	+/- 0.08 ppm
10 sec	20.7 mm	+/- 0.8 mm	b = -0.06 ppm	+/- 0.03 ppm

It is possible to make VRS RTK measurements with good accuracy - even at the distance of 40 ... 45 km from the nearest physical reference station.

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1. THE CLASSICAL RTK GPS

In the classical RTK GPS technique, developed at the beginning in early nineties, the stationary reference receiver is located at a known point and the position of the moving receiver, the rover, is determined. This differential GPS method needs at least four common satellites for tracking simultaneously at both sites and also good satellite geometry. The main principle is that the known coordinates of the reference station are used to calculate corrections to the observed pseudoranges. After that corrections are transmitted normally via the mobile equipment to the rover. So it is possible to calculate the position of the rover dramatic more accuracy than in the mode of the single point positioning.

Two correction methods are in used. In the first method, the reference receiver at a known point calculates its position with the same satellites as the rover. The difference between the known coordinates and calculated coordinates yields position corrections. These values are then applied to the rover for improving the position. This method needs more complex satellite selection. The second method is based on pseudorange corrections: the difference between calculated ranges and observed pseudoranges at the known point. The observed pseudoranges of the rover may be corrected by applying pseudorange corrections of the known point. The method is more flexible, gives higher accuracy, and is the one in general use. (HOFMANN-WELLENHOF et al.1992).

The first commercial RTK GPS system was launced in 1993/94. The system was capable of computing coordinates in a real time. Computing of coordinates in a real time also allowed to use the GPS positioning for staking out. Shortly after the introduction of the first system with a single frequency, a dual-frequency version of the RTK GPS -system appeared, opening up GPS's widespread use for surveying. The initialization is needed for getting coordinates with the sufficiently accuracy. By using modern RTK GPS- equipments up to 30 seconds is needed for gaining an initialization. If the contact to at least four satellites remains in both the reference receiver and the rover after the initialization, the coordinate accuracy better than five centimeters can be achieved once a second or more often. (JENSEN 2000).

2. THE ACCURACY OF THE CLASSICAL RTK GPS

The RTK GPS –users need very different accuracy from several hundred meters to the centimeter level. Most GIS GPS -users make measurements with an accuracy of the meter level. But in the geodetic RTK-measurements, i.e. detail measurements, an accuracy of the centimeter level is required.

For investigating the accuracy of the classical RTK GPS in detail measurements of the mapping, the RTK GPS -equipments of four different manufacturers were tested in the Otaniemi test field of IG/HUT (SANTALA & VÄISÄNEN 2000).The radio modem and also the GSM modem were used for transmitting the corrections to the rover. Five reference stations were used; the distances between the reference points and the rover were 350 m, 2200 m, 4800 m, 12500 m and 21000 m. For determining the accuracy of the RTK mapping the discrepancies dx, dy and dH between the measured coordinates, plane coordinates x, y and ortometric height H, and the corresponding reference coordinates of the test field were calculated. For analyzing the accuracy, a total discrepancy of the plane coordinates, *(a)*, and a 3D-total discrepancy, *(b)*, were calculated: $(a)^2 = dx^2 + dy^2$ and $(b)^2 = dx^2 + dy^2 + dH^2$.

At the plane, in the regression analysis the value of the constant term of *(a)* varied between 17 mm ... 28 mm and the value of the relative term of *(a)* depending on the distance varied between 0.2 ppm ... 4.2 ppm. Considering also the discrepancies of the ortometric height dH, the corresponding values in the regression analysis of *(b)* were 25 mm ... 45 mm and 3.2 ppm ... 17.6 ppm. In the classical RTK GPS the distance between reference station and the rover weakens significantly the accuracy of coordinates.

3. RTK-NETWORK VIRTUAL CONCEPT

High accuracy Real-Time Kinematic (RTK) GPS positioning is one of today most widely used surveying techniques, but its use is restricted by many GPS errors such as ionosphere and troposphere effects which create systematic errors in the raw data. In practice, this means that the distance between a rover (mobile) receiver and its reference station has to be quite short (< 10-15 km) in order to work efficiently and with good quality.

The concept of Virtual Reference Stations (VRS, Fig. 1) gives a new enhanced opportunity for high accuracy RTK surveys. VRS RTK-Network means linking together several permanent reference stations. VRS is an integrated system of GPS hardware, software and communication links that utilizes data from permanent reference stations to model GPS errors throughout network region. In VRS concept, the systematic errors in the reference station data are either reduced or eliminated by the real time modeling of atmosphere errors. This allows a user to increase the distance between the rover receiver and physical reference stations (reference stations spaced even at 60 to 80 km), it also increase the reliability of the system and the quality of the measurements, and reduces the OTF initialization time.

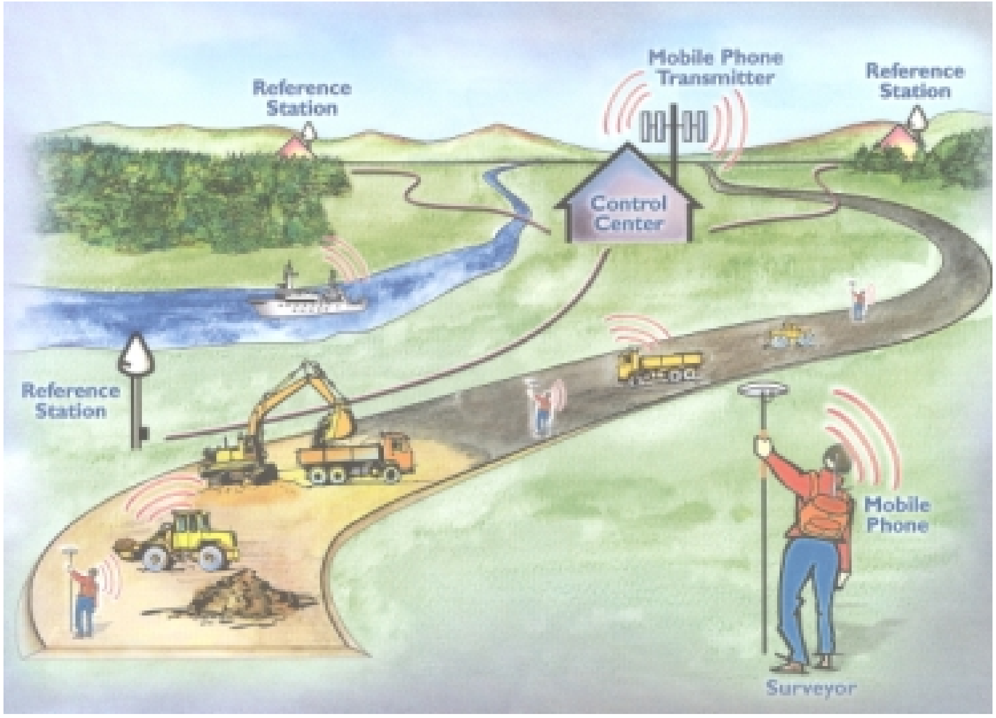

Fig. 1. VRS RTK-Network concept

In VRS concept all reference stations are connected to VRS control center and GPS observation data from all these stations is continuously transmitted to VRS server over modem, frame relay, internet or other communication link. The computer at the control center runs a VRS software suite called RTK-Network (made by Trimble Terrasat), this is the nerve center of the VRS concept.

RTK-Network software (Fig. 2) has several major tasks including:

- Monitoring the system and controlling the quality
- Raw data import and quality checks
- Reports from analyzing of the system and all data, alarm generation, and failure or error reporting via email and/or SMS (Short Message Service)
- RINEX and compact RINEX data storage
- Antenna phase center corrections (IGS models)
- Real Time modeling and estimation of systematic errors; troposphere, ionosphere, satellite orbit, multipath
- The calculation of the virtual reference stations (VRS) for users

– The generation and the transmission of RTK virtual data to the users
– Internet Web server for administration and distribution of all archived RINEX observation, navigation, meteorological and almanac files.The RTK virtual data stream can be transmitted as either RTCM or the more compact Trimble CMR format.

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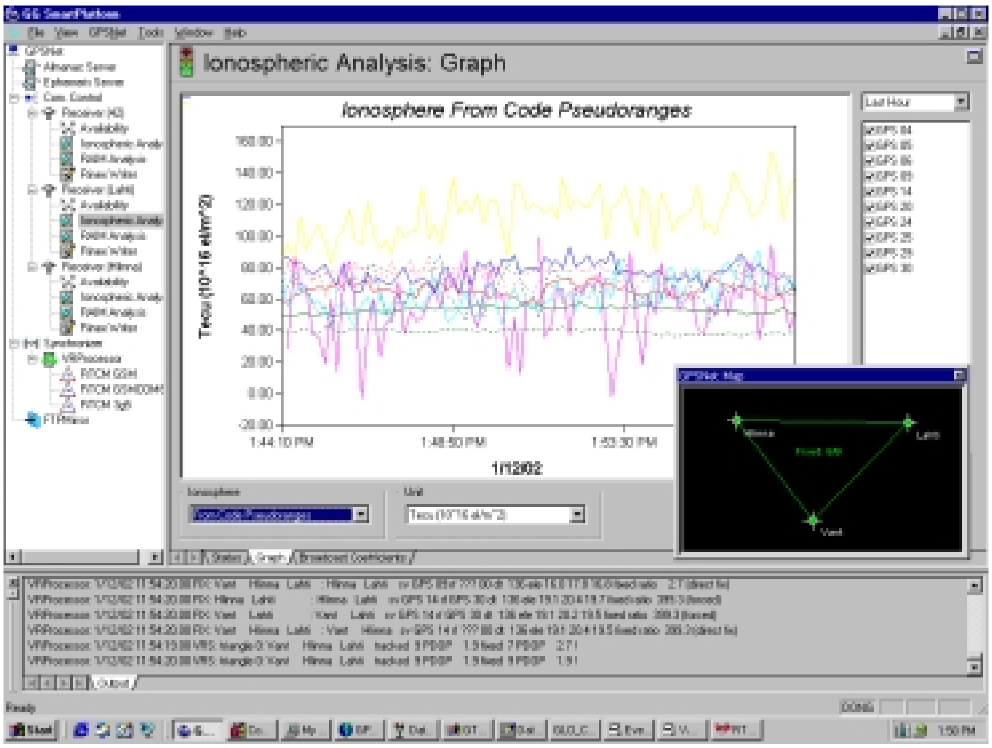

Fig. 2. VRS RTK-Network software (Trimble Terrasat)

How the VRS system works using mobile data link: First, the GPS Rover sends its approximate position to the VRS control center via cellular modem (GSM etc.) using standard NMEA GGA string. The control center automatic receives this position information, calculates “virtual reference station” for that individual rover, and sends RTK virtual data for the rover. This technique, of creating raw reference station data for a new, invisible, unoccupied station, is what gives the station its name, “The Virtual Reference Station”.

4. THE CALIBRATION FRAME FOR TESTING THE RTK-NETWORK

For calibrating the RTK-Network virtual concept the GPS-test net of Southern Finland of IG/HUT was applied. This net is used for testing and studying GPS- methods. This net has, in addition to the three points no. 1, 6 and 10 of the Klaukkala test field, five points, three of which viz. Rokokallio, Saari and Svartbäck, are the points of the Finnish First Order Triangulation, Sjökulla is a station of the Finnish Geodetic Institute (FGI) having several determinations with different space geodetic methods (GPS, VLBI, DORIS, as well as geodetic tie to the Space Geodetic Station Metsähovi) and Ilmala has also been tied geodetically to the first order triangulation. The distances between the points vary from 3 km to 80 km. All sides of the GPS-test net have been measured several times both in the measurement campaign of the HUT in 1994 and also earlier by the HUT and the FGI. The coordinates of the test net have been calculated by using the Bernese software and the precise ephemeris. The net can be utilized in testing GPS-receivers, evaluating different modes of GPS, studying tropospheric and ionospheric effects and studies of computation programs. (PARM 1994).

For testing the RTK-Network, the GPS-test net of Southern Finland was tied with the static GPS positioning to the three known points, i.e. the reference stations Vantaa, Hämeenlinna and Lahti. The distances between the reference stations are about 82 km, 84 km and 64 km. In addition, before RTK-test measurements the point no. 9968 named Hyvinkää was connected to the test net with the static GPS positioning. The whole test net (Fig. 3) consists of the points Sjökulla, Rokokallio, Ilmala, Svartbäck, 1, 6, 10, 9968, Saari, Vantaa, Hämeenlinna and Lahti. The static GPS positioning was made with five Geotracer 3220 receivers with five Minigeodetic antennas L1/L2.

The coordinates of the test net were calculated in IG/HUT by using the PRISM/SNAP adjustment program. In the network adjustment Vantaa, Hämeenlinna and Lahti were used as the known reference points. In the adjustment the biggest relative error of the vectors of the test net was 0.7 ppm. The coordinates of the three reference points were determined by the firm Geotrim Oy in the EUREF-FIN -coordinate system by Trimble Terrasat Geogenius2000 post processing software and using 7 days data set of all three stations and precise ephemerides. The final reference coordinates of the test net were obtained by transforming the adjusted coordinates to the EUREF-FIN plane coordinates (*x, y;* EUREF-FIN) and to the ortometric heights (*H*) by using the geoid model FIN-95. In the same way, the coordinates of the RTK-test measurements were transformed to the plane coordinates (*x, y;* EUREF-FIN) and ortometric heights (*H)*.

The test measurements included nine test points (known points) at the distance of 15…40 km from the nearest physical reference station, both inside and outside of their triangle.

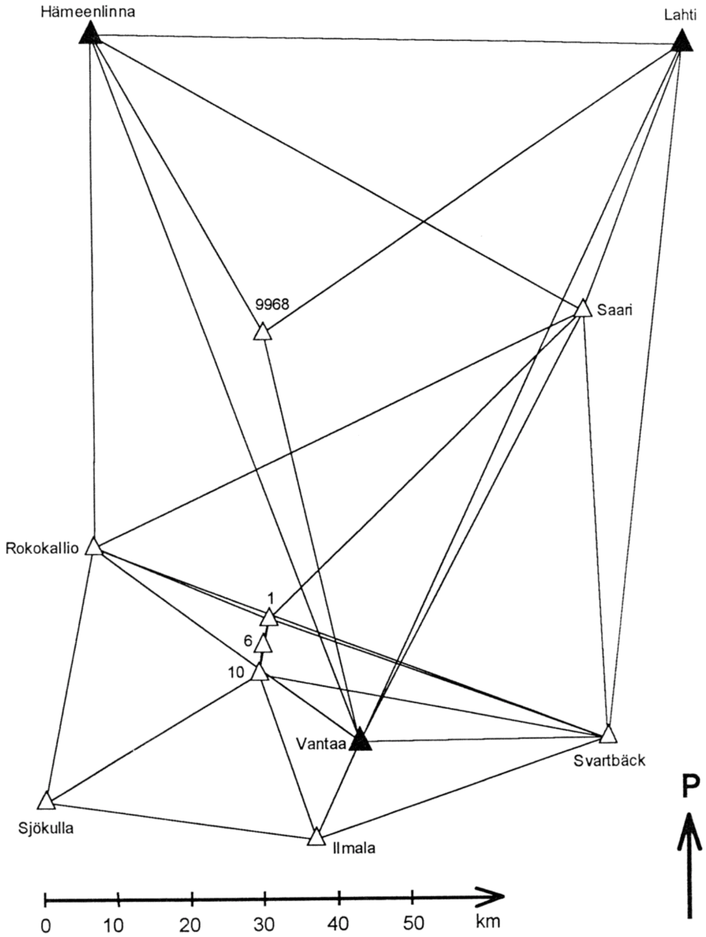

Figure 3. The test net for testing the VRS RTK-network.

5. VRS RTK TEST MEASUREMENTS

The Virtual Reference Stations (VRS) RTK GPS test measurements were made during September and October 2000 (Sept. 22nd, 24th, 25th, 27th, 28th and Oct. 3rd, 12th). The tests were made every day between 7 am. and 7 pm. local time. The test measurements included 9 test points (Fig. 3: Sjökulla, Rokokallio, Ilmala, Svartbäck, 1, 6, 10, 9968, Saari) at the distance of 15 km …40 km from the nearest physical reference station, both inside and outside of their triangle. The measurements were made by Trimble/Spectra Precision Geotracer 3220 RTK system with Minigeodetic L1/L2 GPS antenna. In every test point was measured 10 independent VRS OTF fixed solutions. Always when system got fix solution then point was measured using stop&go VRS RTK mode, two 2 sec. and one 10 sec. measurements. During tests number of tracked satellites varied from 5 to 9 and PDOP values were from 1.6 to 5.5. OTF initialization times were controlled too in these test and initialization times were from 10 to 180 seconds, 90 % < 60 seconds.

6. THE ANALYSIS OF THE TEST RESULTS OF THE VRS RTK-NETWORK

For determining the accuracy of the RTK-Network virtual concept the following calculations and analysis were made:

The standard deviation (precision or inner accuracy) of the coordinates was calculated for all the points measured with the VRS RTK-Network. The values of the standard deviation were calculated at the interpolation area and at the extrapolation area of the triangle formed by the reference points Vantaa, Hämeenlinna and Lahti. In every test point was measured 10 independent VRS OTF fixed solutions. Always when system got fix solution then point was measured using stop&go VRS RTK mode, two 2 sec. and one 10 sec. measurements. The standard deviation was calculated from every 10 independent initializations and separately from both 2 sec. measurements and 10 sec. measurements.

The discrepancies between the coordinates measured with the VRS RTK-Network and the reference coordinates of the test net were calculated, both at the interpolation area and the extrapolation area, for estimating the real accuracy and the standard deviation of the VRS RTK-Network measuring method. From these coordinate discrepancies a total discrepancy of the plane coordinates, *(a)*, and a 3D- total discrepancy, *(b)*, were calculated. The mean values of the discrepancies and of the total discrepancies were further calculated considering every 10 initialization with different measuring times two 2 sec. and one 10 sec.

By calculating the means of the coordinate discrepancies and of the total discrepancies the areal accuracy of the VRS RTK-Network was got both at the interpolation and at the extrapolation area. The areal accuracy was also estimated from every 10 initialization with measuring times two 2 sec. and one 10 sec.

7. THE RESULTS

7.1 Precision (Inner Accuracy) of the VRS RTK-Network at the Interpolation Area

No. of point/ Standard deviations (*mx*, *my* and *mH)* of coordinates measuring time measured with VRS RTK-Network in millimetre

	mx	*my*	*Mh*
1/ 2 sec.	6	5	14
1/ 2 sec.	4	5	13
1/ 10 sec.	5	5	13
6/ 2 sec.	4	4	11
6/ 2 sec.	4	5	8
6/ 10 sec	4	5	6
10/ 2 sec.	5	5	10
10/ 2 sec	5	5	9
10/ 10 sec	6	4	12
9968/ 2 sec	9	5	10
9968/ 2 sec	8	5	11

9968/ 10 sec.	9	4	12
Saari/ 2 sec.	12	7	15
Saari/ 2 sec	11	8	15
Saari/ 10 sec.	12	8	14

7.2 Precision (Inner Accuracy) of the VRS RTK-Network at the Extrapolation Area

No. of point / Standard deviations (*mx*, *my* and *mH)* of coordinates measuring time measured with VRS RTK-Network in millimetre.

	mx	*my*	*Mh*
Ilmala/ 2 sec.	6	5	9
Ilmala/ 2 sec.	4	5	6
Ilmala/ 10 sec.	3	4	5
Rokokallio/ 2 sec.	9	7	12
Rokokallio/ 2 sec.	9	6	13
Rokokallio/ 10 sec.	9	7	10
Sjökulla/ 2 sec.	9	5	14
Sjökulla/ 2 sec	9	6	13
Sjökulla/ 10 sec.	8	6	13
Svartbäck/ 2 sec.	8	4	8
Svartbäck/ 2 sec.	6	4	6
Svartbäck/ 10 sec.	6	4	7

7.3 The Accuracy of the VRS RTK-Network at the Interpolation Area

No. of point / The mean values of the coordinate discrepancies measuring time and of the total discrepancies (*Mdx*, *Mdy, MdH and M(a), M(b))* of VRS RTK-Network in millimetre

	Mdx	*Mdy*	*MdH*	*M(a)*	*M(b)*
1/ 2 sec.	23	12	90	26	94
1/ 2 sec.	23	12	91	26	95
1/ 10 sec.	24	13	93	27	97
6/ 2 sec.	15	12	64	20	67
6/ 2 sec.	15	12	61	20	65
6/ 10 sec	14	13	62	19	65
10/ 2 sec.	4	7	62	9	62
10/ 2 sec	5	7	62	9	63
10/ 10 sec	5	7	63	9	63
9968/ 2 sec	7	13	15	16	2
9968/ 2 sec	6	14	16	16	24
9968/ 10 sec.	. 7	14	19	16	26
Saari/ 2 sec.	19	13	33	25	43
Saari/ 2 sec	18	12	33	23	43
Saari/ 10 sec.	18	12	33	22	43

The means of the mean values of the discrepancies

	MMdx	*MMdy*	*MMdH*	*MM(a)*	*MM(b)*
2 sec.	14	11	53	19	58
2 sec.	13	11	53	19	58
10 sec.	14	12	54	19	59

7.4 The Accuracy of the VRS RTK-Network at the Extrapolation Area

No. of point/ The mean values of the coordinate discrepancies measuring time and of the total discrepancies (*Mdx, Mdy, MdH and M(a), M(b))* of VRS RTK-Network in millimetre:

	Mdx	*Mdy*	*MdH*	*M(a)*	*M(b)*
Ilmala/ 2 sec.	18	5	8	20	22
Ilmala/ 2 sec.	20	4	4	21	22
Ilmala/ 10 sec.	19	5	4	20	21
Rokokallio/ 2 sec.	19	6	38	20	38
Rokokallio/ 2 sec.	18	5	37	20	37
Rokokallio/ 10 sec.	18	6	36	19	37
Sjökulla/ 2 sec.	7	15	65	17	68
Sjökulla/ 2 sec	7	15	66	17	69
Sjökulla/ 10 sec.	7	16	68	18	70
Svartbäck/ 2 sec.	17	9	38	19	43
Svartbäck/ 2 sec.	16	10	37	19	42
Svartbäck/ 10 sec.	15	10	38	19	43

The means of the mean values of the discrepancies

	MMdx	*MMdy*	*MMdH*	*MM(a)*	*MM(b)*
2 sec.	15	7	30	15	34
2 sec.	15	9	36	19	43
10 sec.	15	9	37	19	43

7.5 The Areal Accuracy at the Interpolation Area.

<u>7.5.1 The Regression Analysis of the *(a)* Values Depending on the Distances from the Nearest Reference Station</u>

(â) = a + b*s , were a is the constant term (in millimeters) and b is the relative term (in ppm)

2 sec.	a = 16.9 mm	+/- 8.6 mm,	b = 0.10 ppm	+/- 0.34 ppm
2 sec.	a = 17.3 mm	+/- 8.3 mm	b = 0.09 ppm	+/- 0.33 ppm
10 sec	a = 17.4 mm	+/- 8.4 mm,	b = 0.06 ppm	+/- 0.33 ppm

7.5.2 The Regression Analysis of the *(b)* Values Depending on the Distances from the Nearest Reference Station

2 sec.	a = 101.9 mm	+/- 18.5 mm	b = - 1.94 ppm	+/- 0.74 ppm
2 sec.	a = 101.4 mm	+/- 18.9 mm	b = - 1.91 ppm	+/- 0.76 ppm
10 sec	a = 101.5 mm	+/- 19.7 mm,	b = - 1.88 ppm	+/- 0.79 ppm.

7.6 The Areal Accuracy at the Extrapolation Area

7.6.1 The Regression Analysis of the *(a)* Values Depending on the Distances from the Nearest Reference Station

2 sec.	a = 20.6 mm	+/- 2.3 mm	b = -0.06 ppm	+/- 0.08 ppm
2 sec.	a = 22.1 mm	+/- 2.4 mm	b = -0.10 ppm	+/- 0.08 ppm
10 sec	20.7 mm	+/- 0.79 mm	b = -0.06 ppm	+/- 0.03 ppm

10 sec. a = 20.7 mm, b = -0.06 ppm +/- 0.03 ppm.

7.6.2 The Regression Analysis of the (b) Values Depending on the Distances from the Nearest Reference Station

2 sec.	a = 7.7 mm	+/- 23.4 mm	b = 1.28 ppm	., +/- 0.81 ppm
2 sec.	a = 7.4 mm	. +/- 24.9 mm	b = 1.28 ppm	+/- 0.86 ppm
10 sec	a = 6.0 mm	+/- 25.7 mm	b =.1.34 ppm	+/- 0.88 ppm

8. CONCLUSIONS

In the classical RTK GPS measurements the effects of atmospheric refraction on the GPS radio signal restrict the use of the RTK measurements up to distances of 10-15 km from the reference station to the rover. In addition the accuracy of classical RTK GPS is the distance depending which means that the distance between reference station and the rover weakens significantly the accuracy of coordinates.

The solution for reduce or eliminate the RTK relative positioning error depending on the distance of the rover from the reference station is the technique of the virtual reference station (VRS) by linking together several permanent reference stations for forming the RTK network. This gives a lot of benefits compared to classical RTK surveys. VRS improve significantly both productivity and measurement quality. VRS concept can eliminate the need to set up a reference station so user needs only a GPS rover unit. VRS RTK-Network software monitor continuously in real time the whole RTK- Network system and all data for users is high quality checked. The accuracy of VRS RTK measurement is high quality (reliability and accuracy) in whole Network region (reference stations spaced even at 60 to 80 km), the distance from a rover to reference station not weakens the accuracy, ppm effect is very close to 0.

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