Comparison of TurboRogue and Trimble SSi GPS receivers for ionospheric investigation under anti-spoofing

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Summary: TurboRogue SNR-8000 and Trimble 4000SSi GPS receivers are compared using the observations from "near" and "far" calibration arrangements under anti-spoofing. In the case of the near calibration the Single Station and Single Satellite Method of the ionospheric investigations proved to be a good procedure to estimate the differential receiver biases, namely the difference of the receiver code synchronization biases (ΔCB) and the difference of the phase center variations on the optimum ionospheric combinations. The repeatability of the ΔCB bias was ±0.24 nsec in the case of near and ±0.94 nsec in the case of far calibration arrangement. In spite of that the noise level of the TurboRogue receiver is better by about 10% with respect to the Trimble SSi, their performances are practically the same.

Zusammenfassung: Die TurboRogue SNR-8000 und Trimble 4000SSi GPS-Empfänger wurden mit Hilfe eines „nahen" und eines „weiten" Kalibrierungsaufbaus unter Anti-Spoofing miteinander verglichen. Bei dem „nahen" Kalibrierungsaufbau stellte sich heraus, daß die „Single Satellite and Single Station" Methode ein geeigneter Ansatz zur Bestimmung der differentiellen Verzögerungsdifferenzen der Empfänger, d. h. der Differenz zwischen der Code-Synchronisationsfehlern (ΔCB) und der Differenz der Phasenzentrumsvariationen, ist. Die Wiederholbarkeit bei der Schätzung von ΔCB betrug ±0.24 nsec bei der „nahen" und ±0.94 nsec bei dem „weiten" Kalibrierungs-aufbau. Obwohl der Rauschpegel des TurboRogue Empfängers um ca. 10% niedriger als der Rauschpegel des Trimble-Empfängers liegt, ist die Qualität der beiden Empfänger praktisch die gleiche.

Keywords: GPS measurements, code synchronization bias, total electron content of ionosphere and plasmasphere, single layer model, GPS receivers, calibration

1 Introduction

The series of Rogue GPS receivers produced by the Allen Osborne Associates were the very first instruments providing reliable dual frequency data under anti-spoofing using the method of cross-correlation for practical and scientific applications (*Meehan* 1992). That is the reason why the Rogue receivers are preferred in the network of International GPS Geodynamic Service (IGS). However, the two latest models of Trimble geodetic receivers (SSE and SSi) are also capable to provide a comparably good quality of cross-correlation data. Therefore, these instruments are also used frequently at different permanent stations even in the case of IGS network.

The Scientific and Technical Co-operation Project initiated by the Institute of Physical Geodesy of TH-Darmstadt and the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences have addressed the thorough comparison of Trimble SSi and TurboRogue SNR-8000 GPS receivers available at the institutions for the purpose of ionospheric investigation under the limitation of anti-spoofing. In this paper the practical results of the co-operation are summarized.

2 Observation arrangements and observation sites

For the comparison of different receiver types and for the investigation of the Single Station and Single Satellite (S^4) method developed for GPS ionospheric investigation, two different observation arrangements were used.

In the case of the so-called "near calibration" arrangement the two antennas were placed at the same platform, the Rogue antenna north and the Trimble antenna south of the reference station of the TH-Darmstadt situated at the roof of the Institute's building. The horizontal distance between the antenna centers was 71 cm. Assuming that the ionospheric effects should be the same, this arrangement is very suitable to estimate the differences of receiver biases and the level of observation noise. Three days of observations were carried out in Darmstadt using 30 s sampling rate between October 27 and 29, 1995.

In the case of the "far calibration" arrangement the TurboRogue receiver was moved back to the GPS Ionospheric Station Sopron (GISS) in Hungary and the observations were repeated between November 9 and 11, 1995. Comparing the receiver biases estimated from the two different arrangements, we can investigate the usefulness of the S^4 method, too.

Unfortunately, during the first measurements there were some interference problems at the GPS reference station in Darmstadt, which made the P-code tracking of Trimble SSi on the L2 channels practically useless. Using the cross-correlation tracking the data were acceptable but a lot of gaps and cycle slips were encountered.

The GISS station in Sopron is also situated at the roof of the Institute's building. The choke-ring antenna is placed at the height of the wire system which is built to avoid the lightning. During P-code tracking the TurboRogue receiver indicates a very low noise level. In the case of cross-correlation tracking the noise level is considerably higher.

3 Method of data processing

During the data processing the experiences of our previous investigations (*Bányai* and *Eper-Pápai* 1996) were taken into account.

The basic observables are the geometry-free linear combinations of code and phase measurements:

$$R_2 - R_1 = c\,(\mathrm{d}t_R^r + \mathrm{d}t_R^s) + \frac{1}{\sin E'}\,\frac{A}{2}\,\frac{f_1^2 - f_2^2}{f_1^2\,f_2^2}\,I_v + \varepsilon_R \tag{1}$$

$$\lambda_2\,\phi_2 - \lambda_1\,\phi_1 = (\lambda_2\,N_2 - \lambda_1\,N_1) + c\,(\mathrm{d}t_\phi^r + \mathrm{d}t_\phi^s) - \frac{1}{\sin E'}\,\frac{A}{2}\,\frac{f_1^2 - f_2^2}{f_1^2\,f_2^2}\,I_v + \varepsilon_\phi \tag{2}$$

where

R	pseudorange or code observable (m)
ϕ	phase observable (cycles)
$\mathrm{d}t_R^r$	code synchronization bias of the receiver
$\mathrm{d}t_R^s$	code synchronization bias of the satellite
$\mathrm{d}t_\phi^r$	phase synchronization bias of the receiver
$\mathrm{d}t_\phi^s$	phase synchronization bias of the satellite
N	phase ambiguity (unknown initial phase)
f	frequency (1/s)
c	speed of light (m/s)
λ	wavelength (m)
A	constant (80.6 $\mathrm{m}^3\,\mathrm{s}^{-2}$)
ε	random observation errors and not modeled errors: multipath, phase center variation and higher order ionospheric effects.

The indices 1 and 2 mean the L1 and L2 carriers, respectively. The elevation angle (E') of the mapping function and the first order vertical total electron content (I_v) of the ionosphere (and plasmasphere) are referred to the so-called ionospheric point, which is computed from the single layer model defined by the mean height of the ionosphere (and plasmasphere).

These equations are valid if the L1 and L2 phase centers coincide. In the case of TurboRogue antenna 2.30 cm mean height difference is reported (*Breuer* et al. 1995) which is significantly larger then the accuracy of phase measurements. The effect of this bias on the geometry-free combinations varies with the satellite elevation (E) with respect to the observation site. Because this bias and the $E'-E$ differences are small it cannot be separated from I_v. It can be corrected by the reported value or may be neglected during the ionospheric investigations because the effect is below 0.1 ns.

The geometry- and ionosphere-free linear combinations contain only biases and observation errors:

$$R_2 - R_1 + \lambda_2\,\phi_2 - \lambda_1\,\phi_1 = c\,(\mathrm{d}t_R^r + \mathrm{d}t_R^s) + (\lambda_2\,N_2 - \lambda_1\,N_1) + c\,(\mathrm{d}t_\phi^r + \mathrm{d}t_\phi^s) + \varepsilon\,.$$

Removing the cycle slips this combination should be a constant value, however significant linear trend was experienced even in the case of P-code measurements (*Bányai* and *Eper-Pápai* 1996). To solve this problem, the

$$A0 + A1 * (t - t_m)$$

polynomial fit is proposed where t_m is the mean observation time (UT), $A0$ contains the mean biases at t_m and $A1$ describes the linear trend. This model leads to the optimum ionospheric combination:

$$\lambda_2\,\phi_2 - \lambda_1\,\phi_1 - A0 = -\frac{1}{\sin E'}\,\frac{A}{2}\,\frac{f_1^2 - f_2^2}{f_1^2\,f_2^2}\,I_v - c\,(\mathrm{d}t_R^r + \mathrm{d}t_R^s) + \varepsilon\,, \tag{3}$$

which is practically the shift of (2), where the phase ambiguities (and biases) are replaced by the more meaningful code synchronization biases.

While the relative accuracy of this combination can be characterized by the accuracy of phase measurements the repeatability of the code synchronization biases can be concluded from the standard deviation of the linear fit. All the errors of the $A0$ value constantly bias the least-square estimate of the code synchronization biases.

Before the least squares adjustment it is reasonable to rearrange our observation equation as

$$\varepsilon = \frac{1}{\sin E'}\,P(\phi, t) + \mathrm{CB} - L\,,$$

where the vertical ionospheric effects ($P(\phi, t)$) and the sum of the code synchronization biases (CB) are expected in meter dimension, ε is the residual and L is the observation term. In the case of the world-wide used multi satellite approach (*Sardón* et al. 1994, *Wanninger* et al. 1994, *van der Marel* and *Georgiadou* 1994) the $P(\phi, t)$ function is approximated by a low order surface polynomial, where ϕ is a spherical latitude and t is the local time of the ionospheric points.

As a possible alternative a Single Station and Single Satellite (S^4) Method was introduced, where the two variables are replaced by one variable (ϑ). The solution is given on the analogy of the spherical distances:

$$\cos(\vartheta_{AB}) = \sin(\phi_A)\sin(\phi_B) + \cos(\phi_A)\cos(\phi_B)\cos(t_A - t_B)\,,$$

where A and B denote two neighbouring ionospheric points and the local time is scaled by $\pi/12$ from hour to radian.

From the series ϑ_{AB} values along one satellite pass we can compose a new variable which includes the information from the original surface system.

Because of the high correlation between the CB and the estimated coefficients a zero and odd order terms of the Legendre polynomial proved to be the best choice as an ionospheric trend function.

4 Results of the investigations

Because our main goal was the intercomparison of the different receiver types and the S^4 Method of ionospheric investigations we refer only to those satellite passes which were observed without gaps and cycle slips by the two receivers simultaneously.

In the first step of the computations the geometry-free combinations are subtracted from the binary data files in a satellite by satellite sense. In the second step the observations below 20 degrees of elevation angle with respect to the observation site are deleted, the data gaps, the cycle-slips and the symmetry of the observations are controlled as well as the optimum ionospheric observables are derived. In the next step the parameters of the ionospheric points are computed. The final step is the separation of the CB and the vertical ionospheric effects using the zero and odd number terms of the Legendre polynomials up to 5th order.

The most representative results of the different arrangements can be found in Table 1 and Table 2 where the TurboRogue minus Trimble SSi differences of the receiver code synchronization biases (ΔCB) , the differences between the vertical ionospheric effects estimated by the trend functions at the reference time ($\Delta P(0)$) and the 1σ standard deviations of the linear fit of the different receivers are presented. In the case of "near calibration" arrangement the direct statistical investigation of the estimated vertical ionospheric delay differences (ΔVID) are also included.

The first conclusion is the very high noise level of the observations described by the 1σ standard deviations of the linear fit. Especially in the case of the observations in Sopron, where a value worse than 0.6 ns was not expected. The changes of the estimated CB values (not included in the Tables) are in accordance with the 1σ values and are the same from statistical point of view.

In the case of "near calibration" arrangement the noise level is always smaller by 10% in the case of TurboRogue receiver. In spite of the high noise level the differences given in Table 1 are very stable which proves the usefulness of the near calibration arrangement and the similar behaviour of the two receiver types.

The bias of the $\Delta P(0)$ values should be due to the fact that the difference between the L1 and L2 mean phase center heights is not the same for the two receiver types. According to *Breuer* et al. (1995) these differences are −0.0037 m for the Trimble SSi and −0.0230 m for the TurboRogue receivers, respectively. The difference between the two antennas is −0.0267 m, which agrees quite well with the mean bias of $\Delta P(0)$ (-0.0209 ± 0.0035 m). The same results can be concluded from ΔVID differences. One typical example can be found in Fig. 1 a, b. The Fig. 1 a shows the estimated vertical ionospheric effects after the CB delays are removed. The curve of the Trimble SSi observations shows a larger random error variations than the curve of the TurboRogue observations. The curve of the differences (Fig. 1 b) shows a systematic sinusoidal variable term with about 1 cm amplitude around the average value.

In the case of the "far calibration" arrangement the $\Delta P(0)$ values are also biased by the phase center offset, but it cannot be separated from the ionospheric effect because the observation sites are 629 km apart and the signals should travel on different paths in the ionosphere. The changes of the estimated ΔCB values do not show such a good repeatability as in the case of the "near calibration". This fact proves that the S^4 Method of ionospheric investigation produces results which agree well with the absolute accuracy of the optimum ionospheric observables even in the case of "far calibration" arrangement.

Table 1. Near calibration GPS measurements in Darmstadt by TurboRogue and Trimble SSi Receivers, October 1995. $\Delta P(0)$ – difference of vertical ionospheric delays estimated by the trend functions at the reference time, ΔCB – difference of receiver code biases, σ – std. dev. of linear fit of the geometry- and ionosphere-free linear combinations, ΔVID – mean and std. of the estimated vertical ionospheric delays

Day	Sat	$\Delta P(0)$ (m)	ΔCB (ns)	σ (ns) Rogue	σ (ns) Trimble	ΔVID (m)
27	14	−0.0204	−8.59	0.92	1.03	−0.0204 ± 0.0044
29		−0.0170	−8.80	0.73	1.04	−0.0170 ± 0.0036
27	29	−0.0191	−7.98	0.91	0.92	−0.0190 ± 0.0040
29		−0.0210	−8.44	0.90	1.12	−0.0210 ± 0.0045
27	18	−0.0248	−8.38	0.97	1.01	−0.0248 ± 0.0045
29		−0.0249	−8.64	0.88	0.91	−0.0249 ± 0.0035
27	27	−0.0200	−8.18	0.91	1.02	−0.0200 ± 0.0035
29		−0.0199	−8.36	0.93	0.98	−0.0199 ± 0.0035
27	5	−0.0288	−8.13	0.83	0.93	−0.0290 ± 0.0066
29		−0.0193	−8.19	0.70	0.91	−0.0193 ± 0.0045
27	20	−0.0177	−8.48	0.85	0.94	−0.0177 ± 0.0046
29		−0.0184	−8.50	0.72	0.92	−0.0183 ± 0.0045
mean:		−0.0209 ± 35	−8.39 ± 24			

Table 2. Far calibration GPS measurements in Sopron by TurboRogue and in Darmstadt by Trimble SSi Receivers, November 1995. $\Delta P(0)$ – difference of vertical ionospheric delays estimated by the trend functions at the reference time, ΔCB – difference of receiver code biases, σ – std. dev. of linear fit of the geometry- and ionosphere-free linear combinations

Day	Sat	$\Delta P(0)$ (m)	ΔCB (ns)	σ (ns) Rogue	σ (ns) Trimble
9	17	0.1653	−9.15	0.54	1.01
11		0.1154	−9.75	0.45	1.05
9	4	−0.2815	−8.20	1.64	0.88
11		0.1413	−10.51	1.35	0.92
9	18	−0.1636	−8.72	1.14	0.95
11		0.1279	−10.26	0.81	0.98
9	26	−0.2688	−7.72	0.91	0.85
11		−0.3567	−7.52	0.67	0.86
9	5	−0.0932	−8.81	0.70	0.91
11		−0.1220	−9.76	0.65	0.97
9	25	−0.0772	−9.11	0.99	0.85
11		−0.0576	−9.20	1.04	0.88
mean:			−9.06 ± 94		

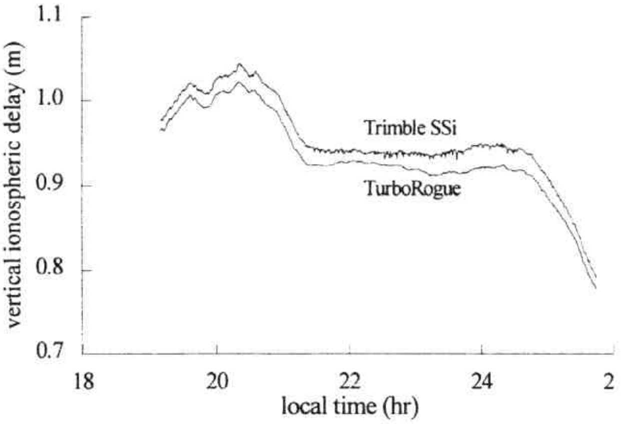

Fig. 1 a. Estimated vertical ionospheric delays from near calibration arrangement (PRN 5, 29.10.1995)

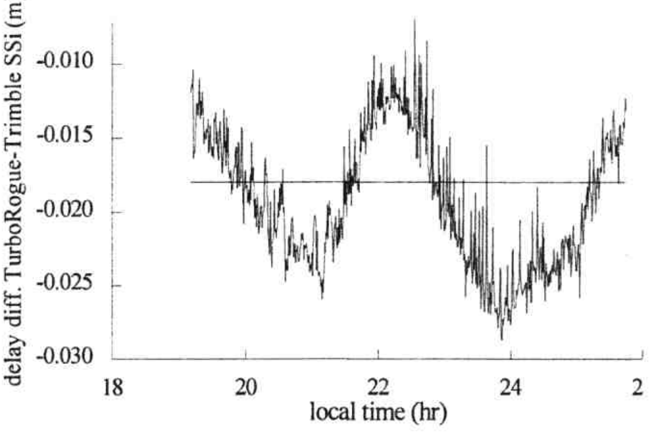

Fig. 1 b. Vertical ionospheric delay differences between TurboRogue and Trimble SSi receivers – effect of the phase center differences (PRN 5, 29.10.1995)

5 Conclusions

The "near calibration" observation arrangement and the Single Station and Single Satellite Method of the ionospheric investigations proved to be a good procedure to estimate the difference of the receiver code synchronization biases (ΔCB) and to indicate the effect of the phase center variation differences of the antennas on the optimum ionospheric combination.

In spite of the experienced relatively high noise level of the optimum ionospheric combinations (±1 ns) the average ΔCB value for different satellite passes in different days is better than 0.3 ns which proves a similar performance of the two receiver types. The estimated average value and the sinusoidal difference between the vertical ionospheric delays are in good accordance with the reported phase center characteristics of the TurboRogue and the Trimble SSi antenna. Removing this systematic effect the random part can be characterized by ±3 mm which agrees well with the expected phase measurement accuracy.

In the case of the "far calibration" arrangement the phase center offsets cannot be separated from the ionospheric effects and the repeatability of the ΔCB values is worse (±0.9 ns). In spite of that they are in accordance with the noise level of the optimum ionospheric combinations, it can be used to characterize the accuracy of the ionospheric investigations under anti-spoofing.

In spite of that the noise level of the TurboRogue receiver is better by about 10% with respect to the Trimble SSi, their performances are practically the same. The only significant bias is the elevation-dependent difference of the phase center variation, which should be considered in the case of common high precision geodetic applications.

The "near calibration" observation arrangement and the Single Station and Single Satellite Method is proposed for the regular calibration of the GPS receivers used in ionospheric networks. The antenna phase center differences can be controlled and the differences of the receiver code synchronization biases can be estimated with the accuracy of 0.3 ns even under anti-spoofing.

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Tagungen, Symposien, Ausstellungen

3. AdV-Symposium ATKIS, 29. und 30. Oktober 1996 in Koblenz

Am 29. und 30. Oktober 1996 fand in Koblenz das dritte Symposium der Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland (AdV) zum Amtlichen Topographisch-Kartographischen Informationssystem ATKIS statt. Die Veranstaltung wurde durch das Landesvermessungsamt Rheinland-Pfalz ausgerichtet. Mitveranstalter waren die Fachfirmen AED Graphics, Bonn – Dornier, Friedrichshafen – ESRI, Kranzberg – IBM Deutschland, Bonn – Intergraph Deutschland, Ismaning – LUM, Selfkant-Hillensberg – ibR, Bonn und Siemens-Nixdorf, München. Die Vorträge sowie Firmen- und Fachpräsentationen fanden unter der Gesamtthematik „Das Geoinformationssystem ATKIS und seine Nutzung in Wirtschaft und Verwaltung" im Rhein-Mosel-Congress-Centrum (Rhein-Mosel-Halle) statt. Der Veranstaltung wohnten ca. 450 Teilnehmer bei; sie stammten aus den Bereichen Vermessungsverwaltung (36%), allgemeine Verwaltung (18%), Kommunalverwaltung (10%), gewerbliche Wirtschaft (32%) und Hochschulen/Universitäten (4%).

Kernstück des Symposiums bildeten 27 Fachvorträge. In jeweils zusammenfassenden Vortragsblöcken wurde berichtet zu: „ATKIS-ALB/ALK Geobasisdaten der Landesvermessung und des Liegenschaftskatasters", „ATKIS in Planung und Umweltschutz", „ATKIS in Einsatzleitung und Ereignisanalyse", „ATKIS-Software und ATKIS-Anwendungen/Firmenpräsentationen", „Aktualisie-