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A Comparison of Broadcast and Final Orbits on GPS Delays in GPS-VLBI Hybrid Observation

Younghee Kwak[1†], Jungho Cho[1], Tetsuro Kondo[2], Hiroshi Takiguchi[3], Jun Amagai[2], Tadahiro Gotoh[2], Mamoru Sekido[2], Ryuichi Ichikawa[2], Tuhwan Kim[4], Tetsuo Sasao[5]

[1]Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
[2]National Institute of Information and Communications Technology, Ibaraki 314-0012, Japan
[3]Auckland University of Technology (AUT) Duthie Whyte Building, Level 1, 120 Mayoral Drive, Auckland 1010, New Zealand
[4]Ajou University, Suwon 443-749, Korea
[5]Yaeyama Star Club, 2097-2 Arakawa, Ishigaki, Okinawa 907-0024, Japan

ABSTRACT

We carry out an error analysis of 24-hour global positioning system (GPS)-very long baseline interferometry (VLBI) (GV) hybrid observation data. In this paper, we focus on the impacts of broadcast and final orbits on the GPS delays of the GV hybrid observation by analyzing the residuals, observed - calculated (O-C) values. The residuals show apparent and consistent biases for L1 and L2 signals, respectively. The scatters of the residuals are around a few nanoseconds. The main cause of those observation errors is the absence of the GPS phase and delay calibration system. Most of the satellites show that the differences between the delays, to which broadcast and final orbits are applied, are about 100 times smaller than the current GV hybrid observation errors. We conclude that GPS delays are not greatly affected by orbit accuracies.

Keywords: VLBI, GPS, GV hybrid observation, GPS satellite ephemeris, delay

1. INTRODUCTION

Through observing celestial bodies, e.g. quasars, the moon, or artificial satellites, by means of space geodetic techniques on a global scale, the precise shape and rotation of the Earth can be determined. The space geodetic techniques include very long baseline interferometry (VLBI), global navigation satellite system (GNSS), satellite laser ranging (SLR), and doppler orbit determination and radiopositioning integrated on satellite (DORIS). Each technique estimates limited parameters depending on their observation targets and methods. Therefore, it is required to combine space geodetic techniques in order to determine all kinds of earth shape (station positions and velocities) and rotation (nutation, polar motion, UT1 and their rates) parameters. The combination of the space geodetic techniques can be classified into product level, normal equation level, and observation level based on the combination targets and methods (Altamimi, Sillard & Boucher 2002, Angermann et al. 2004, http://www.iers.org/WGCOL).

As part of combining space geodetic techniques in observation level, the global positioning system (GPS)-VLBI (GV) hybrid system was developed (Kwak 2011). The system integrates two techniques that observe radio signals, VLBI and GPS. The system receives quasar and GPS satellite signals at the same time with directional radio telescopes and omni-directional GPS antennas respectively based on the observation characteristics of each technique. Those signals pass through the same sampling, recording and correlation processes.

Since the GV hybrid system combines two techniques by using an identical frequency standard, common clock parameters are estimated for both techniques so that the systematic errors between two instruments and number

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†Corresponding Author
E-mail: bgirl02@kasi.re.kr
Tel: +82-42-865-2031 Fax: +82-42-861-5610

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of clock parameters to be estimated are reduced. As the amount of observation data is increased, it is possible to estimate the atmospheric parameters more frequently and/or precisely. Dickey (2010), who suggested a similar concept compared to this system, anticipated that it would be possible to directly connect the origin of the VLBI terrestrial reference frame (TRF) to the center of the Earth by combining GPS which could determine the center of the Earth mass and VLBI which determines only the relative baselines. Also, by integrating VLBI which constructs the international celestial reference frame (ICRF) and GPS which determines the orbits of GPS satellites, it would be possible to express the orbits of GPS satellites directly on ICRF.

The 24-hour GV hybrid experiment was carried out over the period between December 25th and 26th, 2009 (Kwak 2011). In this study, we introduce analysis results of the residuals between observed and theoretical values, and discuss the causes of the observation errors. In particular, by applying broadcast and final orbits and comparing both results, we analyze the impacts of GPS satellite ephemerides on the precision of GV hybrid observation.

2. GPS–VLBI HYBRID OBSERVATION

The GV hybrid system measures the arrival time differences of the received radio signals from the same satellite by each GPS antenna. Such a method is different from the one for calculating the distance between the satellite and the GPS antenna based on correlation of the GPS satellite signals and the replica signals in GPS receiver. It is similar to the single difference in the GPS processing technique. The system obtains the values corresponding to the single difference by directly correlating the same GPS satellite signals reaching each GPS antenna (Fig. 1). For such a purpose, the VLBI software correlator is used. While VLBI receives the signals of the single radio source by using the directional radio telescope, GPS uses the omni-directional antenna. Hence, it is possible to simultaneously receive the signals sent by every GPS satellite in the observer's sky. By inserting the predicted value for one satellite to the correlator, other satellite signals are canceled out during correlation and finally only the correlation fringe peak for that satellite are obtained.

The observables for the GPS satellite signals obtained from the GV hybrid observation are defined as the delay of the signal arrival time in the same way as the terms used for VLBI. Fig. 2 shows those observables. Every delay varies based on the orbital motion of each satellite. The observation equation for the GPS observables τ_{Gi} of *i-th* satellite is shown in Eq. (1).

$$\tau_{Gi} = \frac{\left|\vec{R}_{Si} - \vec{r}_l\right|}{c} - \frac{\left|\vec{R}_{Si} - \vec{r}_m\right|}{c} + \tau_{Ci} + \tau_{Ai} + \varepsilon_i \qquad (1)$$

where $\vec{R}_{Si}$ is the satellite position vector, while $\vec{r}_l$ and $\vec{r}_m$ are the position vectors of the reference points for the *l*- and the *m-th* GPS antennas. τ_{Ci}, τ_{Ai}, ε_i and c mean the clock synchronization error, the atmospheric delay, the observational error and the speed of light. The VLBI observation equation is given in Eq. (2).

$$\tau_V = -\frac{\vec{B} \cdot \vec{s}}{c} + \tau_C + \tau_A + \varepsilon_V \qquad (2)$$

where $\vec{B}$ is the baseline vector, while $\vec{s}$ is the position

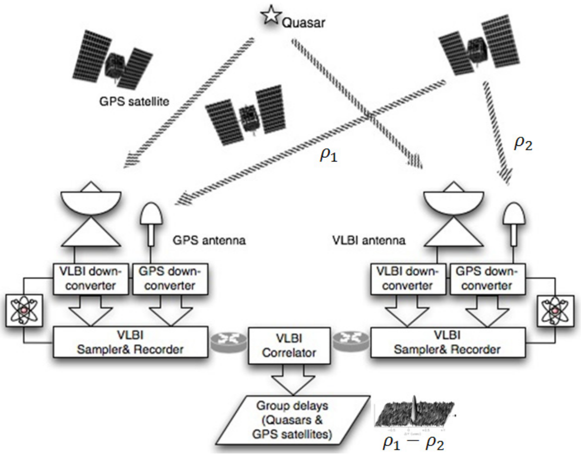

Fig. 1. Conceptual diagram of the GV hybrid system (Kwak et al. 2012).

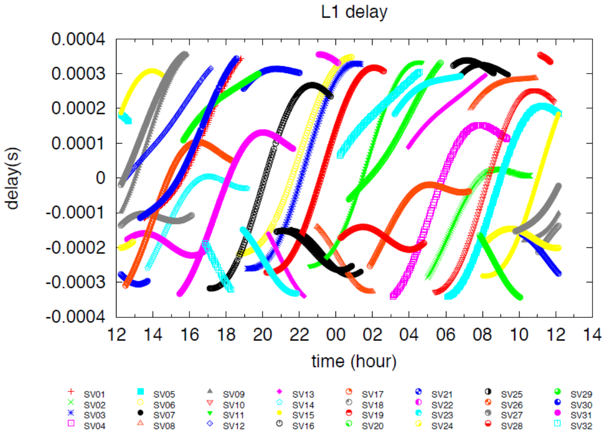

Fig. 2. The L1-band observables. L2-band also has identical trends. Each symbol means the PRN number for the identification of the satellite (Kwak 2011).

vector of the radio source. By combining the two observation equations shown above, clock and atmospheric parameters are estimated as common parameters for both techniques.

3. GPS SATELLITE EPHEMERIDES

The GPS master control station predicts the GPS satellite orbits in advance and transmits them to the GPS satellites. GPS satellites broadcast that orbit information called broadcast orbits to users in the form of the navigation message. The broadcast orbits provide orbital element values for each GPS satellite every two hours. The accuracy for the broadcast orbits is relatively lower than those of other GPS satellite ephemerides. However, since the broadcast orbits are given at the same time when the observation is carried out, it can be used as a priori value during data processing. The accuracy for the broadcast orbits is announced as 1 m (http://igscb.jpl.nasa.gov/components/prods.html) at present. The International Global Navigation Satellite System Service (IGS) calculates and provides the precise final orbits based on the observation data given by the IGS network distributed throughout the world. Unlike the broadcast orbits, the final orbits provide the X, Y and Z components of the satellite position vectors represented on the earth-centered earth-fixed (ECEF) coordinates every 15 minutes. At present, the accuracy for the final orbits is 2.5 cm (http://igscb.jpl.nasa.gov/components/prods.html). Thus, they are utilized when a high level of geodetic precision is required in such cases as the precise geodetic survey or the crustal movement researches.

The GV hybrid observation aims for the simultaneous estimation of station coordinates, earth orientation parameters (EOP) and satellite orbits directly after the observation. Then the broadcast orbits are only available for a priori orbits and thus are used to calculate theoretical values. In order to determine EOP and GPS satellite orbits, a globally distributed network is required. As this study deals with the observation of the single and short baseline, only the theoretical values are calculated without the estimation for EOP and satellite orbits.

4. OBSERVATION OUTLINE

The 24-hour GV hybrid observation was conducted in Kashima and Koganei, Japan from December 25 (12:12:00 UTC) until 26 (13:00:00 UTC), 2009. The baseline length between the two stations is about 109km. The cutoff angle was set as 15 degrees since the signals of the satellites at low elevations are intensively influenced by atmosphere and multi path. The number of satellites appearing in both skies, above 15 degrees in elevation, during the experiment is shown in Fig. 3.

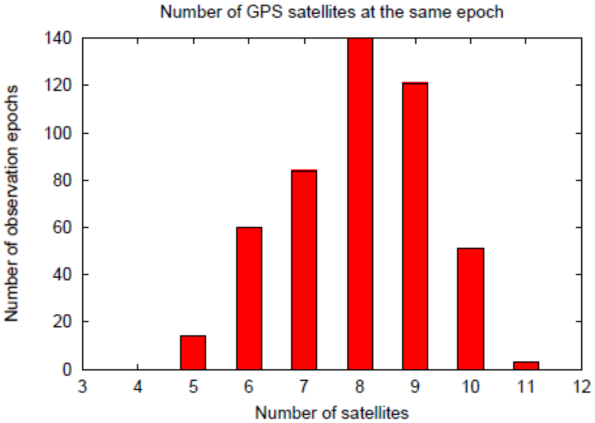

Fig. 3. Number of the observed GPS satellites above 15 degree cutoff angle in elevation for 24 hours (Kwak et al. 2011).

In order to carry out the observation by using the VLBI system, a schedule file used in the VLBI system is required. After the geodetic VLBI system which receives quasar signals scans a radio source during hundreds of seconds, it moves antennas and scans another radio source. Therefore, a schedule file of a geodetic VLBI observation should include the coordinates of the target sources and stations, and the observation order and time. Even though it is a 24-hour observation, actual recording time is around eight hours due to the movement of the antenna. Since GPS does not have to move the antenna, it can receive the GPS satellite signals continuously for 24 hours. Thus, the GPS schedule file is completed only with the information for the start and finish times of the observation.

For the data sampling and recording processes, K5/VSSP32 (Kondo et al. 2008), which was developed by National Institute of Information and Communications Technology (NICT) of Japan, was used. K5/VSSP32 supports 16-channel recording. Each control PC deals with every four channels. However, since the identical PC cannot support to scan both quasars and GPS satellites, three control PCs process four S-band channels and eight X-band channels of quasar signals and one control PC processes L1- and L2-band channels of GPS signals (Fig. 4). In this experiment, we took 1-minute on and 2-minute off GPS observation strategy for every three minutes. According to Kwak et al. (2010b), 1-minute observations of the GPS signals are sufficient to get a high signal-to-noise ratio (SNR). Hence, such a method could be regarded as an efficient way of reducing data volume. The 24-hour GV hybrid observation data

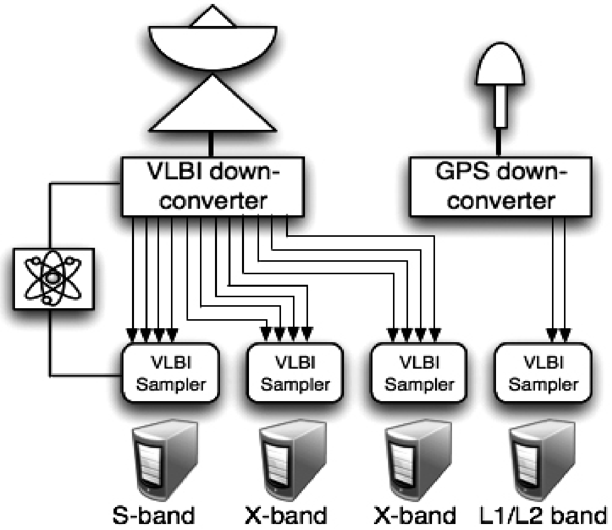

Fig. 4. Backend structure of the VLBI system used for the 24-hour GV hybrid observation.

was correlated by the K5 VLBI software correlator (Kondo, Koyama, & Osaki 2003).

5. RESULTS AND DISCUSSION

The L1- and L2-band signals of GPS satellites were successfully processed within the VLBI system. Through the correlation, we could obtain the correlation fringe peak that corresponds to the GPS observation values (Kwak, 2011). The delays of the radio signals in the ionosphere depend on the frequencies. Thus, by using Eq. (3), it is possible to remove ionospheric delays from the observed values (Thompson et al. 2001).

$$\tau_{ion\ corrected} = \frac{f_1^2\tau_G(f_1) - f_2^2\tau_G(f_2)}{f_1^2 - f_2^2} \qquad (3)$$

where f_1 and f_2 are the observation frequencies and $\tau_G(f_1)$ and $\tau_G(f_2)$ are the observed values obtained in each frequency band. In case of GPS, the frequency channels of L1 (1.57542 GHz) and L2 (1.2276 GHz) are close to each other. According to Eq. (3), after dual frequency ionosphere correction, the scatters of the GPS delays become greater than those of the VLBI delays that have 2 and 8 GHz observation band. Therefore, we analyze the precision of the individual frequency band data before the ionosphere correction. As a factor for the precision of the data, we use the residuals left by subtracting the theoretical values from the observed values of the GPS satellite signals.

The residual for each GPS satellite is shown in Fig. 5. Every satellite data have the identical biases. Kwak et al. (2012) reported that even though they used the same clock for VLBI and GPS, they obtained the differences of about -119.5 and -126.7 nanoseconds for L1 and L2 in comparison with the VLBI observation values. They also predicted that un-calibrated phases would affect delays in the form of observational errors. Kwak (2011) reported that the scatters of the residuals for the GPS data were a few nanoseconds, which were considerably bigger than general uncertainties of VLBI group delays, 0.1 nanoseconds level.

The general VLBI system is equipped with the phase and delay calibration system. Such a calibration system inserts the comb tone signal into the front-end of the receiver in order to calibrate the arbitrary initial phase which occurs in the down converter or other instruments. Also, by measuring the cable length between the antenna and the backend, it corrects the cable delays as shown in Fig. 5. The VLBI part of the GV hybrid system used the current VLBI system as it was so that the phase and delay calibration system had been already installed in the VLBI part. Meanwhile, in GPS part, the calibration system was not considered so that such calibrations stated above were not conducted.

Table 1. The average values of the differences between the delays based on the broadcast orbits and the final ones for each GPS satellite (Units: picoseconds).

PRN	Delay (Broadcast orbits) – Delay (Final orbits)	PRN	Delay (Broadcast orbits) – Delay (Final orbits)	PRN	Delay (Broadcast orbits) – Delay (Final orbits)
01	-61.3	02	-6.6	03	12.0
04	-10.6	05	-11.7	06	1.2
07	-2.2	08	-4.2	09	-9.2
10	9.9	11	10.2	12	-26.0
13	3.5	14	-16.1	15	-8.0
16	15.3	17	-10.1	18	3.1
19	-8.0	20	8.5	21	-1.8
22	-8.4	23	1.1	24	-5.1
25	-10.4	26	3.3	27	-0.7
28	7.7	29	-7.1	30	-11.8
31	-4.1	32	0.7		

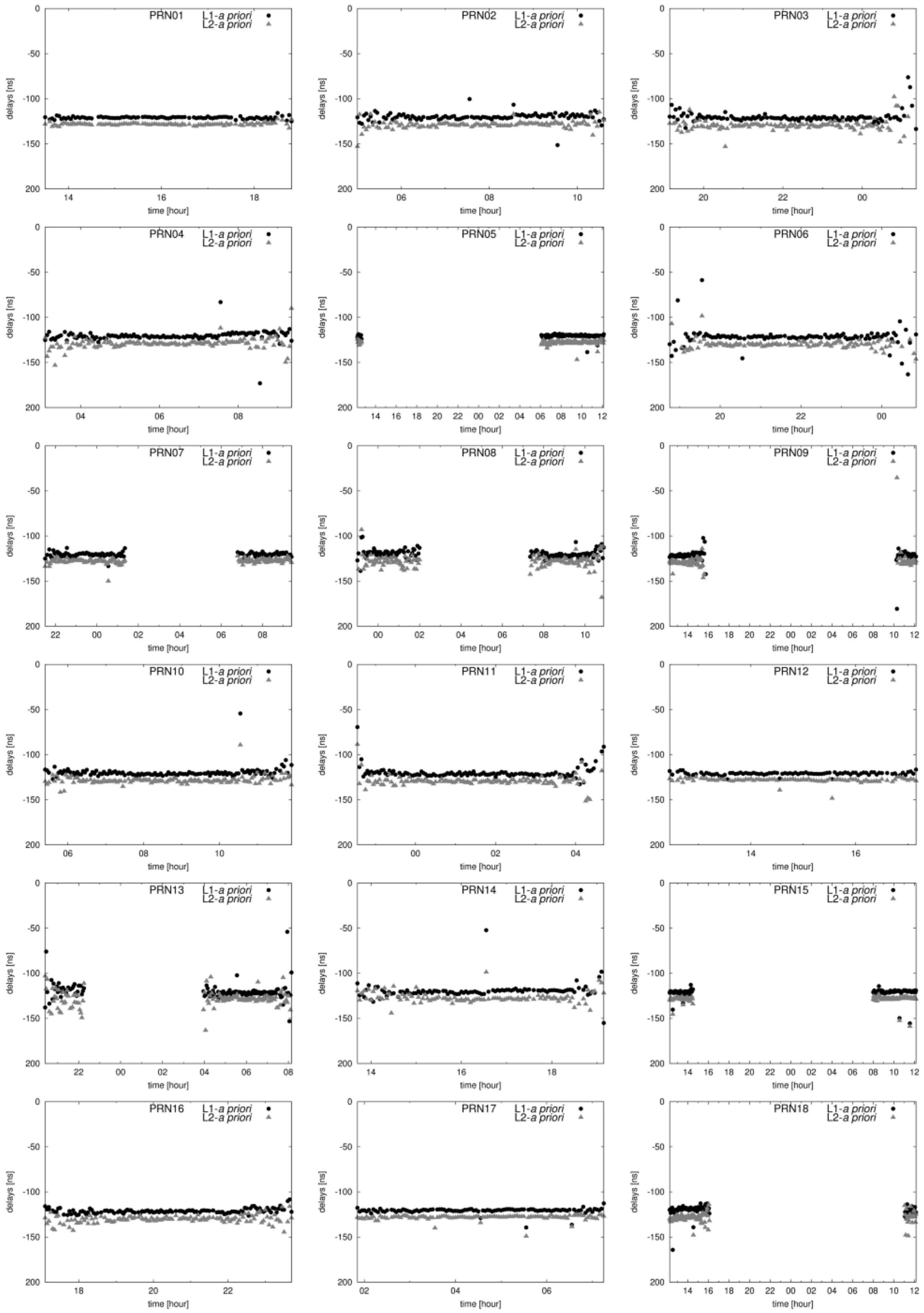

Fig. 5. The residuals for each GPS satellite (Observed – Calculated values). The horizontal axis means the observation time (unit: hour of day), while the vertical one means the delay (unit: nanoseconds).

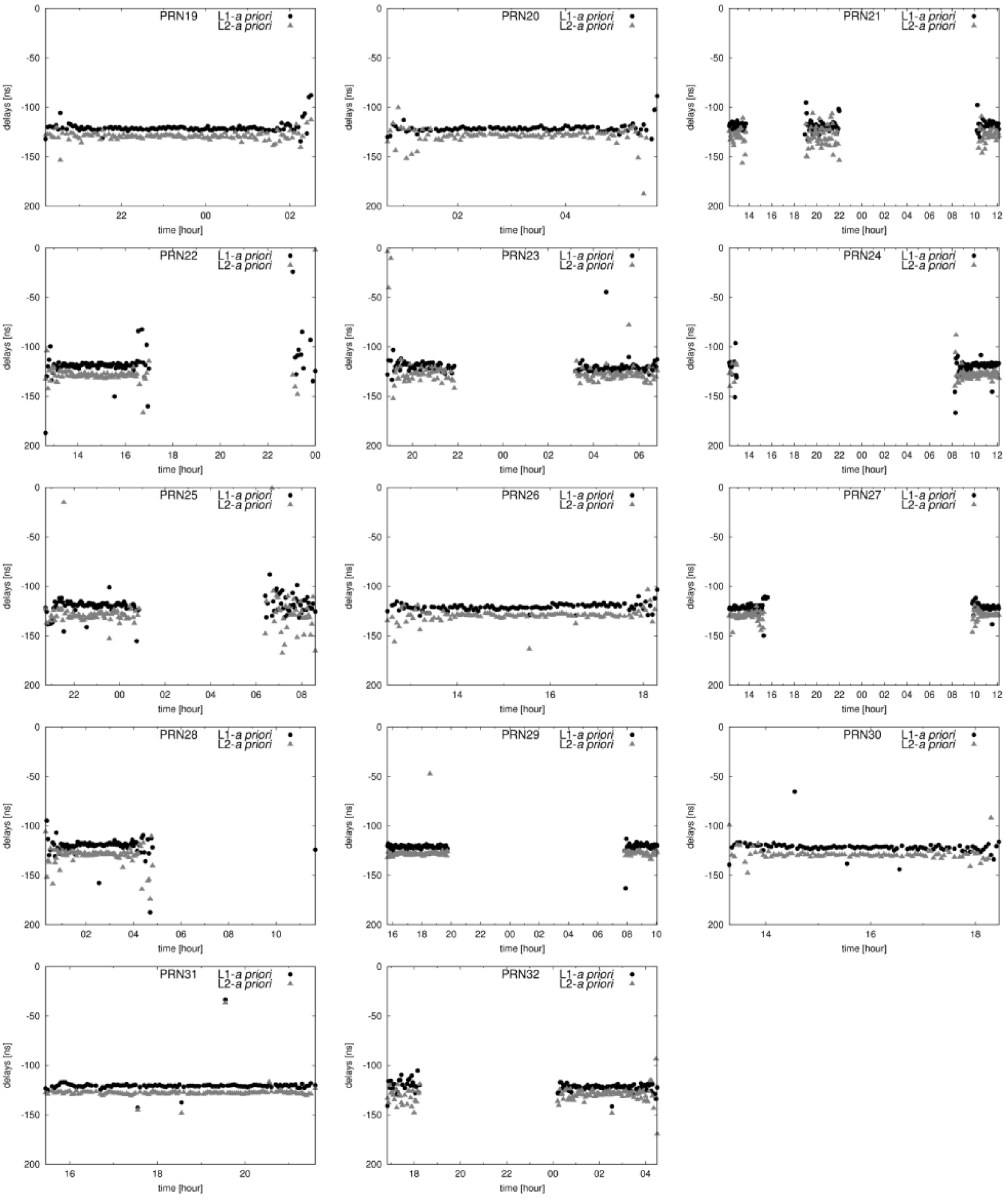

Fig. 5. continued

It is possible to detect and correct the biases partly through the residual analysis. However, for the precise geodetic observation in future, it is necessary to have the phase and delay calibration system. For the unification between the two techniques, it is reasonable to apply the same type of calibration system used for VLBI.

Since this study deals with the single and short baseline observation, the theoretical values are calculated by using the broadcast orbits without estimating the orbits of the GPS satellites. A few nanosecond scatters of delays in Fig. 5 are equivalent to tens of centimeter to a few meters in length. Fig. 6 shows the distance differences between the

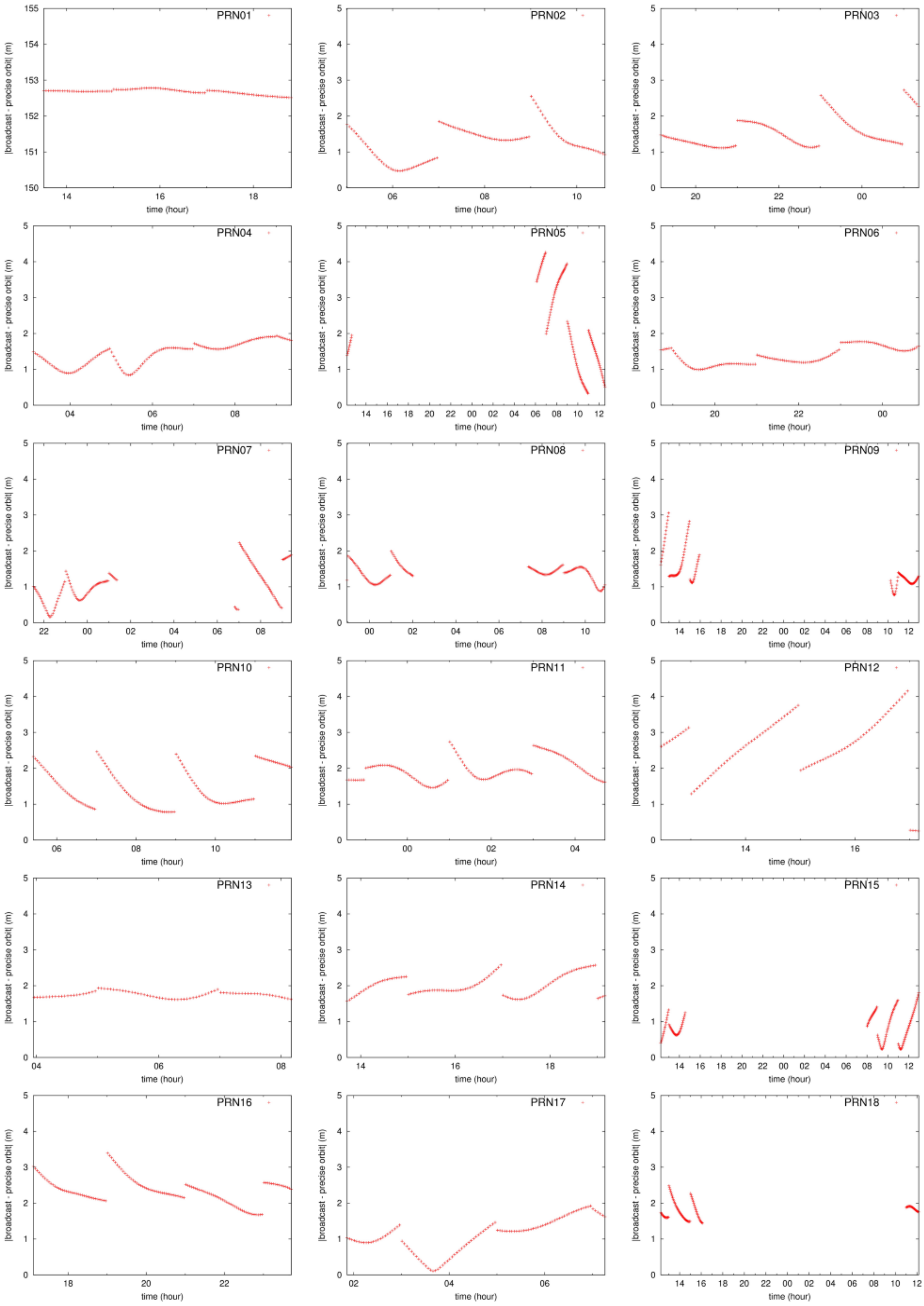

Fig. 6. The distance differences between the broadcast orbits and the final ones. The horizontal axis means the observation time (unit: hour of day), while the vertical one means the distance (unit: meters). The range of the vertical axis for the PRN01 satellite is 150-155 m, while the range of the vertical axis for other satellites is 0-5 m.

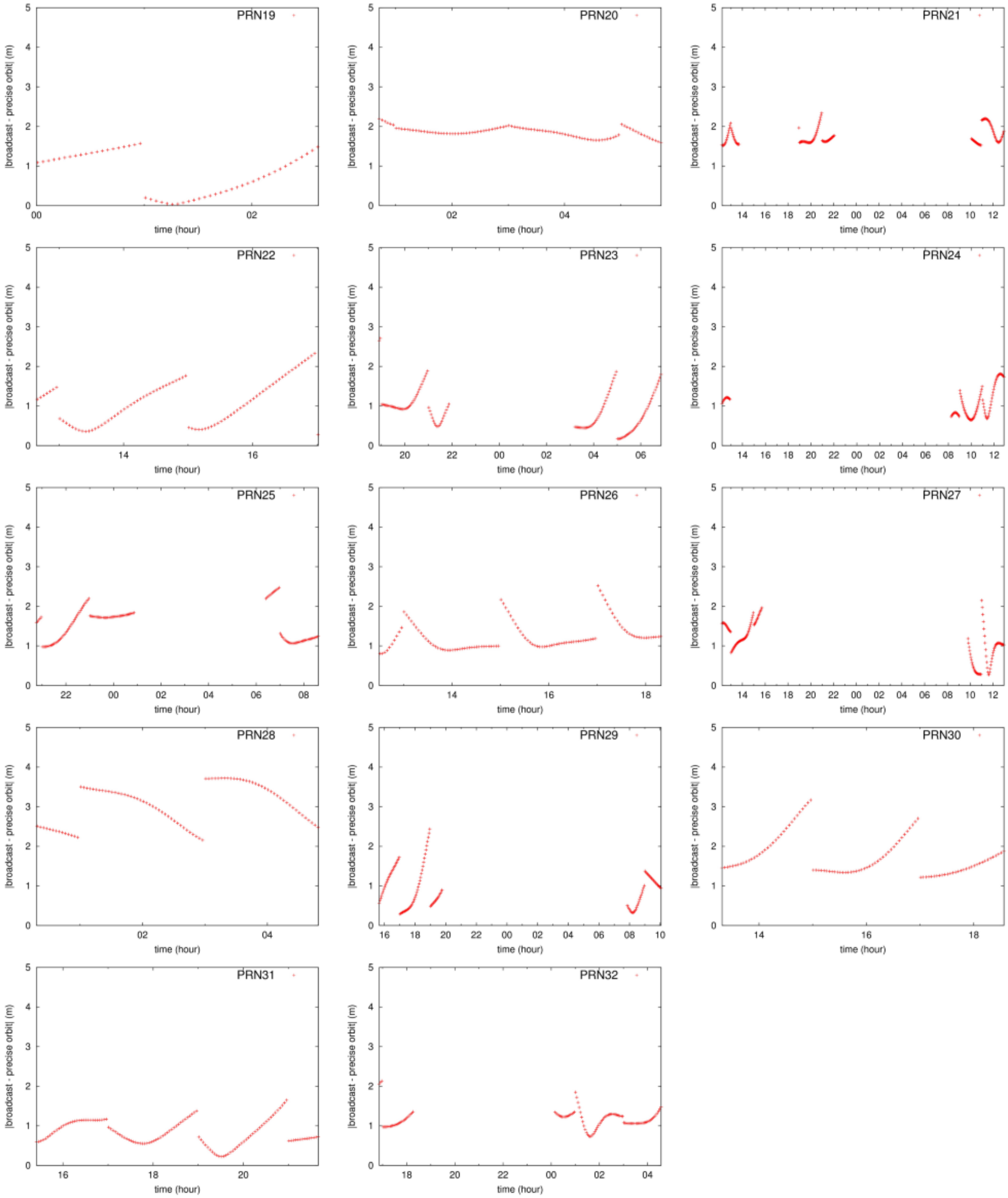

Fig. 6. continued

broadcast orbits and the final ones. The empty spaces in some of graphs mean that those satellites are located under 15 degree elevations. As shown in Fig. 6, except for the pseudorandom noise (PRN) 01 satellite in the state of “Unhealthy”, the differences of the satellite positions based on the broadcast orbits and the final ones are about 0-5m. In order to verify if lower observation precision is caused by the broadcast orbits, we analyze the impacts of the GPS satellite ephemerides on delay errors.

Fig. 7 shows the differences between delays based on the broadcast orbits and the final ones for each GPS satellite according to Eq. (1). Table 1 shows their average values. Except for the PRN 01 satellite, all other satellites show the differences within 100 picoseconds. Such values are

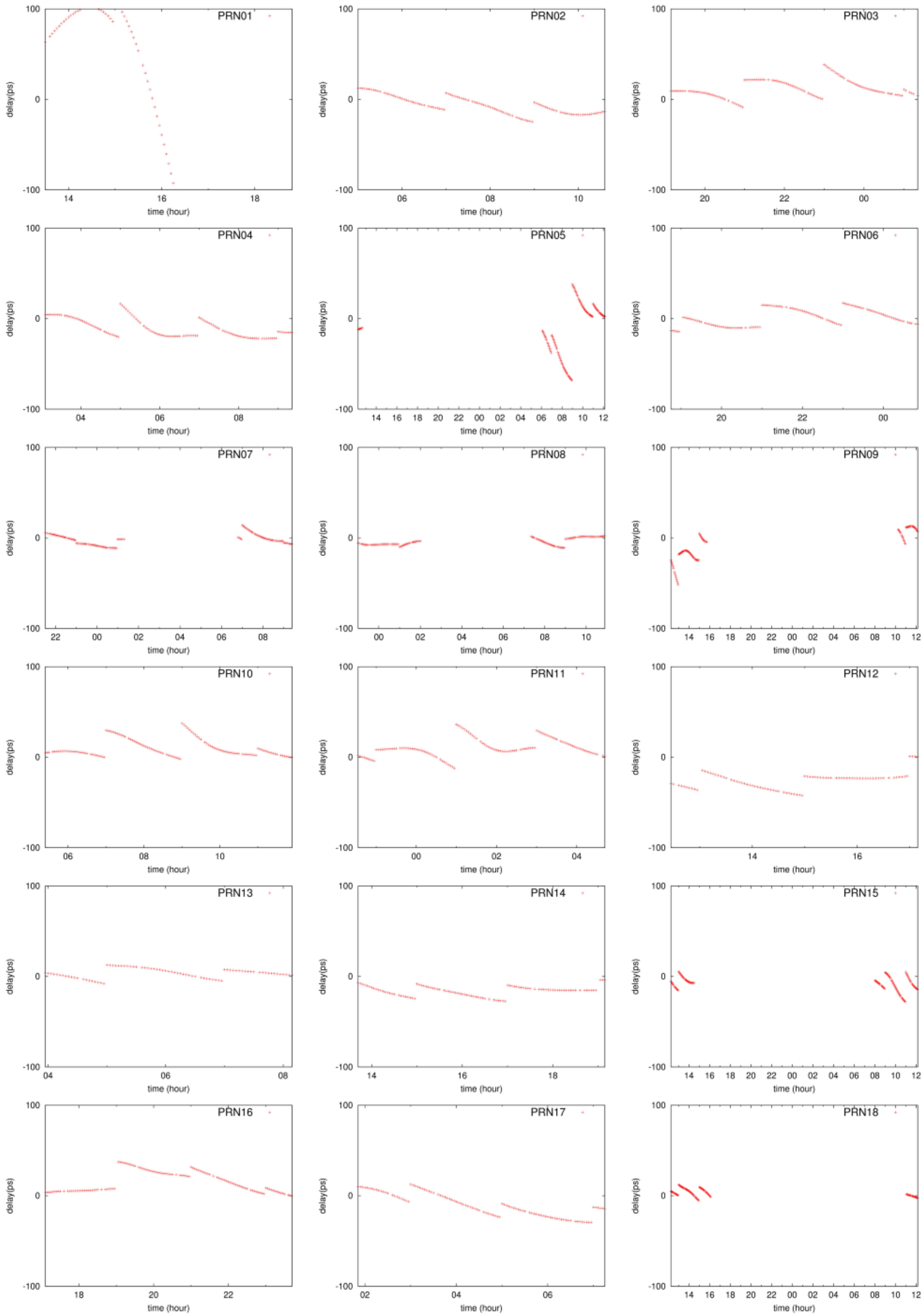

Fig. 7. Difference between delays based on the broadcast orbits and the final ones for each GPS satellite. The horizontal axis means the observation time (unit: hour of day), while the vertical one means delays (unit: picoseconds).

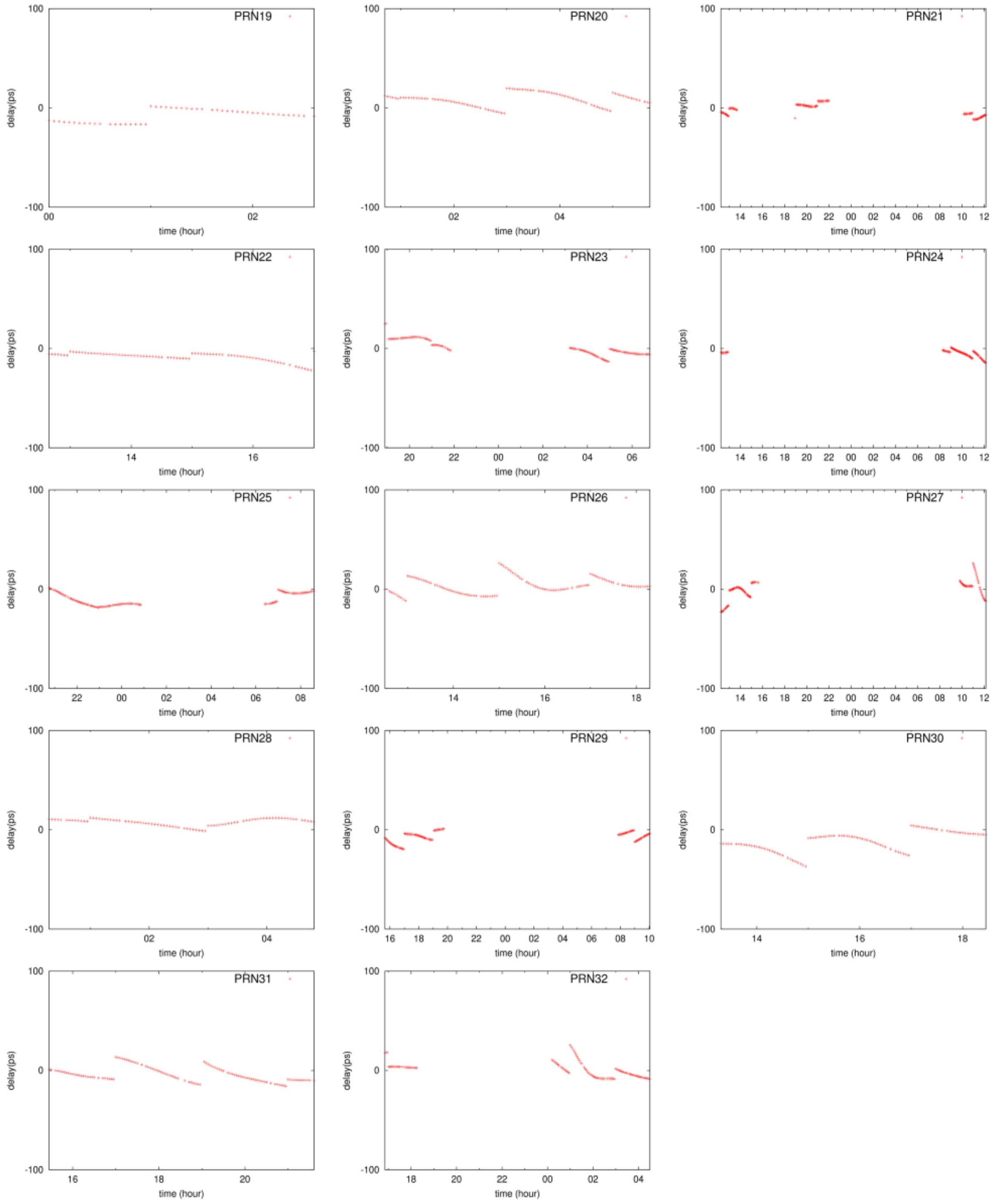

Fig. 7. continued

relatively small with the level of 1/100 compared to the observation errors with a few nanoseconds. Therefore, we can verify that the impacts of the satellite ephemerides on GPS delays are relatively small in the current level of precision. The GV hybrid observation can cancel out the errors related to satellites by observing the same GPS satellite like the single difference technique. As a result, the influence based on the orbital errors seems to be reduced greatly.

6. SUMMARY AND CONCLUSION

In order to analyze the impacts of the GPS satellite ephemerides on the GPS delays in GV hybrid observation, we carry out the residual analysis for GPS delays. For the L1 and L2 data of every GPS satellite, the residuals show constant biases. The scatters of the residuals are a few nanoseconds. We believe that the major cause of large errors is the absence of the GPS phase and delay calibration system. After comparing and analyzing the delays obtained by individually applying the broadcast orbits and the final ones, we conclude that the impacts of the satellite ephemerides on GPS delays are insignificant. Therefore, we expect that we are able to process and analyze the GPS data of GV hybrid observation with the broadcast orbits. After compensating hardware defects and then removing the current major errors in future, we would reconsider the strategies of utilizing the GPS satellite ephemerides for more precise geodesy. It would be also necessary to make additional efforts to analyze the error causes in various aspects by considering the applications of the exclusive GPS correlation model within the correlator and the latest analysis model.

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