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A Pilot Experiment of the GPS-VLBI Hybrid System

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Abstract We developed a Global Positioning System (GPS) - Very Long Baseline Interferometry (VLBI) hybrid system to combine GPS and VLBI techniques at the hardware level. In the system, we co-locate both GPS and VLBI antennas that simultaneously receive the respective signals from quasars and GPS satellites. Then, both signals are recorded and correlated in the general VLBI way being referred to the identical frequency standard for each site. We conducted a 24-hour pilot observation of the GPS-VLBI hybrid system between Kashima and Koganei, Japan. We obtained correlation fringes with a high signal-to-noise ratio from all GPS satellites simultaneously, thereby substantiating the system's practicality. Furthermore, we obtained reasonable delay values for GPS satellites as well as quasars. The delays of the GPS L1/L2 signals were biased against the reference clock, and they were about 7.2 ns apart from each other possibly due to the absence

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of the delay calibrator and/or differential code biases between two frequency bands. From data analysis, the estimated VLBI parameters for VLBI-only and GPS-VLBI hybrid data were comparable throughout the observation period. However, while improved results were found when one frequency (L1) of GPS was used, problems remained when combining the two frequencies.

Keywords VLBI · GPS · GPS-VLBI hybrid system · Combination of space geodetic techniques

1 Introduction

The International Terrestrial and Celestial Reference Frames and Earth Orientation Parameters (EOPs) are determined by combining various space geodetic techniques, i.e. Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Each technique has a reduced sensitivity when determining all components of reference frames and EOPs. For instance, VLBI cannot determine the origin of the terrestrial reference frame (TRF) as VLBI only measures baselines between stations. The absolute value of the Universal Time 1 (UT1), which is related to the rotation angle of the Earth, cannot be determined from satellite geodetic techniques like GNSS and SLR because the longitude of the ascending node, one of the satellites' orbital elements, is correlated with UT1. For more details see Plag et al (2009).

To compensate for those defects, the International Earth Rotation and Reference Systems Service (IERS) the International Terrestrial Reference System (ITRS) Product Center at the Institut National de l'Information Géographique et Forestière (IGN) combines the products of all space geodetic techniques (Altamimi et al 2002, 2016). The Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) as one of the IERS ITRS Combination Centers combines the normal equations of all space geodetic techniques (Angermann et al 2004; Seitz et al 2012). Both approaches have the goal to derive a combined TRF by tying the techniques at the co-location sites.

The IERS Working Group on Combination at the Observation Level (COL) aims to investigate methods and advantages of combining techniques at the observation level seeking for an optimal strategy to estimate geodetic parameters (`http://www.iers.org/WGCOL`). Unlike IGN and DGFI-TUM, the participants of COL analyze the data of individual techniques with the identical software and identical a priori models, thereby still using normal equations from all participants for the combination. COL is convinced that this way of combination provides greater consistency and homogeneity between the different techniques and yields the same effect as the observation level combination. The German consortium (GGOS-D) and the French Groupe de Recherche en Geodesie Spatiale (GRGS) already demonstrated the idea successfully (Rothacher et al 2011; Coulot et al 2007; Pollet et al 2014). There were also several prior studies which combined a pair of techniques: Thaller et al (2011) for GNSS-SLR using the Bernese GPS Software (Dach et al 2015) and Hobiger et al (2014) and Hobiger and Otsubo (2014) for VLBI-SLR and GNSS-VLBI using the c5++ software, respectively, However, from instrumentation, systematic effects/biases/errors between the techniques are still there as each technique has its own weaknesses in the calibration and processing.

Unifying space geodetic techniques by using identical hardware is an alternative option. In the past decade, several concepts were presented and experiments were carried out to connect space geodetic techniques at the hardware level (Dickey 2010; Tornatore and Haas 2010; Bar-Sever et al 2011). In this work, we deal with the combination method at the hardware level on the ground of the Global Positioning System (GPS) and VLBI. The most efficient combination method of two radio techniques would be to perform sampling, recording and correlation in the same way, while maintaining the advantageous characteristics for radio-wave reception in each of the observation techniques. This concept is referred to as GPS-VLBI (GV) hybrid system (Kwak et al 2010). Compared to other combination methods like product level, normal equation level, and observation level combinations, the data types are totally different as the GV system produces interferometric GPS measurements.

Following a successful VLBI type observation of GPS by Kwak et al (2010), we conducted a 24-hour pilot GV hybrid observation. In this paper, we focus on the feasibility and prospects of the observation. In principle, other GNSS techniques like GLONASS or Galileo can also be applied, given appropriate GNSS antennas and down-converters.

2 GPS-VLBI Hybrid System

The GV hybrid system is an observation concept to combine GPS and VLBI at the hardware level. This combination seems easier than the combinations between any other pairs of space geodetic techniques as both techniques use radio signals and similar signal processing. The VLBI antennas receive the identical signals from quasars and these signals are correlated between the stations (Whitney et al 1976). On the other hand, a general stand-alone GPS antenna receives the radio signals from the GPS satellites and these signals are correlated with replica signals inside a GPS receiver because GPS is not based on an interferometry. In the GV hybrid system, however, a signal transmission cable is directly connected from the output terminal of a GPS antenna to a normal geodetic VLBI backend system (Fig. 1).

The concept of the GV hybrid system is straightforward. A co-located pair of GPS and VLBI antennas within the GV hybrid system simultaneously receives respective signals from quasars and GPS satellites. Referencing to an identical hydrogen maser clock, the same VLBI sampler and recorder perform sampling and recording of both signals. Finally, both data are correlated in the same way, which means that the GPS signals of both GPS stations are correlated with each other and not with replica signals. The correlator outputs are interferometric measurements between two GPS stations. Thus, the GPS antenna can be regarded as an additional VLBI antenna tracking GPS satellites at the same site.

As a GPS antenna is an omni-directional antenna, the system can obtain more data from various directions in the sky at the same observation epoch than by tracking a GPS satellite with VLBI antennas. This feature will improve the estimation of atmospheric delays that vary rapidly in time and space and thus enhance the precision of VLBI geodesy.

Obviously, the radio instruments, e.g. down converters, samplers, and formatters, are able to process radio waves. However, for a long time, it has not been affordable to process the GPS signals properly in a VLBI system. In the early

2000s, the MIT Haystack Observatory and the National Institute of Information and Communications Technology (NICT) have developed high-speed VLBI samplers. Current high-speed VLBI samplers can now sample wide-band signals with bandwidths of more than 32 MHz. Therefore, the samplers can cover the whole main lobes of the L1 and L2 spectra.

Since the geodetic VLBI down-converters are dedicated to down-converting S/X band signals and commercial GPS down-converters are unsuitable for converting the GPS L1/L2 band signals to input signals of general VLBI samplers, an additional GPS down-converter is introduced in our GV hybrid system. For more details see Kwak et al (2010).

Hard disks have been introduced in the Mark5 and K5 VLBI systems as recording media (Whitney 2004; Kondo et al 2008). The large data volumes of hard disks are also able to record the wide-band sampled data and the continuous 24-hour GPS observation data. Both data from quasars and GPS satellites are recorded in a common geodetic VLBI data format, K5 or Mark5.

In principle, VLBI type data from any radio sources can be correlated in a normal VLBI correlator. A VLBI software correlator, e.g. K5 software correlator (Kondo et al 2003) or DiFX (Deller et al 2007), enables a huge amount of data to be correlated in a reasonable amount of time with high-performance processors since the run time of the software correlator solely depends on the performance of the computer processors. In GV hybrid observations, the correlator outputs are the time delays between the S/X band and the L1/L2 band signals for quasars and GPS satellites, respectively.

In short, the largest obstacles in realizing the GPS-VLBI combination at the hardware level were related to the capabilities of VLBI hardware. The advanced digital technology eventually enables the current VLBI system to process GPS signals. Furthermore, the design of the GV hybrid system can also be introduced

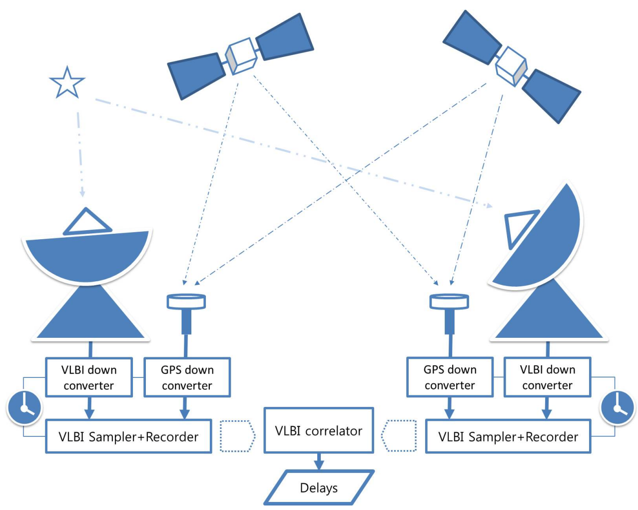

Fig. 1 The schematic diagram of the GPS-VLBI hybrid system

```
     $EXPER GV9359
     $SOURCES
      0212+735 $        02 17 30.81335583   73  49  32.6217976  2000.0 0.0 GLB1069
      0552+398 $        05 55 30.80560918   39  48  49.1650002  2000.0 0.0 GLB1069
(1)   0607-157 $        06 09 40.94954217  -15  42  40.6725954  2000.0 0.0 GLB1069
      0642+449 $        06 46 32.02598441   44  51  16.5901254  2000.0 0.0 GLB1069
      0727-115 $        07 30 19.11246873  -11  41  12.6004928  2000.0 0.0 GLB1069

                                  ...............
     $SKED
     3C84      10 SX PREOB  09359121050     23 MIDOB      0 POSTOB R-G- 1F000150 1F000150 YYYN    23    23
(2)  4C39.25   10 SX PREOB  09359121204     65 MIDOB      0 POSTOB R-G- 1F000000 1F000000 YYYN    65    65
     0552+398  10 SX PREOB  09359121455    189 MIDOB      0 POSTOB R-G- 1F000027 1F000027 YYYN   189   189
     NRAO150   10 SX PREOB  09359121844    120 MIDOB      0 POSTOB R-G- 1F000107 1F000107 YYYN   120   120
     3C454.3   10 SX PREOB  09359122130     61 MIDOB      0 POSTOB R-G- 1F000157 1F000157 YYYN    61    61
     0212+735  10 SX PREOB  09359122317    197 MIDOB      0 POSTOB R-G- 1F000000 1F000000 YYYN   197   197

                                  ...............
```

Fig. 2 A schedule file for the VLBI part in the GV hybrid observation. It follows the standard VLBI schedule file format. Relatively insignificant parts are not presented in this figure. (1) List of radio source names (1st column) and their coordinates in right ascension (3rd-5th column) and declination (6th-8th column). (2) Actual scan order with source names (1st column), the start time of scans (5th column), and scan duration (6th column).

in the next-generation VLBI system, the VLBI Global Observing System (VGOS, Hase and Pedreros (2014)), as well as the current VLBI systems.

3 24-hour GPS-VLBI Hybrid Observations

3.1 Observation Schedule

A schedule of geodetic VLBI observations includes the coordinates of the target sources and stations as well as the epochs and duration of the observations (Fig. 2). However, because GPS antennas are omni-directional, a GPS schedule file does not need the coordinates of GPS satellites. Therefore, the start and end times of each scan [1] and the positions of antennas are sufficient for a GPS schedule file (Fig. 3). The 24-hour GV hybrid observation session was held from December 25th (12:12:00 UTC) to 26th (12:12:00 UTC) in 2009. The observations were performed with the baseline between the Kashima and Koganei stations in Japan (109 km). In principle, a continuous 24-hour schedule of the GPS part is possible as it is not necessary to slew the GPS antennas. In this observation, however, we took a 1-minute-on and 2-minute-off observation strategy for the GPS part to save data volume and processing time. According to Kwak et al (2010), a 1-minute observation interval of the GPS part is sufficient to get a high signal-to-noise ratio (SNR).

3.2 Hardware

For VLBI antennas, we used the 11-m radio telescopes at Kashima and Koganei. Two commercial GPS L1/L2 survey antennas, NeroAntenna Technology Inc. APS1027 for Koganei and JAVAD MarAnt GGD for Kashima, were installed at a distance of 25 m and 23 m from the respective VLBI antennas (Fig. 4). In

[1] In VLBI terminology, a scan denotes a set of two or more antennas simultaneously observing the same source. The observation is the result of cross-correlating the signal from two antennas in a scan (`http://www.evga.org/teaching/VLBI_school_2013/VLBI-school-2013_04_Gipson.pdf`). In case of single-baseline, scan equals observation.

```
    $EXPER GV9359
    $SOURCES
(1) GPSALL $       01 21 41.59504260   11  49  50.4131870  2000.0 0.0 GLB1069
                                  ...............
    $SKED
    GPSALL    10 L  PREOB  09359121200     60 MIDOB      0 POSTOB R-G- 1F000058 1F000058 YYYN   60   60
(2) GPSALL    10 L  PREOB  09359121500     60 MIDOB      0 POSTOB R-G- 1F000096 1F000096 YYYN   60   60
    GPSALL    10 L  PREOB  09359121800     60 MIDOB      0 POSTOB R-G- 1F000000 1F000000 YYYN   60   60
    GPSALL    10 L  PREOB  09359122100     60 MIDOB      0 POSTOB R-G- 1F000050 1F000050 YYYN   60   60
    GPSALL    10 L  PREOB  09359122400     60 MIDOB      0 POSTOB R-G- 1F000100 1F000100 YYYN   60   60
                                  ...............
```

Fig. 3 A schedule file for the GPS part in the GV hybrid observation. The format is identical with Fig. 2. (1) There is only one source name (GPSALL) for GPS because the antenna is omni-directional and it receives all the signals from all the satellites in the sky. GPS antennas do not need to be steered towards the satellites. (2) Observation starts every three minutes (5th column) and the observation duration is 60 seconds (6th column).

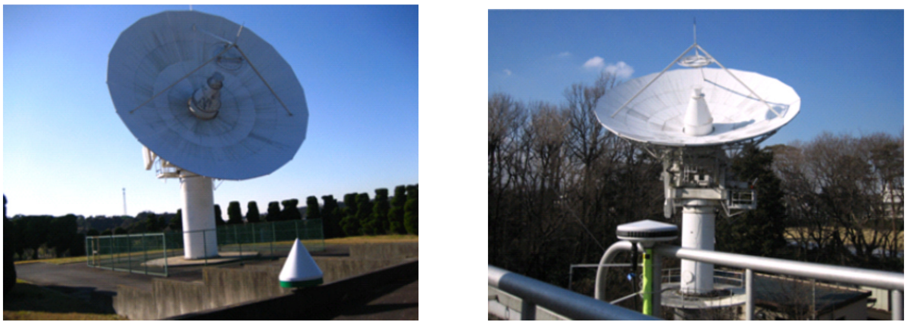

Fig. 4 GPS and VLBI antennas at Kashima (left) and Koganei (right)

this experiment, we did not measure the local tie vectors between the GPS and VLBI reference points.

We used four units of K5/VSSP32 (Kondo et al 2008), which has been developed by NICT as a high-speed sampler, for sampling and recording data. Each K5/VSSP32 unit can handle four observation channels. While typically they are used to cover the 14 (8 in X-Band, 6 in S-band) channels in normal VLBI, adjustments had to be made for this experiment. One unit was reserved for the two GPS L1 and L2 channels, the eight X-band channels used two units and in the last unit four (instead of typically six) S-band channels were recorded (Table 1).

As discussed in Sect. 2, the commercial GPS down-converters are not able to properly convert GPS L1/L2 band signals to the input signals of a general VLBI sampler. Therefore, we applied dedicated GPS down-converters for K5/VSSP32. For more details see Kwak et al (2010). Fig. 5 shows the circuit diagram of the GPS down-converter.

The data were recorded in K5 data format as we used the K5 software correlator (see Sect. 3.3). The data can also be converted to Mark5 data format (Imai et al 2005).

3.3 Correlation

To correlate the GV hybrid data, we used the K5 software correlator in this experiment. Since 2000, NICT has developed the K5 software correlator for geodetic

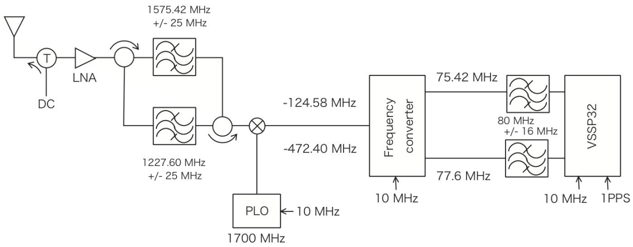

Fig. 5 The circuit diagram of the GPS down-converter of the GV hybrid system in this experiment

Table 1 Allocation of the frequency channels during the 24-hour GV hybrid observation

K5/VSSP32 Unit	Central Frequency (MHz)	Bandwidth (MHz)
Unit 1 (X-band)	7699.99	8.00
	7714.99	8.00
	7809.99	8.00
	8059.99	8.00
Unit 2 (X-band)	8349.99	8.00
	8519.99	8.00
	8559.99	8.00
	8599.99	8.00
Unit 3 (L1/L2-band)	1575.42	32.00
	1227.60	32.00
Unit 4 (S-band)	2249.99	8.00
	2294.99	8.00
	2349.99	8.00
	2369.99	8.00

VLBI data processing in parallel with its development of the recording system, i.e. the K5 system. It is a software package written in C language, which is able to run on various operating systems such as FreeBSD, Linux or Windows.

For the VLBI, S/X band signals from quasars were correlated for every channel. Subsequently, the correlated data were used to generate group delays using bandwidth synthesis in normal VLBI way. The signal from a GPS satellite received at one station is directly correlated with that received at the other station in the VLBI way without demodulation and decoding. Even though all the satellite signals are mixed in the identical channel, every satellite has its own distinguishable pseudorandom noise (PRN) code. Moreover, every satellite signal has a distinct velocity with respect to the observing stations and thus the received signals contain all the GPS satellite signals with different Doppler shifts. In the VLBI correlator, the fringe peaks are searched by a priori delays and delay rates. Using the difference of delay rates, i.e. the difference of the Doppler shifts, we could identify a certain GPS satellite signal. Therefore, the correlation process should be repeated for the same signal, each time using a different a priori 'search window (delay and delay rate)', corresponding to the various satellites in the sky. The correlator output for the GPS signal is also the difference in arrival times of the GPS signals

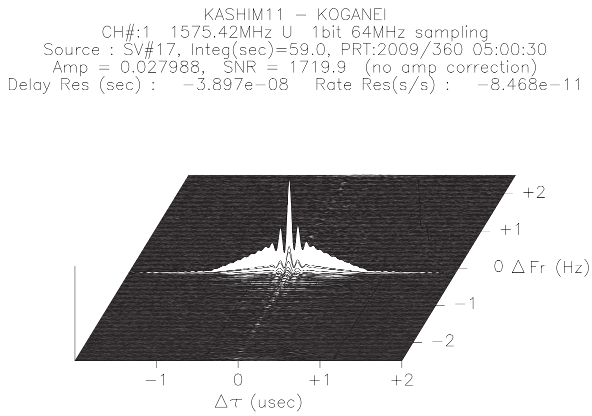

Fig. 6 A correlation peak of the L1 signal from a GPS satellite, space vehicle (SV) 17, at 05:00:30 UTC 26th December 2009

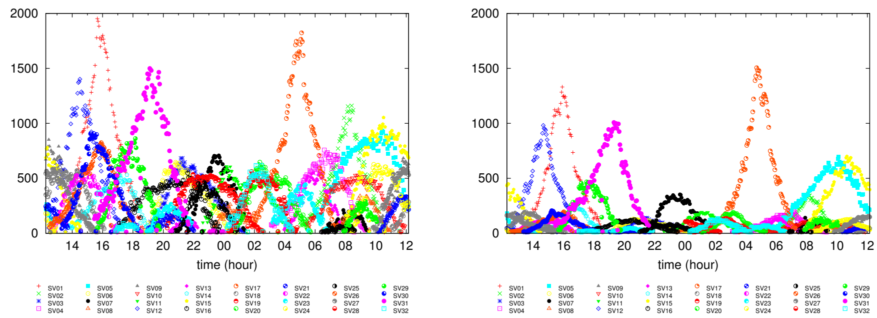

Fig. 7 SNR variation of the L1 (left) and L2 (right) correlation peaks of all GPS satellites during the observation. Each symbol depicts a satellite.

between two stations, i.e. the interferometric measurement. Thus, L1 and L2 data do not refer to normal GPS phase measurements in this paper.

Fig. 6 shows an example of the correlation peak of a GPS satellite signal. The SNRs of the peaks over the observation period are depicted in Fig. 7. The SNRs of L1 are always larger than of the L2 signals, driven by the fact that L1 carries the C/A and P codes while L2 only contains the P code. Since a GPS antenna is not a directional antenna, the SNRs are not steady and basically depend on the elevation of the satellites. Nevertheless, an omni-directional antenna is able to receive the signals from various directions of the sky (Fig. 8) so that it is expected to improve the precision of the estimated parameters.

4 Observation Models

A quasar is regarded as an object at an infinite distance, whereas a GPS satellite is an object at a finite distance. The VLBI group delay model as applied to quasar

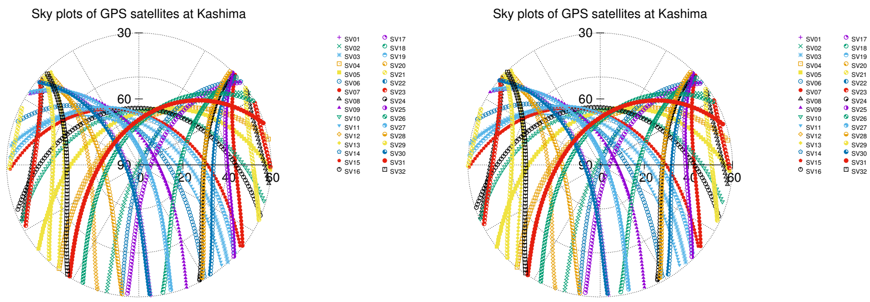

Fig. 8 Sky plots of GPS satellites at Kashima and Koganei during 24 hours. At every scan, there were usually 5 to 6 commonly visible GPS satellites. North is at the top and the azimuth increases in a clockwise direction. Each symbol depicts a satellite.

data reads:

$$\tau_{Vi} = -\frac{\mathbf{D} \cdot \mathbf{s}}{c} + \tau_{Ci} + \tau_{Ai} + \epsilon_i \tag{1}$$

where τ_{Vi} is the group delay of a quasar at the i-th epoch, $\mathbf{D}$ is the baseline vector, $\mathbf{s}$ is the unit vector to the source in the same system, and c is the speed of light. The corrections τ_{Ci} denote clock offsets at the i-th epoch, τ_{Ai} the atmospheric delays at the i-th epoch, and ϵ_i other errors. On the other hand, we define the delay of GPS satellite data in the GV hybrid observation as the difference in reception time at two stations for the signals transmitted by one satellite:

$$\begin{aligned}\tau_{Gjn} = & \frac{|\mathbf{R}_{jn} - \mathbf{r}_l|}{c} \\ & - \frac{|\mathbf{R}_{jn} - \mathbf{r}_m|}{c} \\ & + \tau_{Cj} + \tau_{Ajn} + \epsilon_{jn}\end{aligned} \tag{2}$$

where τ_{Gjn} is a delay of the n-th GPS satellite at the j-th epoch, $\mathbf{R}_{jn}$ the position vector of the n-th satellite at the j-th epoch corrected by the light travel time, and $\mathbf{r}_l$ and $\mathbf{r}_m$ the position vectors of the l-th and m-th stations. That is similar to the single difference technique in the standard GPS analysis. The only distinction is that we acquire the difference values through correlating the identical satellite signals, which is emitted at the same time, of both stations directly. Please note that Eq. 1 and 2 are simplified to highlight the difference between the geometric models. As a pre-requisite, the station coordinates have to be transformed to the same coordinate frames before further analysis. Besides the geometric delay models, other geophysical models are consistent for both techniques.

5 Analysis and Results

In this analysis, satellite positions, source coordinates, and EOPs were regarded as known parameters since the current experiment was conducted on a single and short baseline. The radio source coordinates were fixed to the global solution 1069 (GLB1069, Ma and Baver (1997)) that was obtained in the schedule file and originally provided by the Goddard Space Flight Center (GSFC) VLBI group. The precession and nutation were calculated according to the IERS Conventions 2010 (McCarthy and Petit 2004). The polar motion and UT1 were fixed to the IERS EOP series, i.e. EOP 08 C04. The satellite positions were calculated based on the International GNSS Service (IGS) final orbits where the coordinates for each GPS satellite are provided every 15 minutes (Dow et al 2009). The station coordinates were corrected for tidal effects (solid Earth tide, tidal ocean loading, tidal atmosphere loading, pole tide, and ocean pole tide). The Vienna Mapping Function (Böhm et al 2006) was applied in the processing of tropospheric delays. The tropospheric delays due to the height difference between both instruments were constrained during estimation (Krügel et al 2007; Rothacher et al 2011; Teke et al 2011).

5.1 Delay Biases in the GPS Part

In typical VLBI observations, most of the observing VLBI stations measure and provide cable delays, which include not only the lengths of the cables but also other internal delays inside the system, using the delay calibrators. Thus, one knows the exact delay value at the antenna reference point. However, we could not conduct cable delay measurements in this experiment.

Fig. 9 shows an example of the observed - calculated (O-C) values of the L1 and L2 signals from a GPS satellite. It is evident that there are two different biases against the reference clock offset obtained from VLBI data processing. The two clear biases for the respective frequency bands, L1 and L2, commonly appeared for every satellite (not shown in the figure). In Fig. 5, two frequency bands were split into two terminals through different filters of the respective frequencies. Hence, we can easily presume that the two biases, which are about 7.2 ns apart from each other, are caused by different signal paths. On the other hand, differential code biases, which are common in GPS data, also could cause such biases between two frequency bands. Those biases could be corrected during the analysis by estimating a constant bias but not perfectly in case the biases are changing with respect to time. If the differences between two frequencies are not calibrated completely, the ionospheric delays, which are calculated by forming the ionosphere-free linear combination, would not be perfectly compensated. Therefore, for accurate delay values a delay calibration system needs to be developed and used in the next version of the GV hybrid system.

5.2 Data Analysis

In the analysis, we handled ionosphere-calibrated VLBI data and GPS data which were formed by the combination of dual frequency measurements (Parkinson et al 1996). The total numbers of GPS and VLBI observations were 2340 and 220, respectively, throughout the experiment. Since the quality of the GPS data (the standard deviation of O-C) was worse, we down-weighted the GPS data by a factor of 1/100, i.e. we used 10 ns as the uncertainty of the GPS data. To assess the analysis results, we compared the formal errors of the VLBI estimates for the VLBI-only and GV hybrid observations, while we were not further investigating

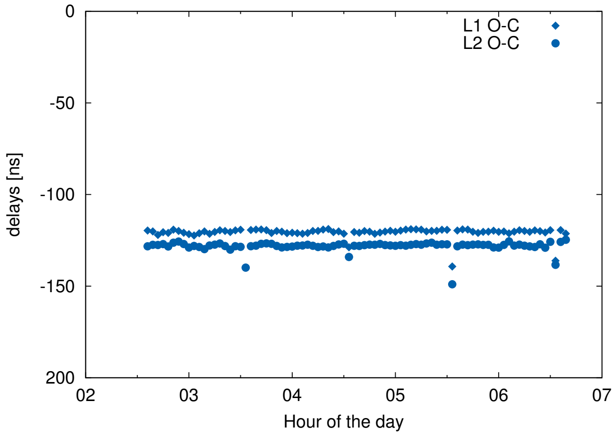

Fig. 9 Observed-calculated values of the L1 and L2 signals from a GPS satellite, SV17. The zero axis (vertical) marks the reference clock offset obtained from VLBI data processing. The figure shows apparent biases of L1 and L2 signals against the reference clock offset from VLBI, −119.5 ns and −126.7 ns, respectively. The offsets between L1 and L2 bands is 7.2 ns.

the GPS-only data. Of course, the formal errors cannot be the representative of the quality of the geodetic solution; however, for this experiment it was the only indicator for the quality assessment since the experiment was held on a single baseline and during 24 hours only. In this experiment, we focused on the feasibility of the concept.

We estimated clock parameters, zenith wet delays (ZWD), and station coordinates with a modified version of the Vienna VLBI Software (Kwak et al 2015; Plank et al 2014). We estimated the piecewise linear (PWL) clock offsets with one-hour intervals, a clock rate, and a quadratic clock term for Koganei per technique and set Kashima as the reference station. The mean formal error (120.7 ps) of the clock offsets in the GV hybrid data is comparable with that (120.5 ps) in the VLBI-only data.

The tropospheric delays due to the height difference between the GPS and VLBI antennas were constrained during estimation. The reference height for the tropospheric parameters is the height of the reference point of the VLBI antenna. The height differences between GPS and VLBI are 6.2 m and 2.4 m for Kashima and Koganei, respectively. The corresponding mean zenith wet delay differences are 0.3 mm and 0.1 mm on average, respectively. The ZWD PWL offsets were estimated every hour for the VLBI-only and GV hybrid data and the mean formal errors of the estimates are 2.44 cm for the VLBI-only data and 2.29 cm for the GV hybrid data (Fig. 10).

For baseline vector adjustments, where Kashima was also set as the reference station, the formal errors of the baseline length are about 17.2 mm for the VLBI-only data and 17.1 mm for the GV hybrid data (Table 2).

From the results presented above, we see the VLBI-only solution does not benefit from the GV hybrid data. However, when we take GPS L1 data instead of ionosphere-free data, the formal errors are significantly improved by a factor of more than 2 (Table 3). Due to the error propagation at the ionosphere-free combination of dual frequencies, the uncertainty of the GPS data gets larger and

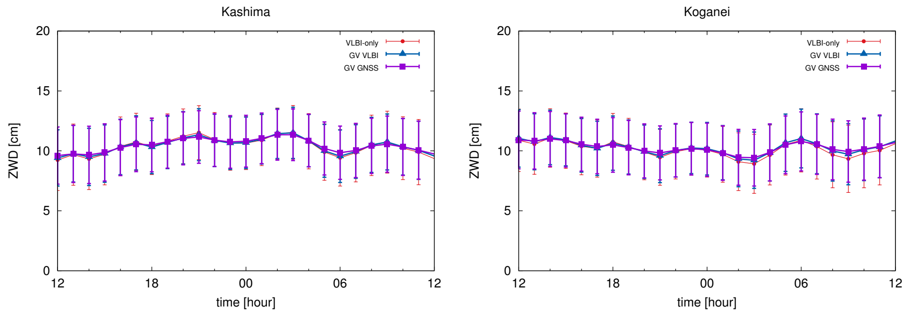

Fig. 10 Estimated ZWD from the VLBI-only data and GV hybrid data at Kashima (left) and Koganei (right). The horizontal axis shows the hour of the day and the vertical axis provides ZWD in cm. The interval of the estimates is 1 hour.

Table 2 Baseline components of VLBI reference points in the VLBI-only solution and GV hybrid solution

Parameter	VLBI-only	GV (ion-free)	GV (L1)
Δ X [m]	55568.234 ± 0.010	55568.236 ± 0.010	55568.236 ± 0.004
Δ Y [m]	91272.475 ± 0.010	91272.472 ± 0.010	91272.472 ± 0.004
Δ Z [m]	-22005.375 ± 0.010	-22005.378 ± 0.010	-22005.378 ± 0.004
baseline [m]	109099.657 ± 0.017	109099.632 ± 0.017	109099.632 ± 0.007

The station coordinates of the reference station Kashima$_{VLBI}$ are X=-3997505.702, Y=3276878.405, and Z=3724240.703

Table 3 Formal errors of the VLBI parameters in the VLBI-only solution and GV hybrid solution

Parameter	VLBI-only	GV (ion-free)	GV (L1)
Clock offsets [ps]	120.5	120.7	50.8
ZWD [mm]	24.4	22.9	9.6
baseline [mm]	17.2	17.1	7.2

thus the formal errors of the estimates are not as good as those of the L1-only results. However, we should stress the fact that L1-only results are better than those of the ionosphere-free data only for this experiment because Kashima and Koganei stations are only 109 km apart from each other and we can assume their ionospheric effects to be almost the same. The differences of ionospheric delays between the two stations as derived from IGS combined ionosphere maps are less than ± 20 ps.

6 Conclusion

In the combination of space geodetic techniques at the hardware level, the incompatibility has been the major hindrance. In particular, although GPS and VLBI have a lot in common, it has been impossible to process one signal with the other technique. The recent digital technology, however, allows the current VLBI system to track the GPS signals.

The GV hybrid observation is a combination method for the radio space geodetic techniques, GPS and VLBI, at the hardware level. While retaining the characteristics of both techniques, it connects them to the identical VLBI backend.

In this work, we conducted a 24-hour pilot experiment. In the experiment, we successfully obtained the delay values of the GPS satellite signals as well as those of quasars. The delays of the GPS L1 and L2 signals were biased against the reference clock offset from VLBI and they were about 7.2 ns apart from each other possibly due to the absence of the delay calibrator and/or differential code biases between the two frequency bands. According to the data analysis, the formal errors of the estimated VLBI parameters are comparable with VLBI-only data when using ionosphere-free GPS data after the dual frequency combination. On the other hand, L1-only data improve the estimation of VLBI parameters, i.e. ZWD, clock offsets, and baseline vectors, in this specific experiment (a short baseline).

Stochastically, one would expect these results when using a big amount of data. In this paper, however, we emphasize the actual implementation of the GV hybrid system and its feasibility rather than the results themselves.

We made use of the same K5 software correlator for both GPS and VLBI considering all signals as white noise. We would acquire more accurate delays if we considered the spectral characteristics of the GPS signals in the correlation model.

The current experiment was carried out on a single and short baseline. Thus, global parameters such as satellite positions, source coordinates, and EOPs, could not be determined. A global GV hybrid network would give the possibility of estimating those parameters together. The global GV hybrid observation will also resolve the correlation of UT1 and nutation with the ascending node of the satellites. That means GPS will contribute to the determination of UT1 and nutation components as well as their time derivatives being connected with VLBI.

While the deficiencies in the current experiment cause limitations, they leave a host of possibilities for improving the current GV hybrid system. After we compensate those defects, we expect that global GV hybrid observations will eventually contribute to the combination of the space geodetic techniques for the realization of the global geodetic observing system. In principle, this concept can be easily applied at the existing VLBI stations if the output of a GPS antenna is properly connected to the input of the VLBI backend.

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