Vol. 46 No. 1 Journal of the Communications Research Laboratory March 1999
Printed in Tokyo, Japan pp. 193−197

8.2 VLBI USING A GPS FREQUENCY STANDARD

By

Tetsuro KONDO, Kouichi SEBATA, and Jun AMAGAI

ABSTRACT

The performance of Global Positioning System (GPS) time-and-frequency reference receivers has advanced to supply a highly stable signals (1×10^{-12}/day) at a low cost. Although their stability is less than that of the hydrogen-maser frequency standard ($\sim 1 \times 10^{-14}$/day) conventionally used for very long baseline interferometry (VLBI), their lower cost is attractive when we consider the wide deployment of VLBI and VLBI-like techniques. The performance of a GPS receiver was evaluated by measuring its phase stability to determine whether it is suitable for supplying a standard frequency for VLBI observations. Test VLBI observations using a GPS receiver were also conducted to confirm its performance at 2 and 8 GHz. It is concluded that a GPS time-and-frequency reference receiver can be used as a frequency standard for VLBI for frequencies up to 8 GHz and for integration periods up to 100 s with a third-order fringe search.

Keywords: GPS, Frequency standard, Coherence, Fringe search

1. Introduction

The performance of Global Positioning System (GPS) time-and-frequency reference receivers has advanced to the point where they are now widely used to supply a highly stable signals (1×10^{-12}/day) at a low cost (less than 1,000,000 Yen). Although their stability is less than that of the hydrogen-maser frequency standard (H-maser clock) ($\sim 1 \times 10^{-14}$/day) conventionally used for very long baseline interferometry (VLBI), their lower cost is attractive when we consider the wide deployment of VLBI and VLBI-like techniques. We evaluated the performance of a GPS receiver by measuring its phase stability to determine whether it is suitable for supplying a standard frequency for VLBI observations. We also conducted test VLBI observations using a GPS receiver to confirm its performance at 2 and 8 GHz. We found that a GPS time-and-frequency reference receiver can be used to supply a standard frequency for VLBI for frequencies up to 8 GHz if a third-order fringe search is used and the integration period is less than 100 s.

2. Evaluation of Stability

We used a commercially available HP 58503A GPS receivers for our evaluation. It supplies 1-pps signals synchronized to the coordinated universal time (UTC) within about 100 ns as well as stable 10-MHz signals. The specified stability of the signals is shown in Fig. 1[1]. For comparison, the stabilities of signals supplied by an H-maser clock, a cesium clock, and a rubidium clock are also shown.

To evaluate the receiver's performance, we placed two GPS antennas close together (about 7 m apart). A receiver (HP 58503A) was independently connected to each antenna. After running the receivers for three days (the prescribed break-in period), we measured the phase difference between their 10-MHz signals for six days. The analog output from a phase comparator (HP K34-59991A) was converted into digital signals with a sampling period of 1 s. The digitized data were stored in a PC (Fig. 2).

Discontinuities were included in the raw phase data due to the inherent characteristics of the comparator, i.e., a trip of 360 degrees occurs when the phase changes across 360 or 0 degrees. We removed these discontinuities before statistically analyzing the data. An example of the phase data before and after removal of the discontinuities is

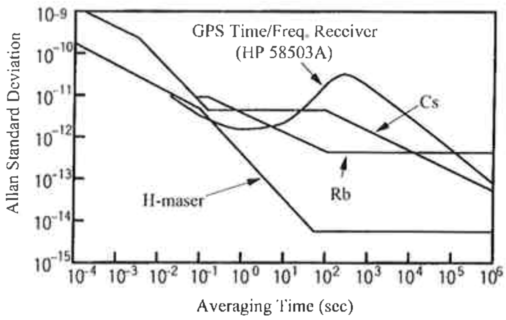

Fig. 1 Stability characteristics of GPS time-and-frequency reference receiver, hydrogen maser clock, cesium clock, and rubidium clock.

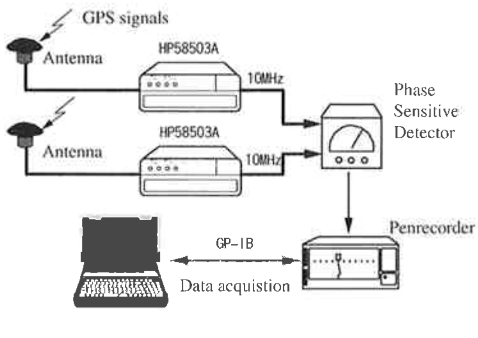

Fig. 2 Diagram of observation system.

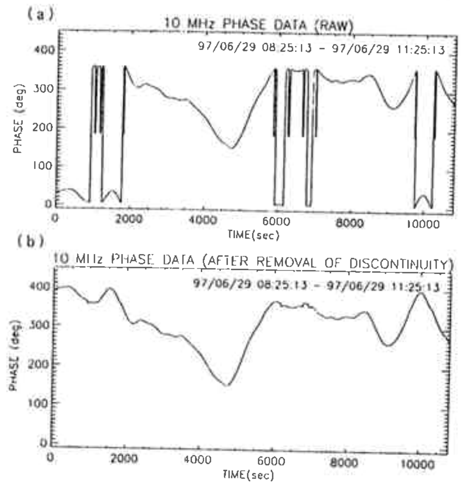

Fig. 3 Phase data observed for three hours (a) before and (b) after removal of discontinuities due to comparator (phase-sensitive detector).

shown in Fig. 3. While some discontinuities remained, they had little effect on the results.

The Allan variance is a good measure for evaluating the stability of reference signals. We calculated the Allan variance for averaging time τ by using

$$\sigma_y^2(\tau) = \langle \sigma_y^2(2,\ \tau,\ \tau) \rangle = \langle (\overline{y_{k+1}} - \overline{y_k}) \rangle / 2, \quad \overline{y_k} = \frac{\phi(t_k + \tau) - \phi(t_k)}{2\pi v_0 \tau} \qquad (1)$$

where $\phi(t_k)$ is the phase data at time t_k and v_0 is the frequency where the phase measurement was made (10 MHz). Because we measured the phase difference between two frequency standards that have almost similar performance is measured in this study, the root Allan variances were $\sqrt{2}$-times larger than the inherent values. We divided the phase data into 24 sets of 6-hour-span data.

As shown in Fig. 4, the stability was better than 10^{-11} for an averaging time range of less than 1000 s. This is almost the same performance as expected from the receiver specifications. The scattering of plots in the time range less than 1000 s is attributed to the small remaining discontinuities. The system noise level was sometimes larger than the receiver performance in the time range less than 10 s. However it reached the level given in the specifications ($\sim 2 \times 10^{-12}$) at 10 s.

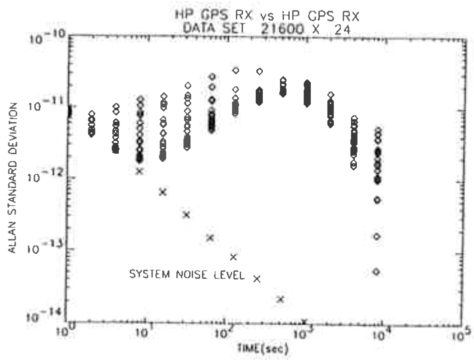

Fig. 4 Root Allan variance calculated for 24 sets of phase data. Each data set spans 6 hours.

3. Coherence Loss

Next, we evaluated the coherence loss when this frequency standard was applied to S (2.2-GHz) and X (8.8-GHz) band observations. Using the measured phase data, we calculated the coherence after N-s integration by using

$$r_N = \frac{1}{N} \left| \sum_{n=1}^{N} e^{i\theta_n} \right|, \quad \theta_n = C \times \phi(t_n), \qquad (2)$$

where C is the ratio of the observation frequency to 10 MHz (220 and 880 for 2.2 and 8.8 GHz) and $\phi(t_n)$ is the phase at time t_n. We assume there is no coherence loss for a 1-s integration. The calculated coherence is shown in Figs. 5 and 6. In this calculation, the phase data were divided into 48 sets of 3-hour-span data. As shown in the figures, the coherence decreased as the integration period was increased. Even at 10-s integration, it fell to about 0.7 and about 0.3 for 2.2 and 8.8 GHz, respectively. It further decreased to 0.1 for 100-s integration, which is the typical accumulation period in geodetic VLBI. Therefore,

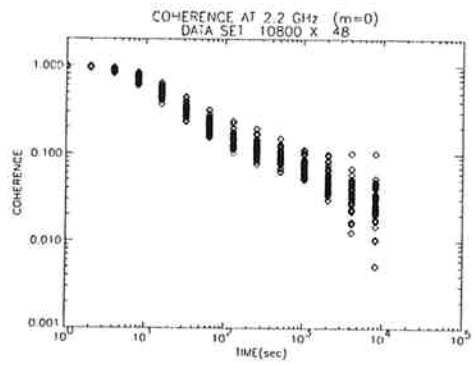

Fig. 5 Coherence calculated from phase data versus integration time for 2.2 GHz.

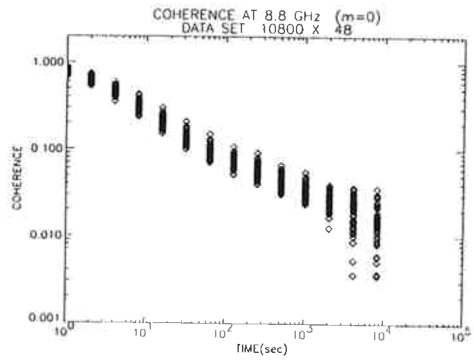

Fig. 6 Same as Figure 5 for 8.8 GHz.

this receiver appears unsuitable for VLBI observation.

However, a fringe search is carried out in correlation processing. The correlator outputs integration results every second or every several seconds. These time-segmented data are further integrated, with the phase change being adjusted using a time-linear function to maximize the integrated correlation amplitude.

We use a similar technique to calculate the coherence. First, we fit the phase variation during the accumulation period to a polynomial function with degrees from 1 to 3 by using a least-squares method. We then calculate the coherence by using the residual phase.

The results of using a first-order polynomial function are shown in Figs. 7 and 8. They are similar to those of a "fringe search" in geodetic VLBI processing. The coherence has increased remarkably. At 100 s, there was almost no loss for 2.2 GHz. Even for 8.8 GHz, the coherence amplitude of 0.3 was remained. As shown in Figs. 9 and 10, using a third-order polynomial function extends the integration period without loss about 300 s for 2.2 GHz and about 100 s for 8.8 GHz. Therefore, if we use the fringe-search process in the integration, we can use a GPS time-and-frequency reference receiver to supply a standard frequency for VLBI observations made in the S and X bands. However, the observed delay time should be carefully examined because the stability of the clock is an important factor in connecting one scan to the next to make a baseline-length analysis. With an unstable frequency standard, clock fluctuations between observations remain as an unknown parameter.

4. Results of Test VLBI Observation

We conducted test VLBI observations on May 13, 1998 on the Kashima-Koganei baseline (about 109 km in length) to confirm the performance of a GPS time-and-frequency reference receiver as derived from phase measurement and Allan variance analysis. The configuration of the test observation is shown in Fig. 11. At the Kashima station, the system-reference frequencies were supplied by a GPS reference receiver (HP 58503A) instead of an H-maser clock, while an H-maser clock was used at the Koganei station. Both "real-time" VLBI and "tape-based" VLBI were carried out. Cross-correlation processing was carried out in real time at the Koganei station using data transmitted through an asynchronous transfer mode network. Cross-correlation processing using the recorded data was performed later. The correlation-period units were set to 3 s. Two types of fringe searches were used in integrating the time-segmented correlation data. One was a normal fringe search in which only the linear-phase change with respect to time was compensated for. The other one was a fringe search using a third-order

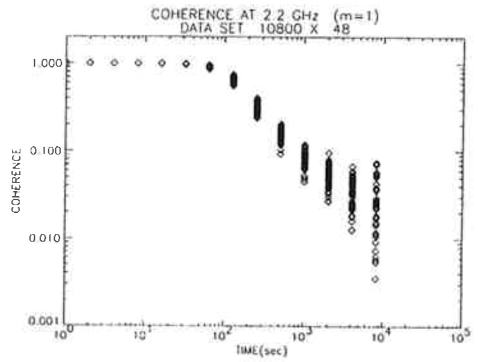

Fig. 7 Coherence calculated using residual phase data after removing linear drift versus integration time for 2.2 GHz.

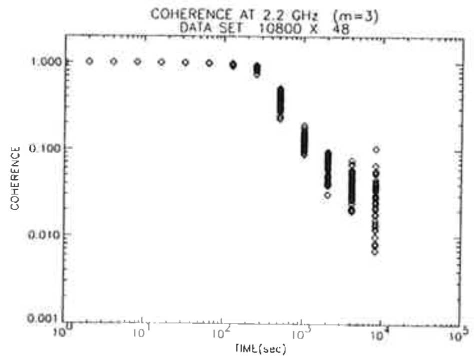

Fig. 9 Coherence calculated using residual phase data after third-order polynomial fitting versus integration time for 2.2 GHz.

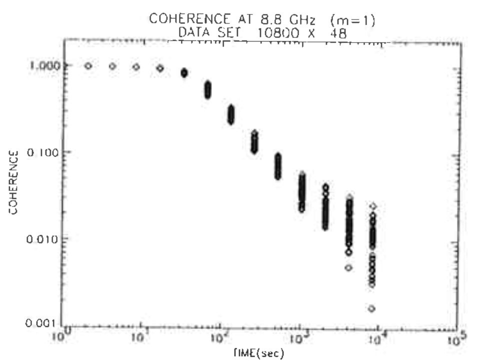

Fig. 8 Same as Figure 7 for 8.8 GHz.

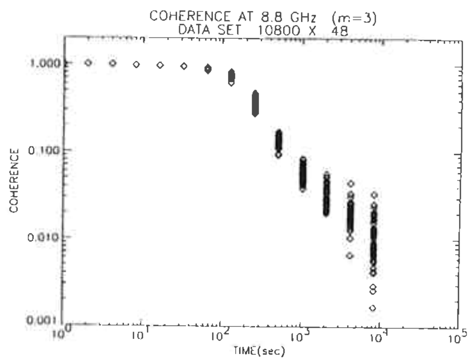

Fig. 10 Same as Figure 9 for 8.8 GHz.

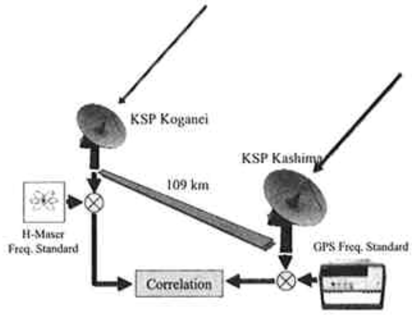

Fig. 11 Configuration of test VLBI observation using GPS frequency standard.

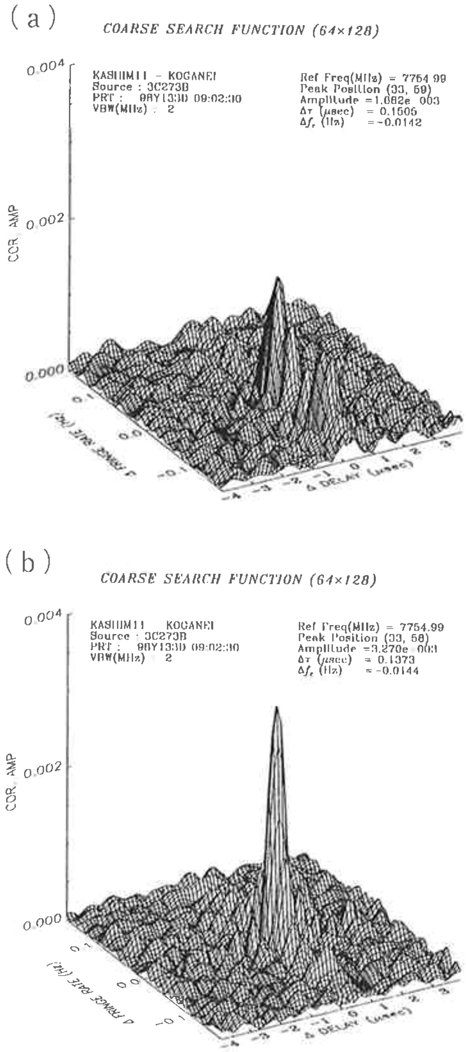

Fig. 12 Coarse delay search function for (a) normal and (b) third-order fringe search.

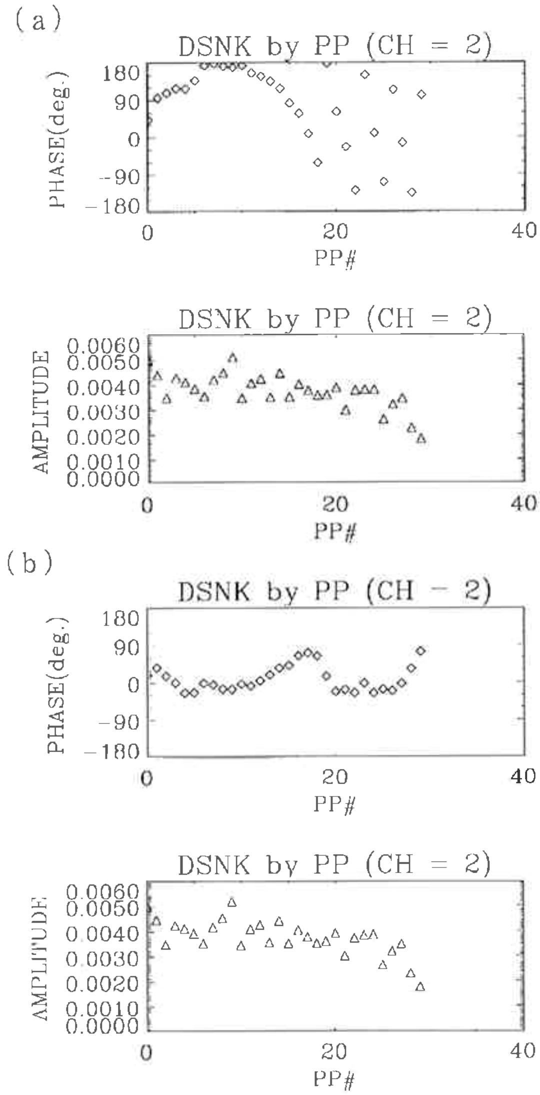

Fig. 13 Plots of residual phase and amplitude for (a) normal and (b) third-order fringe search.

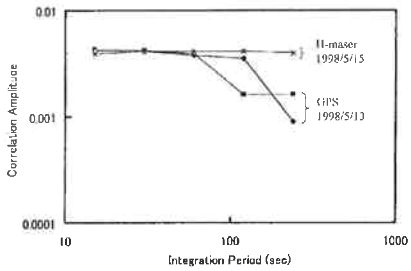

Fig. 14 Relation between correlation amplitude and integration period for two test observations: in one H-maser clocks were used at both stations, and in the other a GPS reference receiver was used at one station.

polynomial function with respect to time.

The coarse-delay search functions[2] obtained using these fringe searches are shown in Fig. 12. The received radio source was 3C273B, and the integration period was 90 s. Only one channel in the 8-GHz band is shown in the figure. There was a scattered structure in the delay rate direction for the normal fringe search (Fig. 12 (a)) due to a higher-order phase change that could not be compensated for by the linear phase-change correction. There was a simple peak structure and a larger correlation amplitude when a third-order polynomial function was applied (Fig. 12 (b)). The difference between these two search results is clearly shown in the residual phase plots (Fig. 13).

To compare these results with those for conventional VLBI observation, we conducted the same observation two days later using H-maser clocks at both stations. The relation between the correlation amplitude and integration period for both observations is shown in Fig. 14. A third-degree polynomial search was used for the observation made using the GPS clock. For the H-maser experiment, no difference was observed between search methods. For the GPS experiment, the correlation amplitude fell when the integration period exceeded 100 s. This meets our expectation based on the phase-measurement data (see Fig. 10). In other words, the GPS frequency standard can be used for VLBI for frequencies up to 8 GHz and for integration period up to 100 s.

5. Conclusions

We have evaluated the performance of a GPS time-and-frequency reference receiver (HP 58503A) to determine whether it can supply a standard frequency for VLBI observations. First, we measured the phase difference between 10-MHz signals output from two independent receivers. Then, we calculated the root Allan variance to evaluate the stability at averaging times ranging from 1 to 10,000 s. The coherence loss was calculated from the actual phase data. We found that a GPS time-and-frequency reference receiver can be used to supply a standard frequency if we expand the fringe-search process at least to compensate for third-order variations against time.

We confirmed this finding by conducting VLBI observations on the Kashima-Koganei baseline. We used the GPS frequency standard for the station reference signals at Kashima. We found that the GPS time-and-frequency reference receiver can be used as a frequency standard for VLBI for frequencies up to 8 GHz and for integration periods up to 100 s with a third-order fringe search.

Acknowledgments

We are grateful to Hiroo Kunimori, KSP/SLR group leader, for providing the GPS receivers used in this study.

References

(1) "HP 58503A GPS Time and Frequency Reference Receiver Getting Started Guide", November 1995.

(2) T. Kondo, M. Sekido and H. Kiuchi, "3.2.3 KSP Bandwidth Synthesizing Software", J. Comm. Res. Lab., **46**, 1, pp.67-76, March 1999.

Tetsuro KONDO
Kashima Space Research Center
Space Geodesy
E-mail: kondo@crl.go.jp

Jun AMAGAI
Keystone Project Team
Hardware development for radio interferometer and satellite laser ranging
E-mail: amagai@crl.go.jp

Kouichi SEBATA
Keystone Project Team
VLBI
E-mail: seba@crl.go.jp