LONG TERM TIME COMPARISON WITH GPS RECEIVERS

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ABSTRACT

The Radio Research Laboratory (RRL) has been making the international time comparison since 1984 by using a GPS (Global Positioning System) time-transfer receiver which was developed by RRL (GTR-1). Time comparisons are made on a routine base between RRL and US/European organizations by the common-view method to contribute data of the atomic clocks and the primary frequency standard of RRL to the TAI.

The time-transfer results between RRL and other time keeping organizations (international and domestic) via GPS using GTR-1 are presented. In the case of international time-transfer, between RRL and USNO, the precision is about 20 ns for more than a few-day comparisons, and in the case of domestic time-transfer, between RRL and TAO, the precision is about 15 ns. The system noise (stability of via SV#i - via SV#j) is 1 - 2 x 10^{-13}/tau(day) in both cases.

The ionospheric effect on time-transfer via the GPS L1 signal was quantitatively estimated by using the total electron contests data measured at RRL. Instabilities due to the ionospheric effects are more than 2.6 x 10^{-13}/tau(day) during around solar maximum and about 8 x 10^{-14} during solar minimum for the intercontinental time-transfers.

1. INTRODUCTION

The Radio Research Laboratory has been long making the international time comparison through the north-west Pacific network of Loran-C, but it is not directly connected with the north Atlantic ones, and has a precision too low for use of time transfers to contribute to TAI by sending our clock data.

The Global Positioning System (GPS)[1] gave possibility of direct time-transfers between RRL and US/European organizations. We started to develop a home-made receiver in 1983 and successfully completed it in 1984. By using the receiver RRL has been making the international time comparison on a routine base since 1984, and sending the time comparison data via GPS to BIH, together with the data of commercial clocks and the primary frequency standard of RRL[2] to contribute to the TAI.

The ionospheric effect is one of the most significant error sources on the

GPS time-transfer. We estimated it by using the total electron contents (TEC) data measured at RRL. The ionospheric effects on international time-transfers cause instability of more than 2.6×10^{-13}/tau(day) during solar maximum and less than 8×10^{-14}/tau(day) during solar minimum.

The time-transfer results by GTR-1 show that in the case of international time-transfer, between RRL and USNO, the precision is about 20 ns for more than few-day comparisons, and in the case of domestic time-transfer, between RRL and TAO, the precision is about 15 ns. The system noise is $1 - 2 \times 10^{-13}$/tau(day) in both cases.

2. GPS RECEIVER DEVELOPED

Figure 1 and 2 show the pictures of the main unit of the GPS time-transfer receiver (GTR-1), the receiver with a computer and the antenna respectively. Table 1 shows the summarized structure and performances[3]. The receiver is fully controlled by a mini-computer, and the computer also process the data and stores them on a mini-floppy disk. The time comparison (UTC(RRL) - GPS Time) data obtained are input to the GE Mark-III computer network system to exchange the data of the other time keeping organizations. The receiving schedule is according to the common-view mode prepared by NBS[4].

Table 1 Structure and performances of GTR-1

Antenna	herical one-turn antenna, and short back-fire antenna(under testing)
C/A code demodurator	Delay-Lock Loop
50 bps navigation data demodurator	Costas Loop
Pseudo-range measurement	internal time-interval counter (50 MHz clock rate)
Control computer	with a compatible CPU of Z-80A
Soft-ware	Written by Fortran and Assembler, size of about 40 kbyte
Data acquisition rate	once per 5 - 6 sec.
Precision	about 20 ns
Receiver delay	651 +/- 15 ns
Temperature coefficent	+3 ns/°C (for main unit)

2. TIME COMPARISON ERROR DUE TO IONOSPHERE

In the case of one-way time-transfer such as GPS time-transfer, there are several error sources,

1) error due to satellite position (uncertainties of satellite ephemeris),
2) error due to satellite clock stability,
3) error due to ionosphere,
4) error due to troposphere, and
5) error due to receiver and estimation error of receiver delay.

Errors due to satellite position or satellite clock can be reduced to several nano-second order by using the common-view technique[6].

The error due to ionosphere is one of the most significant factors on GPS time-transfer with single frequency, especially for long distance case such as intercontinental time-transfers. In this section we discuss the ionospheric effects on GPS time-transfer by using total electron contents data (TEC) measured at RRL.

The ionosphere makes a propagation delay on the radio signal which pass through it. The magnitude of the propagation delay by ionosphere depends on the frequency of the radio signal and the TEC along the path, and is approximately written by the following equation[5].

$$t_{ion}=40.5 \times Nt/f^2/c \quad (s) \qquad (1)$$

where Nt is the TEC along the path in m^{-2}, f is the frequency of the signal in Hz and c is the speed of light in m/s.

The TEC depends on many parameters such as:
1) time of day,
2) season,
3) location, and
4) long term and short term of solar activity.

The TEC which depends on geomagnetic latitude is large in the low latitude region and small in the high latitude region. In the mid-latitude region, the TEC becomes maximum around 13h of local time, and minimum around 5h of local time. Seasonaly, the TEC increases in spring and autumn, and decreases in winter and summer. It is highly related to the solar activity. The solar activity changes cyclicly, and its period is about 11 years. The sun-spot number is one of the parameters which show the solar activity. Figure 3 is a reproduction of a figure from a paper by H. Minakoshi et. al.[7], and shows that the behavior of the average TEC is very similar to that of sun-spot numbers. According to reference [8], the solar activity is maximum around 1979, and minimum around 1986 in this solar cycle.

The RRL has made the observation of the TEC since 1977, using the Faraday rotation of the VHF (136 MHz) signal transmitted from the Engineering Satellite Type II (ETS-II) launched in 1977 and geostationed at 130° E. The measurements of the TEC are made every 15 minutes. Figure 4 shows an example of the effects on the GPS L1 (1.575 GHz) signal by the ionosphere for vertical path calculated with the daily TEC data measured. As is described above, figure 4 denotes the maximum and near minimum ionospheric effects on the GPS time transfer at northern mid-latitude region. The magnitude of ionospheric effects changes about one order, from less than 10 ns to 60 ns for day-time, by the solar activity.

Figure 5 shows the comparison of the daily ionospheric delay data calculated by measured TEC and the ionospheric correction model using the coefficients transmitted from GPS based on the Klobuchar's algorithm[9] for October 1985. It shows the model can reduce the ionospheric effects by approximately 50% during day-time.

Figure 4 shows that the day-to-day variation of ionospheric effects at day-time is more than 25 ns during solar maximum and about 5 ns during near solar minimum. To estimate the ionospheric effects on the stability of GPS time-transfers, we calculated the stabilities (square root of Allan variance) of the propagation delay of GPS L1 signal estimated by the TEC data measured. Figure 6 shows the results for 1979 and 1984. The minimum averaging time is 15 minutes. It shows that the ionosphere causes instability of 2 - 8 x 10^{-13} to the time or frequency comparisons via GPS under short-term measurement (less than several hundred minutes of averaging time) on the vertical path.

Generally, for the international time comparison via the GPS under the common-view schedule, minimum sampling rate is about 1 day for each satellite. We calculated the stability of the propagation delay caused by the TEC at the same time of each day. The results are shown in figure 7 (a) to (c) for 4h (when the ionosphere is calm) and 13h (when the ionosphere is active) of the local time for 1979, 1984 and 1985. These figures present the limitation due to ionospheric effects on time or frequency comparison using GPS single frequency. Approximately, the stabilities show 1/tau characteristic, and the instabilities at day-time are 3 - 4 times larger than those at night-time. And they also show that instabilities during solar maximum are 3 - 4 times larger than near solar minimum. The summarized results are written in table 2.

Table 2 Time-transfer error due to the TEC variation (for vertical path)

	(solar maximum)	(near solar minimum)	
	1979	1984	1985
Local Time			
4h	4.2 x 10^{-14}/tau(day)	2.0 x 10^{-14}/tau(day)	1.0 x 10^{-14}/tau(day)
13h	1.3 x 10^{-13}/tau(day)	6.0 x 10^{-14}/tau(day)	3.9 x 10^{-14}/tau(day)

As these values were calcurated for the vertical propagation path, then we must multiply these values by the slant factor according to the elevation angle toward the satellite. In the case of the elevation angle of 30° which is usual elevation angle under the common-view observation between Japan and US or Japan and Europe, the slant factor is two.

4. TIME COMPARISON RESULTS

Figure 8 shows results of the international time comparisons between UTC(RRL) and UTC(USNO) via GPS and Loran-C during the term of January 1 1984 to October 31. For the GPS time comparison we use GPS SV#6 and SV#9 under the common-view schedule. In this term UTC(RRL) was made rate steering twice, on March 11 and April 22. The peak variation is within about 50-60 ns and the rms value less than 20 ns for each satellite.

For compensation of ionospheric effects on GPS time-transfer, we made the daily TEC-pattern averaged for each month during 1979 to 1984, and use it according to the long term solar activity.

Figure 9 shows the frequency stabilities (square-root of Allan variance) of the time transfer results in figure 8. The stabilities for more than 30 days show the rate steering effect. In the figure 9, the x marks are the system noise via SV#6 and SV#9 by square root of Allan variance of Δt_{6-9}. Δt_{6-9} is giving by the following equation:

$$\Delta t_{6-9}=((t_{RRL} - t_{USNO})_{via\ SV\#6} - (t_{RRL} - t_{USNO})_{via\ SV\#9})/2 \qquad (2)$$

The system noise gives stability of about 1.3×10^{-13} for averaging time of 1 day, and 2×10^{-14} for 10 days. And it does not follow 1/tau line for averaging time of several days. We are investigating the reason of it.

By the common view schedule between RRL and USNO, the elevation angles of SV#6 and SV#9 are about 27° and 30° at RRL, and 31° and 27° at USNO respectively. From table 2 we can estimate that the ionospheric effect is less than 8×10^{-14}/tau(day). It seems that the ionosphere did not influence so seriously on the time-transfer during this term.

Figure 9 also shows the instability of the time-transfer via Loran-C, and it is several times larger than that via GPS, because the north-west Pacific network of Loran-C is not directly connected with the Atlantic ones.

Figure 10 shows results of the time comparisons between RRL and Tokyo Astronomical Observatory (TAO) via GPS and Loran-C. With TAO all of the observations of GPS satellites are in common-view, but in the figure 10 we only plotted one point a day of the time-transfer results via SV#6, 8 and 9. The peak variation is about 50 ns and the rms value is about 15 ns for each satellite. Figure 11 shows the stability of figure 10, and system noise of (via SV#6 - via SV#9). The system noise is slightly smaller than in the case of UTC(RRL)-UTC(USNO).

Because of very near distance between both sites and directly connection via Loran-C ground wave, figure 11 shows that the instability of the time-transfer results via Loran-C is only about two times larger than that via GPS for averaging time of 1 - 10 days.

5. CONCLUSION

Reported were the ionospheric effects on the time-transfer via the GPS L1 signal based on the TEC data measured at RRL. According to the results, it shows the ionospheric effects on international time-transfer are less than 1×10^{-13}/tau(day) during solar minimum, and larger than 2.6×10^{-13}/tau(-day) during solar maximum. We are planning to compensate it by the TEC data measured.

We also reported the time-transfer results between RRL and other time keeping organizations (international and domestic) using GPS time-transfer receiver developed by RRL. The time-comparison results show precision of about 20 ns for more than a few days and stability of the system noise of 1 - 2 x 10^{-13}/tau(day). By using the receiver we have been able to make direct time-transfers between RRL and US/European organizations, and made contributions to the TAI by the time comparison results together with the data of the atomic clocks and the primary frequency standard of RRL.

ACKNOWLEDGEMENTS

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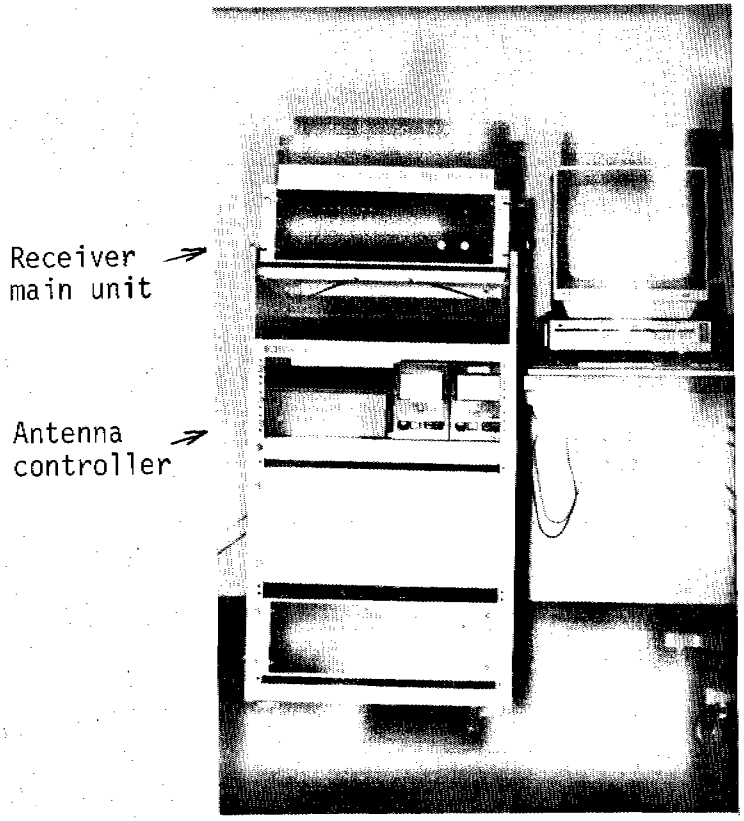

Figure 1. Picture of the GPS receiver main unit.

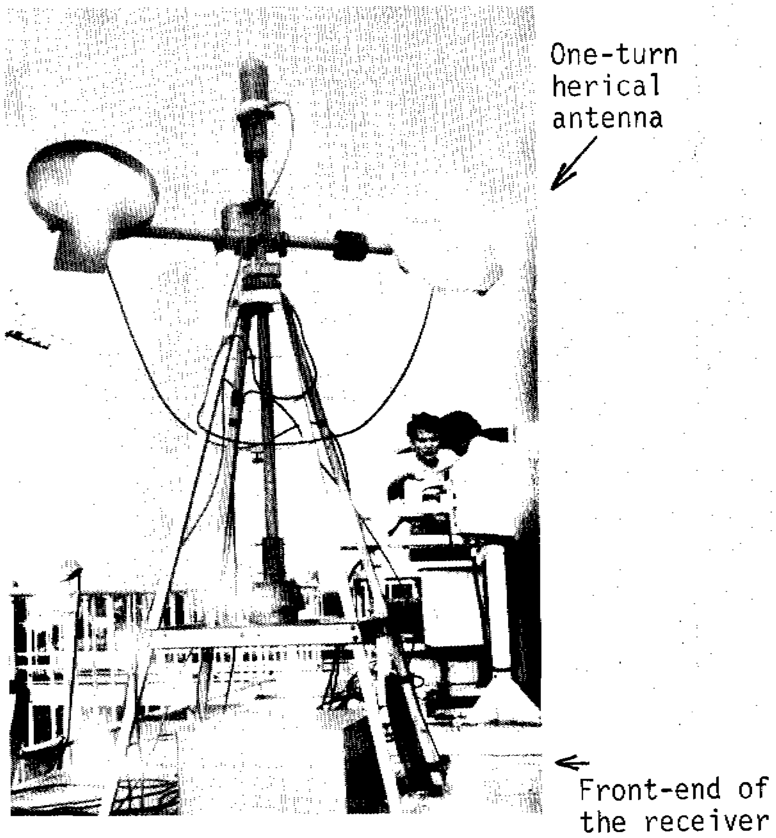

Figure 2. Picture of antnnae and front-end.

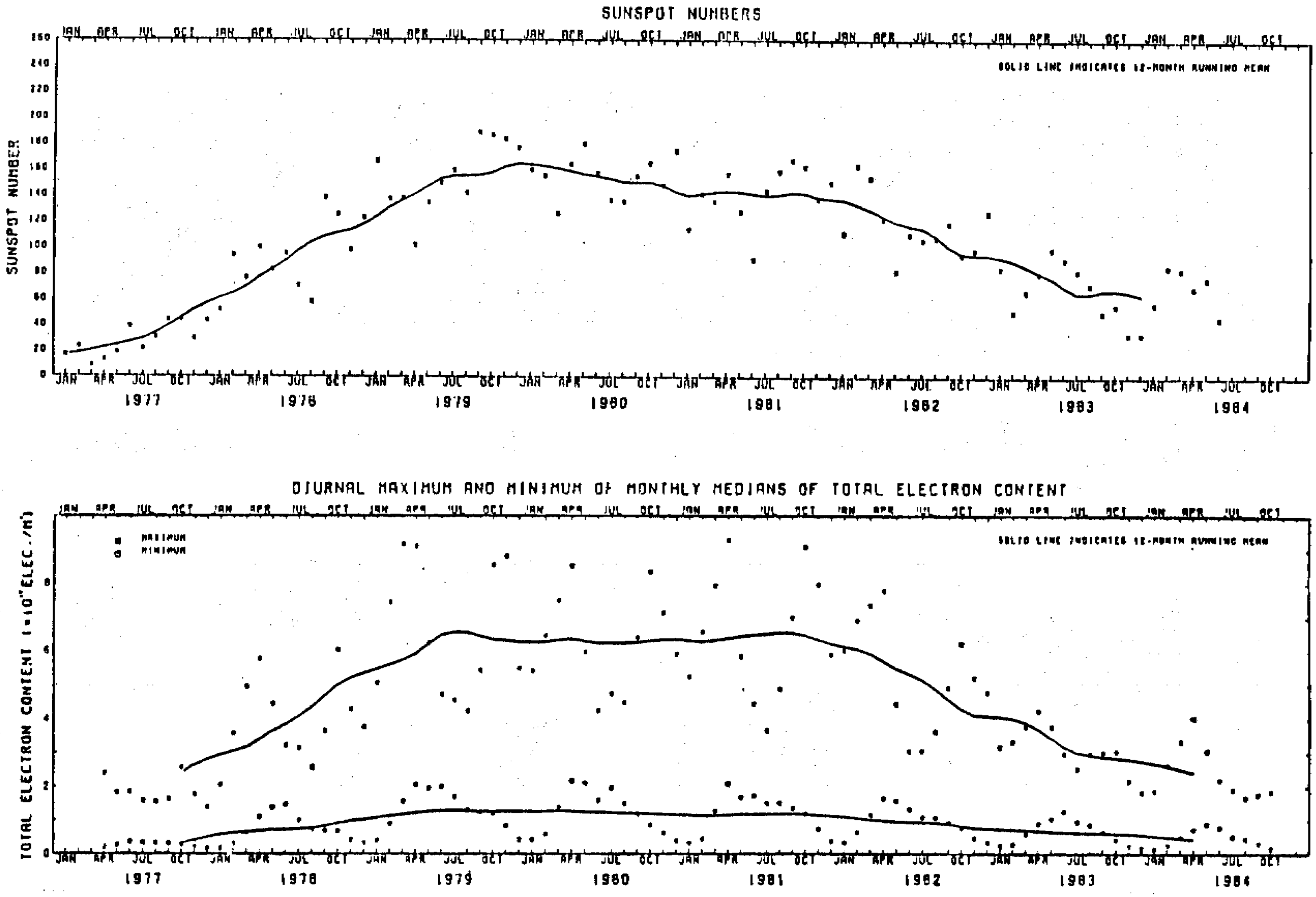

Figure 3. Long-term behavier of the solar activity (sun-spot numbers) and the total electron contents (TEC) measured at RRL (repeoduction from reference (7)).

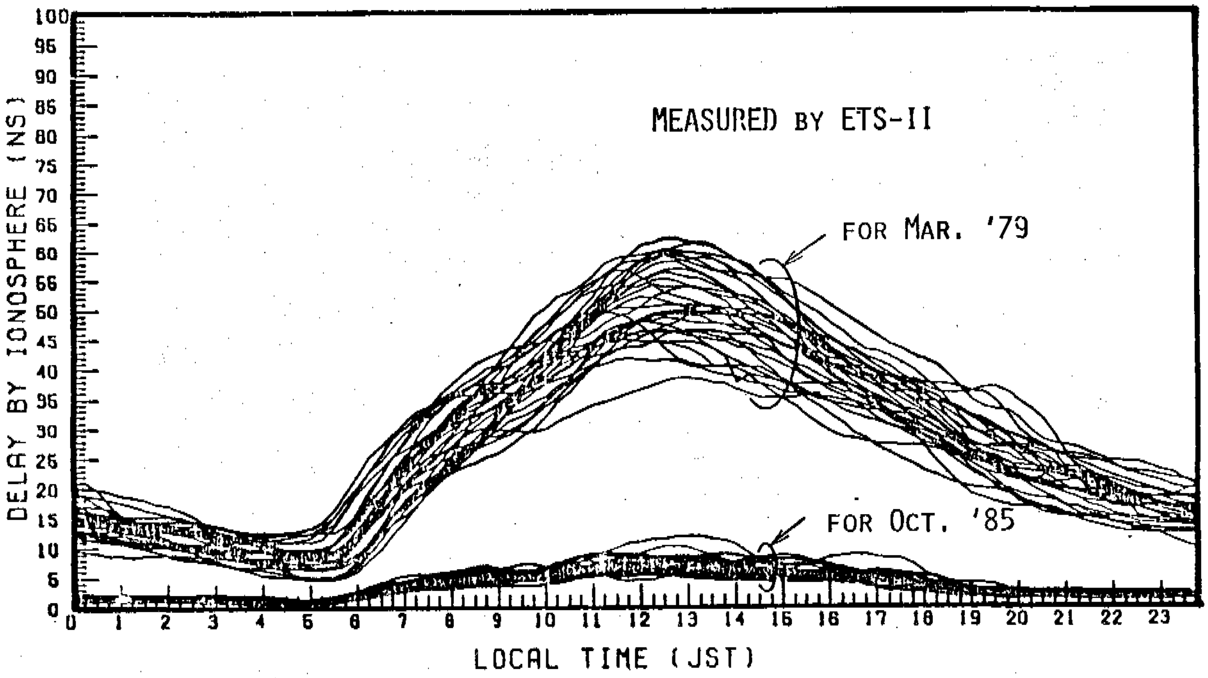

Figure 4. Exsample of the ionospheric effects on GPS L1 signal (calculated by the daily TEC measured) during solar maximum (1979) and near solar minimum (1985).

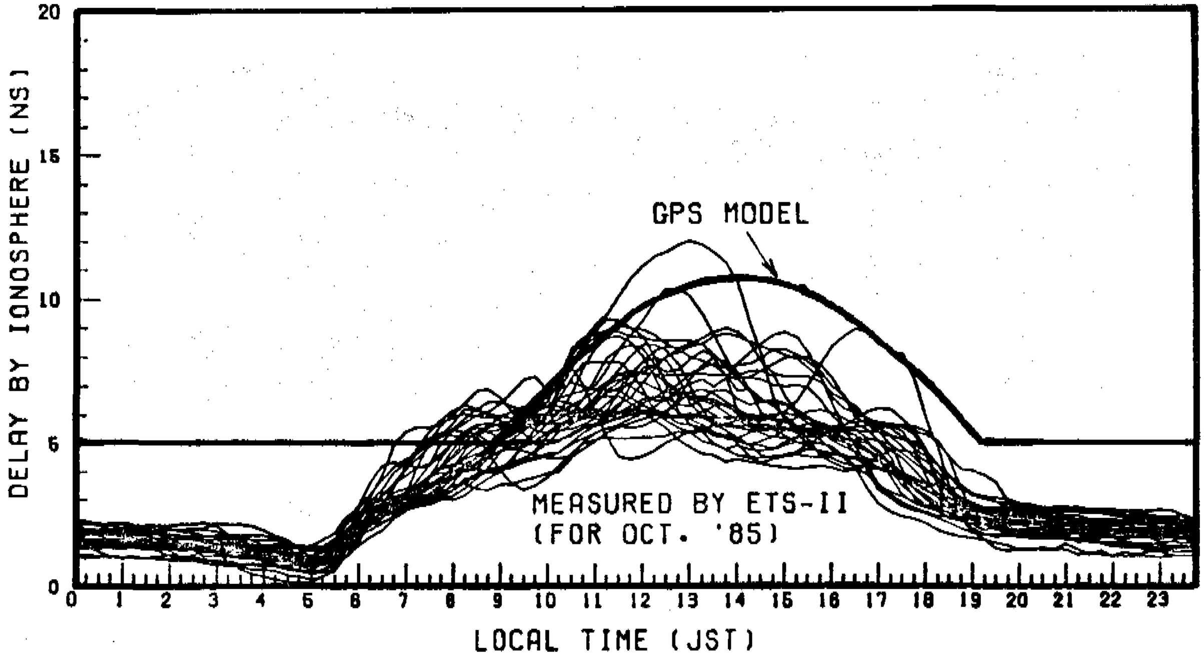

Figure 5. Comparison between the acutual ionospheric effect on GPS L1 signal and ionospheric compensation model transmitted from GPS satellites.

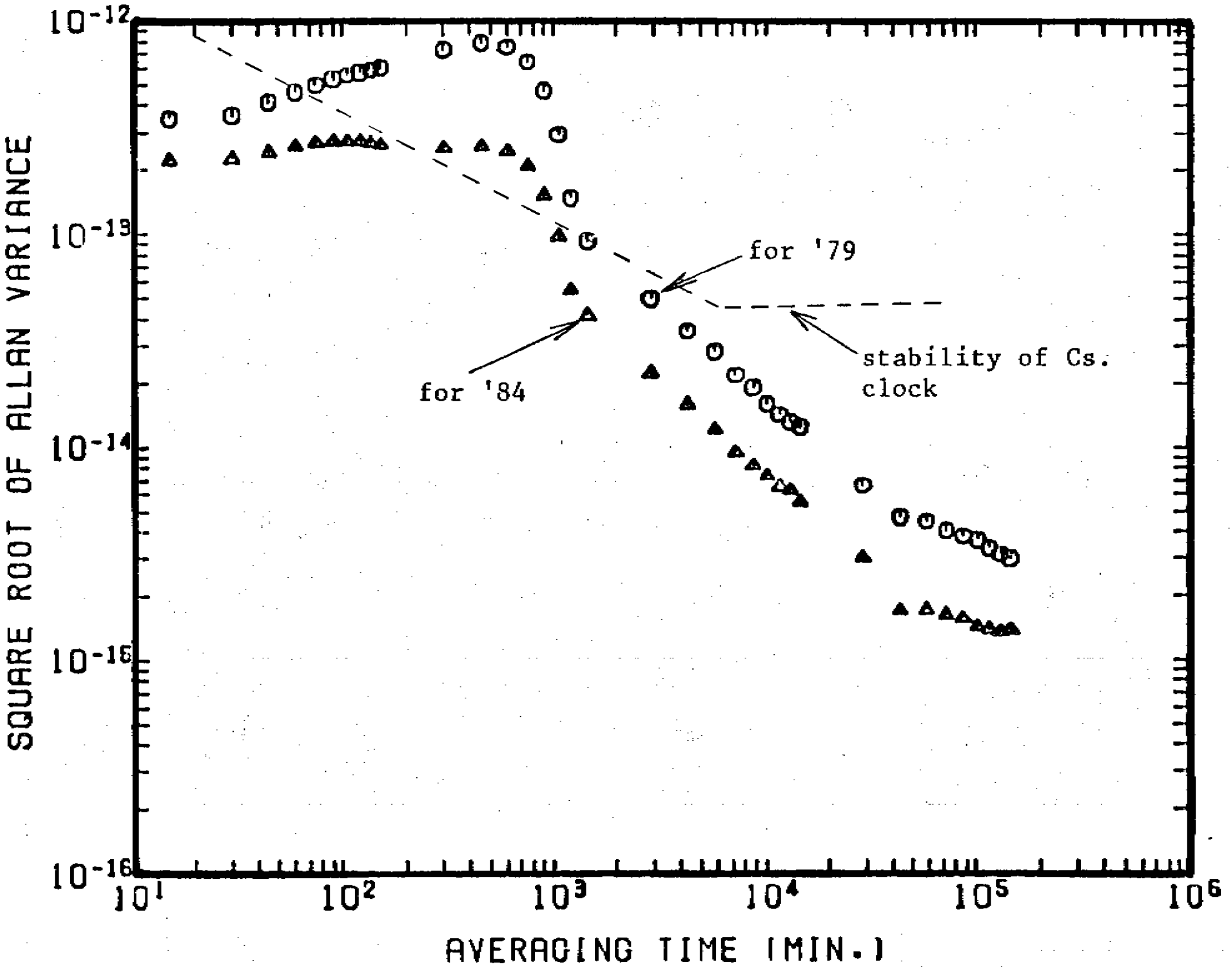

Figure 6. Stabilities of the propagation delay of GPS L1 signal caused by the ionosphere (calculated by the TEC measured).

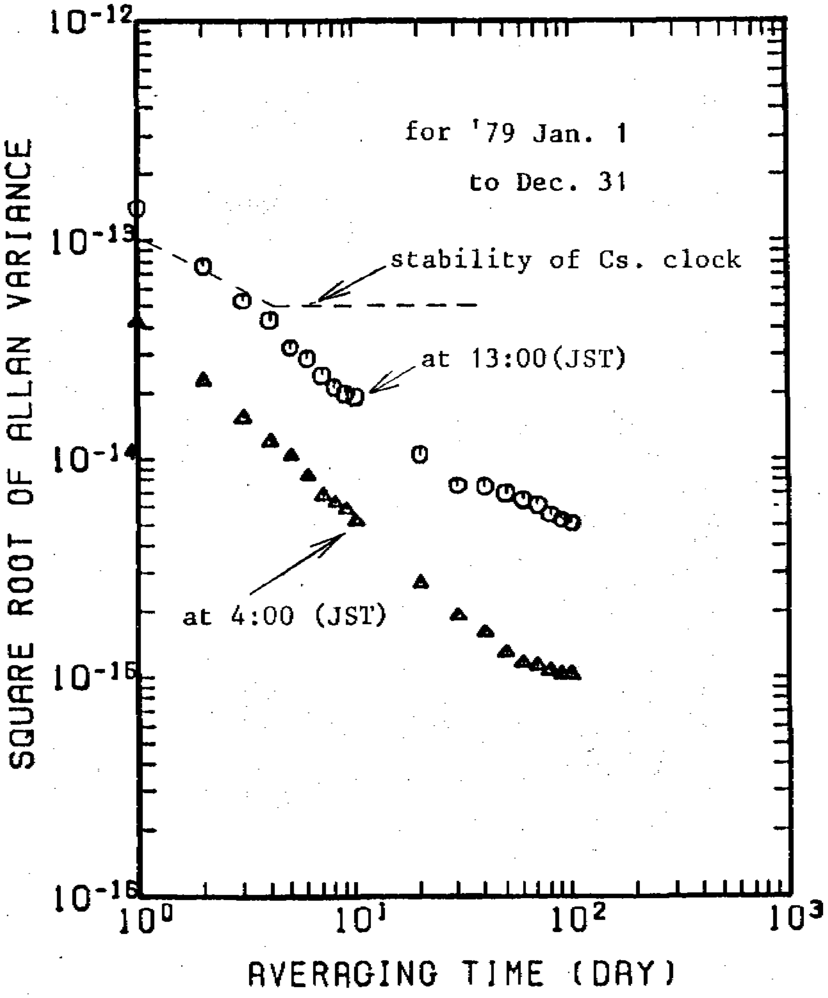

Figure 7. (a) Stabilities of the propagation delay of GPS L1 signal caused by the ionosphere at 13:00(JST) and 4:00(JST).

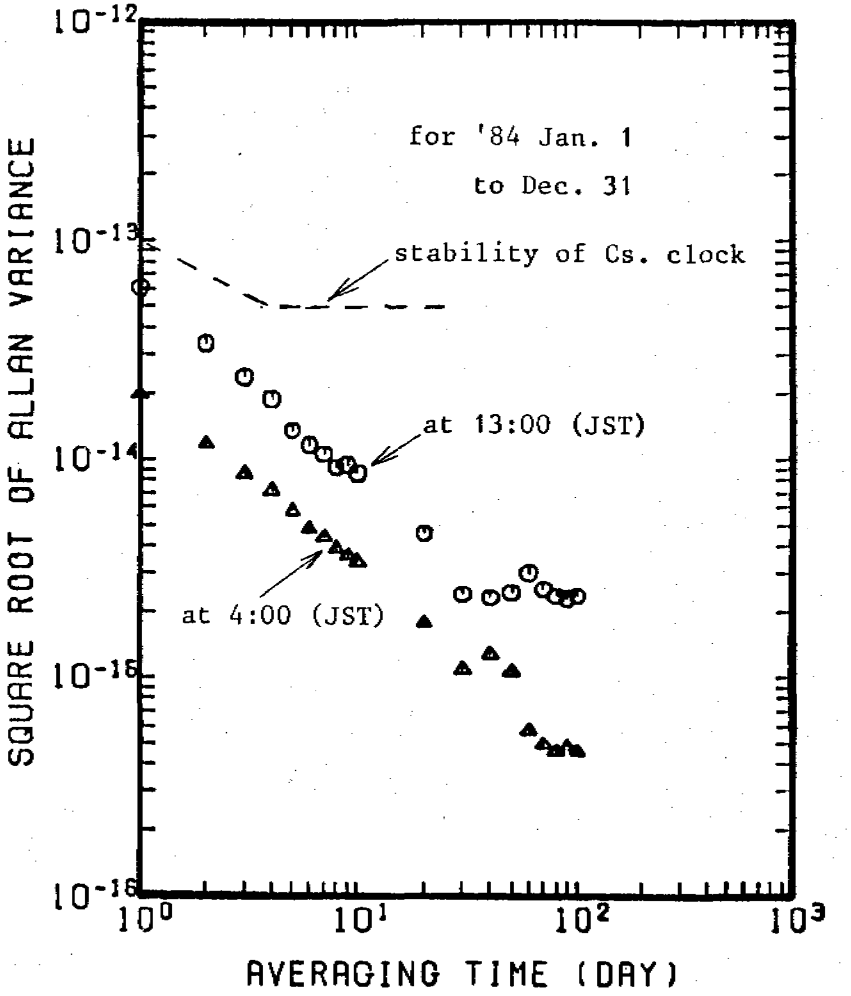

Figure 7. (b) Stabilities of the propagation delay of GPS L1 signal caused by the ionosphere at 13:00(JST) and 4:00(JST).

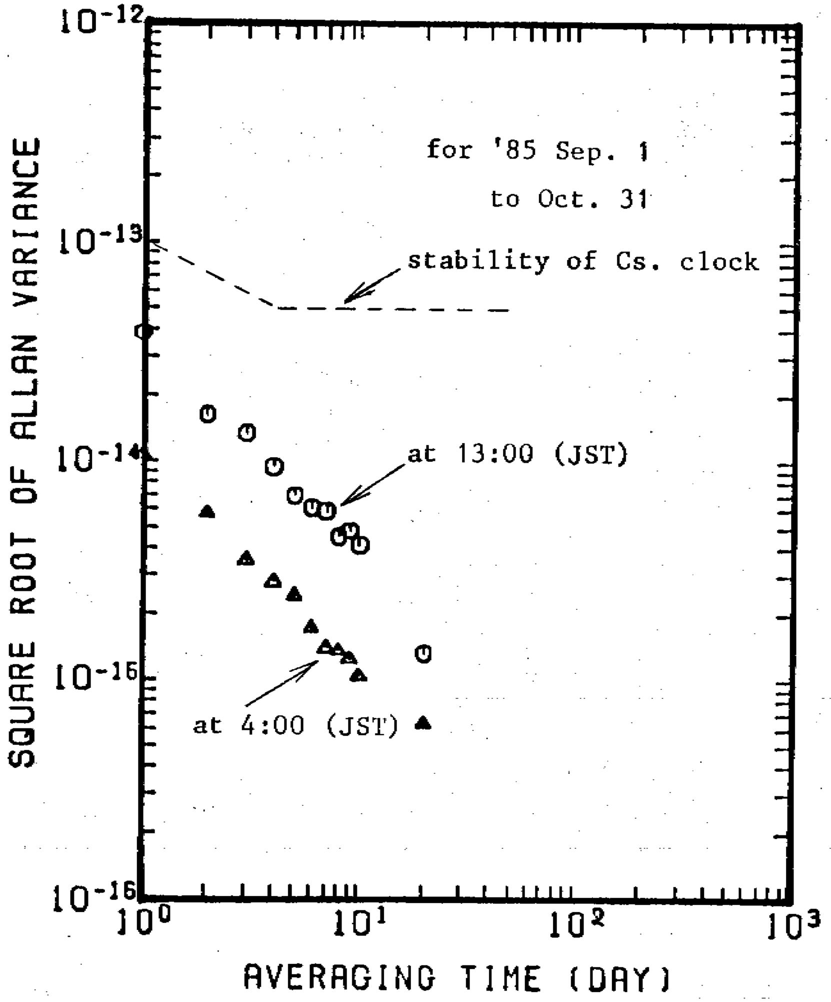

Figure 7.(c) Stabilities of the propagation delay of GPS L1 signal caused by the ionosphere at 13:00(JST) and 4:00(JST).

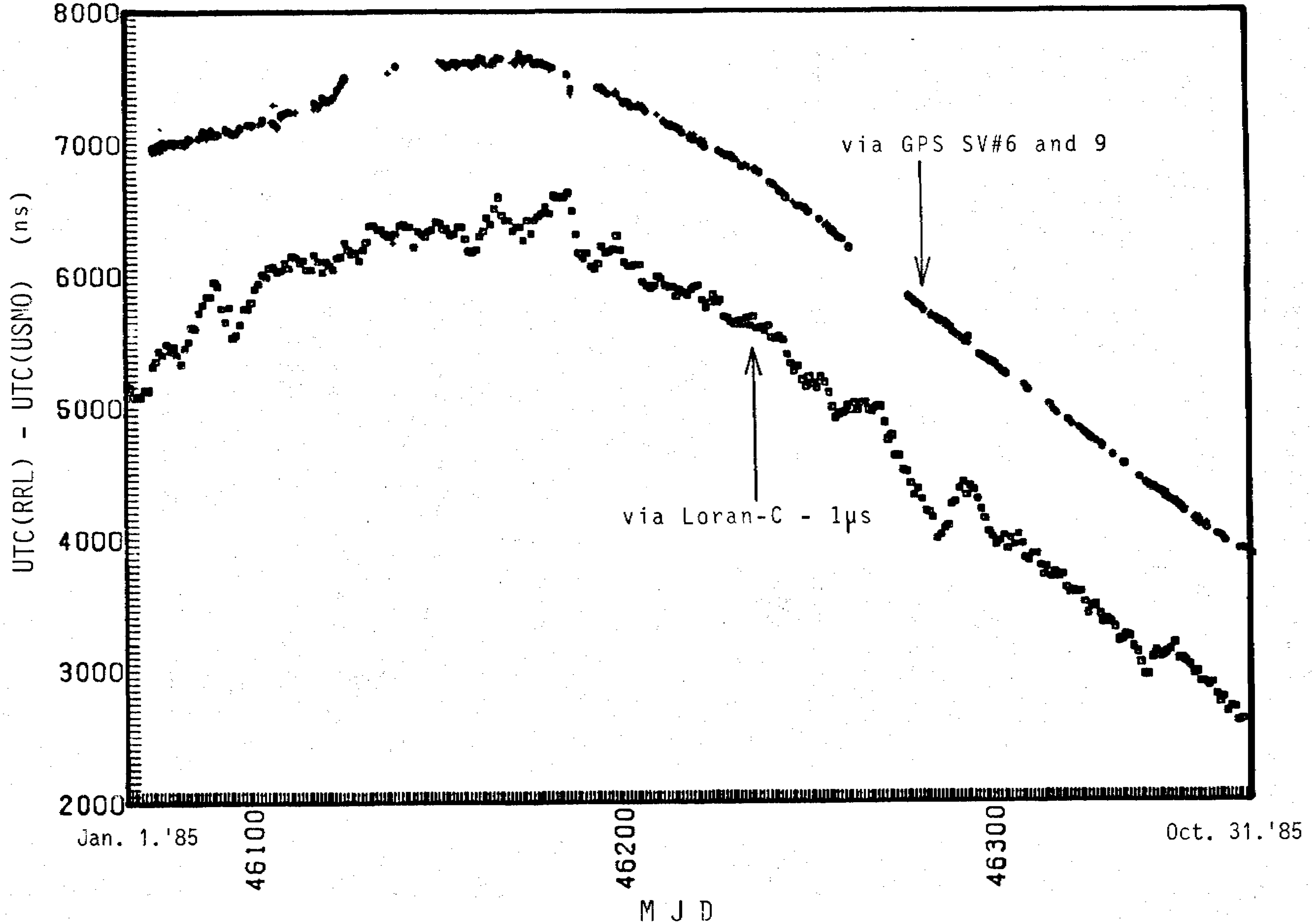

Figure 8. Time comparison results between RRL and USNO via GPS and via Loran-C.

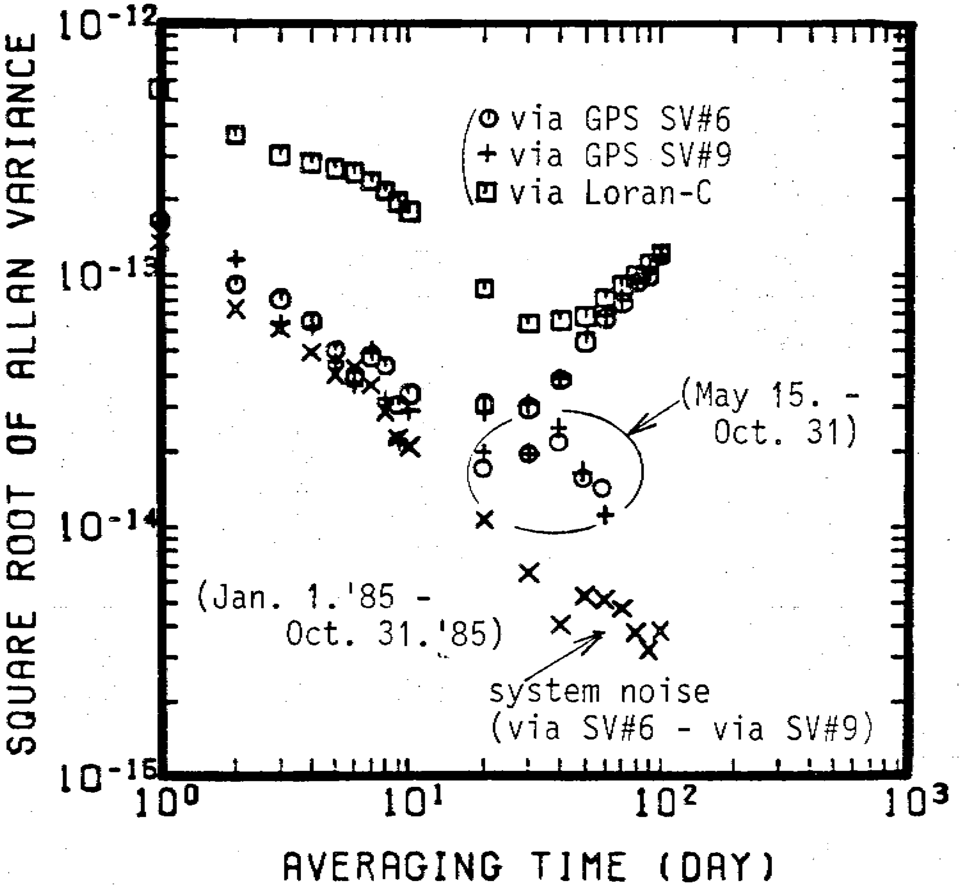

Figure 9. Stabilities (square root of Allan variance) of the time comparison results between RRL and USNO.

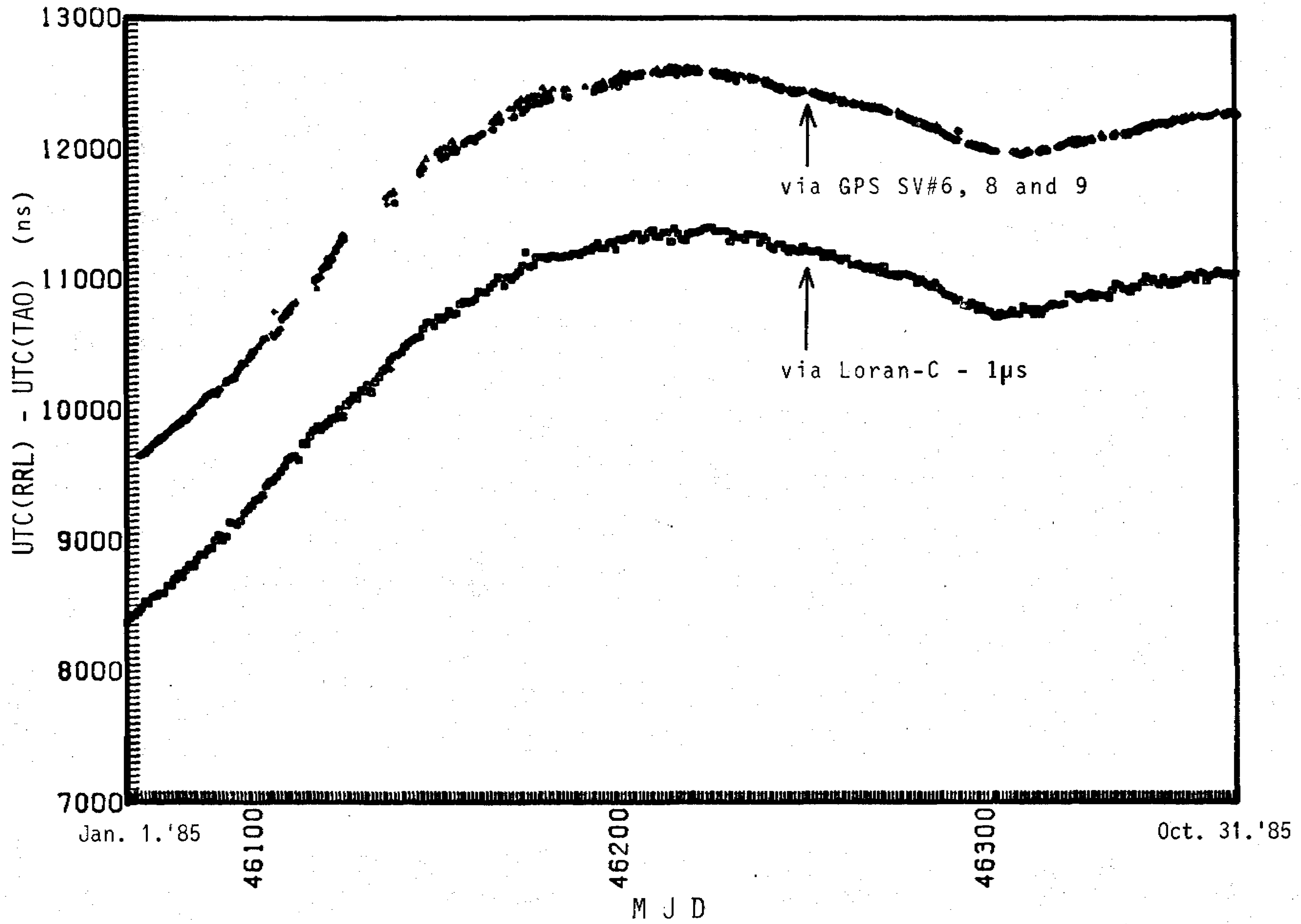

Figure 10. Time comparison results between RRL and TAO via GPS and via Loran-C.

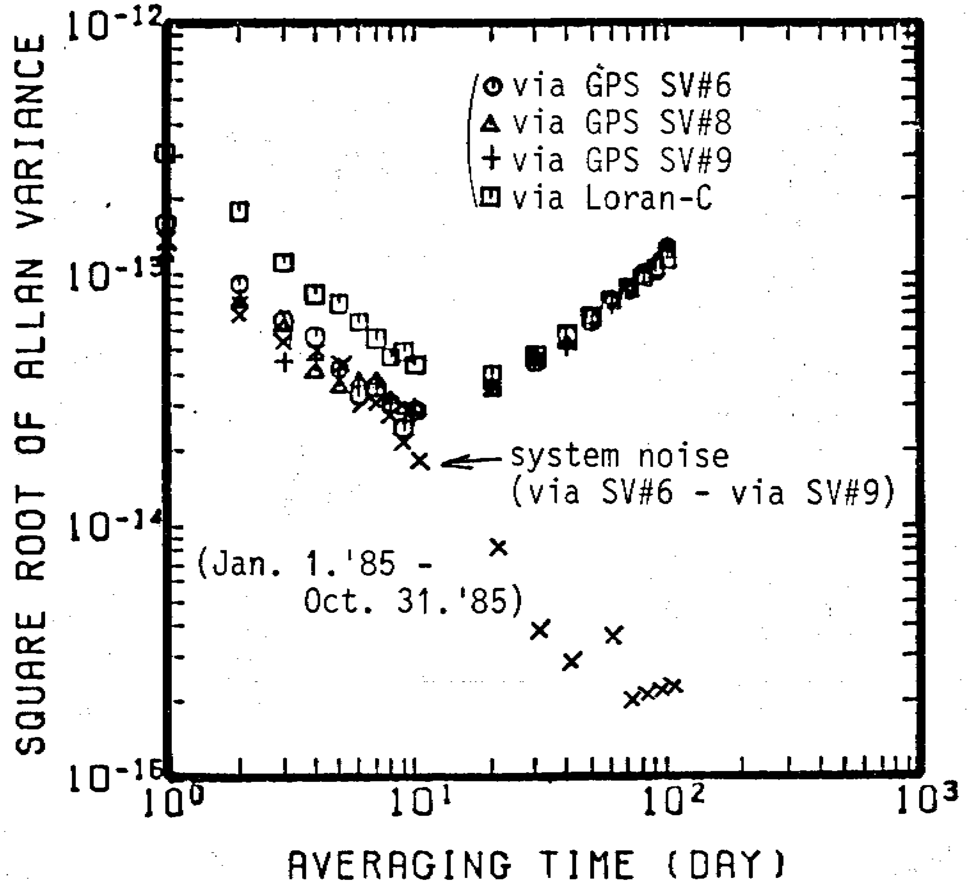

Figure 11. Stabilities (square root of Allan variance) of the time caomparison results between RRL and TAO.