Research Activities on Time and Frequency at the Radio Research Laboratory

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1. Introduction

Recent activities on time and frequency at the Radio Research Laboratory (RRL) are reported, such as work on the Cs beam primary frequency standard, hydrogen masers, new types of standards and precise time comparisons via space links.

2. Work on Frequency Standards

An accuracy evaluation of 1.1×10^{-13} was obtained in May 1984 with the RRL Cs beam primary frequency standards after replacing a 6.0 cm beam focus magnet by a 3.0 cm one to get a slower beam velocity[1] (Fig. 1). With this magnet the frequency shift due to the microwave power change was much improved in its quantity, smoothness and symmetry for beam reversal (Fig. 2). A second evaluation was made in December 1984 and a third in March 1985 with almost the same accuracies and the frequencies are within this accuracy relative to TAI. Further improvements were achieved in the fourth accuracy evaluation in April 1986 to obtain an accuracy of 0.7×10^{-13}, such as optimization of the beam optics, improvement of the electronics circuitry and a precise control of the magnetic C-field[2]. The C-field is automatically controlled by using the transitions of (F=4, m=±1) to (F=3, m=±1). The data were sent to the BIH for contribution to TAI.

Field operable hydrogen masers were successfully developed and have been continuously operated at RRL[3] as an important part of the K-3 VLBI system which has been used for measurements of the crustal plate movements with a precision of less than 3 cm (0.1 ns) and for internal time comparisons[4,5]. The frequency stability is about 2×10^{-15} for an averaging time of a few hundred seconds. The state selection by the Majorana method (Fig. 3) was studied and adopted for the laboratory hydrogen masers[6,7] to improve the magnetic inhomogeneity shift (Crampton effect), the maser oscillation power and the linewidth. Three masers are continuously operated with the Majorana state selection method and newly coated storage bulbs. Two of them (masers #3 & 4) automatically control their cavities by mutual reference to the other signal, while the other (maser #5) is cavity controlled by the fast tuning method in which a 1.4 GHz injected into the cavity is frequency switched by an amount equal to the cavity bandwidth for detection of the frequency shift[8]. The long term frequency stabilities are rather good (Fig. 4), and the data are sent to the BIH with those of the commercial Cs clocks.

Basic experiments on the optically pumped Cs beam frequency standard were made for a Rabi cavity using a laser diode (Fig. 5), and the microwave resonance lines were observed with both π and σ polarized light[9]. Experiments with a Ramsey cavity are underway to facilitate its use as the primary frequency standard in 1987. Basic experiments on the ion storage frequency standard were also made by using an RF quadrapole trap device with Xe^+ and N_2^+ ions (Fig. 6). The storage times of the ions were measured to be about 17 seconds for Xe^+

and 1.2 seconds for N_2^+, which agreed well with a theoretical analysis using the RF resonance absorption method[11]. An effective method for laser cooling of the was proposed and theoretically examined[11]. The new method can cool the beam with a wide range of velocities (300m/s to 5 m/s, for example) by using tapered mirrors (Fig. 7). The mirrors are tapered in such a way as to provide a gradual tuning of the laser frequency in the moving frame of the beam atoms. Cooling of the beam then results by absorption of Doppler-shifted light by hotter atoms, allowing an improved signal-to-noise ratio for the standard.

A 9.2 GHz superconducting cavity stabilized oscillator has been studied at RRL since 1976. Surface preparation of the cavity (Fig. 8) was done by electropolishing, anodizing and degassing under ultra-high vacuum conditions to get a quality factor of 3×10^8. The frequency stability measured with respect to a hydrogen maser was $4.8 \times 10^{-12}/\tau$, which seemed to be limited by the maser stability[12].

3. Development of a Time Transfer System Via Space Links

The overall time transfer using space links between RRL and other organizations is shown in Fig. 9 which appeared as the cover page of the Proceeding of the IEEE in January 1986, although some of the stabilities are modified and different from the real ones[13]. The time transfer links consist of three categories - the domestic link, the Asian link and the US/ European link.

We developed a GPS receiver to make international time comparisons on a routine basis with the USNO under a common view schedule and have been sending the data to the BIH since August 1984[14,15]. Errors in the software have recently been detected and corrected to remove a diurnal variation of about 100 ns (ptp), which affected the international time comparison results with time steps of a few tens of nanoseconds (frequency steps of less than 10^{-14} averaged over 2 months). Transportation of a clock and a GPS receiver have been conducted once a month between RRL and the Tokyo Astronomical Observatory (TAO). The average delay difference of the RRL fixed receiver and the TAO one was estimated to be about 20 ns, but there was a discrepancy of 60 ns or more compared with the results of the clock trips whose accuracy are less than 10 ns[16]. This shows an accuracy limit of the GPS receiver transportation method when different types of receivers are use as in the case of our experiments. Frequency stabilities of UTC(RRL)-UTC(USNO) via GPS satellites #6 and #9 are shown in Fig. 10, from which the precision is estimated as around 15 ns.

A time transfer receiver to receive the ranging signal at a frequency of 1.68 GHz from the Japanese Geostationary Meteorological Satellite (GMS) was also developed and use for time transfers in the Asian-Oceanic area. A preliminary experiment of time comparisons between RRL and the National Measurement Laboratory (NML) of CSIRO in Australia was conducted in June 1985 for one month by receiving four times a day the ranging signal phase-modulated with a 200 kHz tone[17]. The data include the peak-to-peak daily variation of about 100 ns due to a propagation error in the orbit determination, which is made once a day at UTC 0 (Fig. 11). Since February 1986, the time comparison has been done on a routine basis. Fig. 12 shows the frequency stabilities of the time comparisons made in July and August 1986. The precision of the link was estimated as about 20 ns by using hydrogen masers for the signal reception at both sites in October 1986 to reduce the effect of the clocks used as much as possible. It turned out that the precision would almost come from the orbit determination error. Shanghai Observatory and the Korea Standards Research Institute are going to join the experiment in early 1987. Technical cooperations have been made for these organizations to develop their GMS receivers. Now a smaller receiver is being developed at RRL for experiments on receiver transportation.

Very precise time transfer experiments using a Very Long Baseline Interferometer (VLBI) have been conducted with the USNO about once a month since December 1984[18]. Precision of about 0.2 ns and an accuracy of about 10 ns are obtained. The accuracy is expected to be much improved by the experiment done at USNO in October 1986, in which a small VLBI receiver from RRL was transported to the USNO to measure the delay difference of both receivers accurately. Shanghai Observatory and other organizations equipped with VLBI systems will join the time transfer experiment.

Spread-spectrum time transfer equipment has been newly developed to be used for two way time transfer via the domestic communication satellite CS-2 with both precision and accuracy of a few nanoseconds by using a mobile station[19]. The CS link is going to be used when necessary for very accurate time transfers such as the time synchronization between the Kashima station and the RRL Headquarters in the VLBI time transfer experiment. RRL has been conducting time transfer experiments with domestic organizations via a TV link with the Japanese broadcasting satellite BS-2 once a week since the beginning of 1985. Precision of 20 ns or less and accuracy of about 100 ns are attained.

4. Upgrading of the Standard Time and Frequency Transmission System

The data acquisition and processing system for the atomic clocks was upgraded on 1 October 1986 to a high performance computing system. The remote control system for the JJY and JG2AS transmission systems is also being upgraded as part of a five year plan. A real-time atomic time - an ensemble one - is generated for a check of UTC(RRL), and in the near future may be used as UTC(RRL) instead of the steered master clock.

5. Conclusion

Recent activities an time and frequency at RRL were reported. The GMS time transfer link made possible for the first time the direct time comparison between RRL and NML in Australia. Further efforts for improvement of the time transfer links and the atomic standards are being continued.

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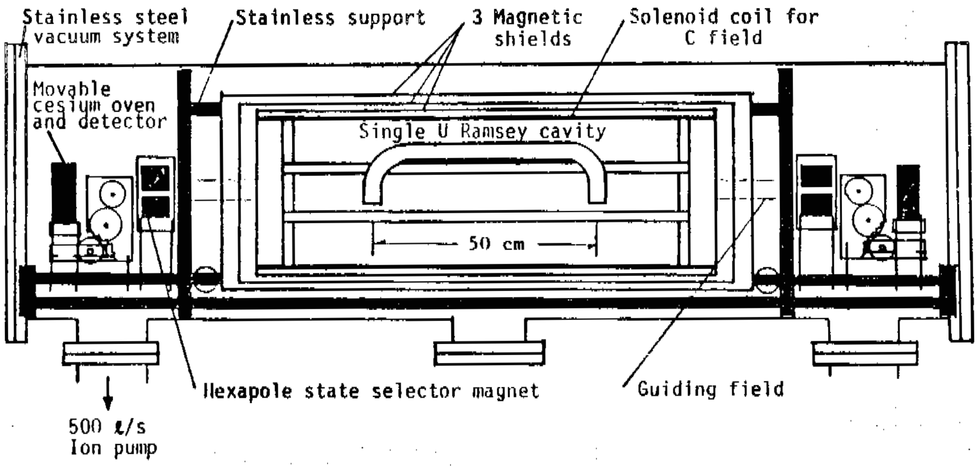

Fig. 1 Structure of RRL Cs-beam primary frequency standard.

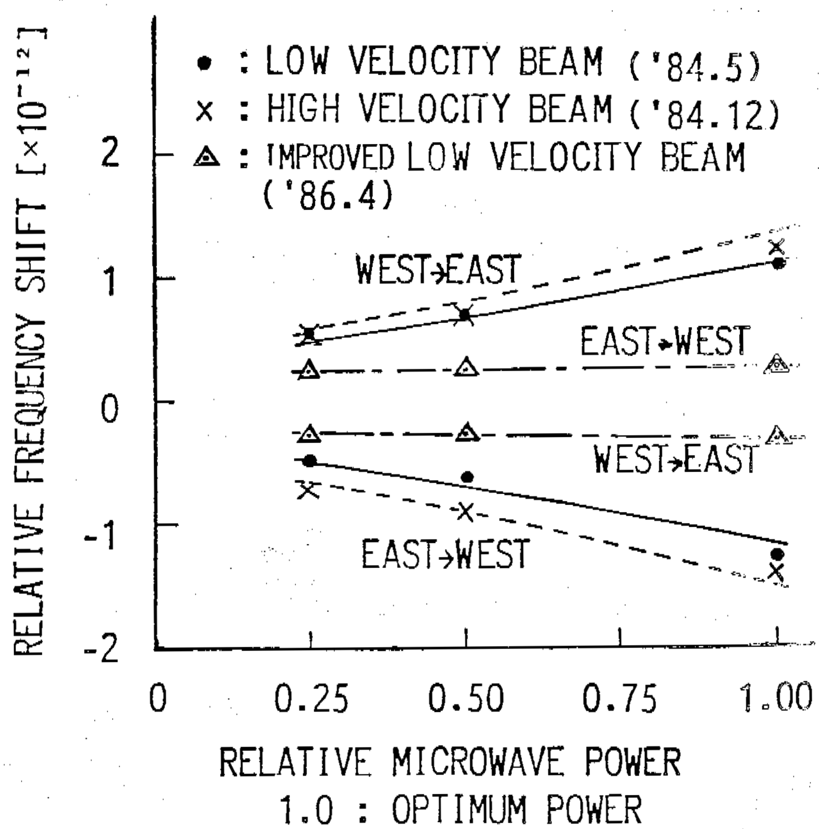

Fig. 2 Power shift characteristics; compared experimental results with calculated ones (straight lines and dashed lines) for different velosity beam.

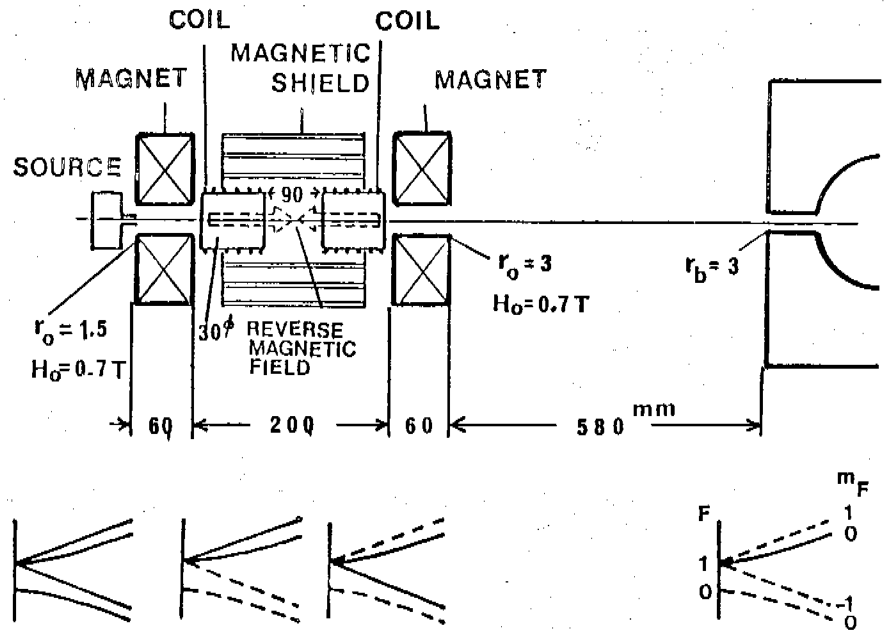

Fig. 3 Structure of the Majorana state selection for RRL hydrogen masers.

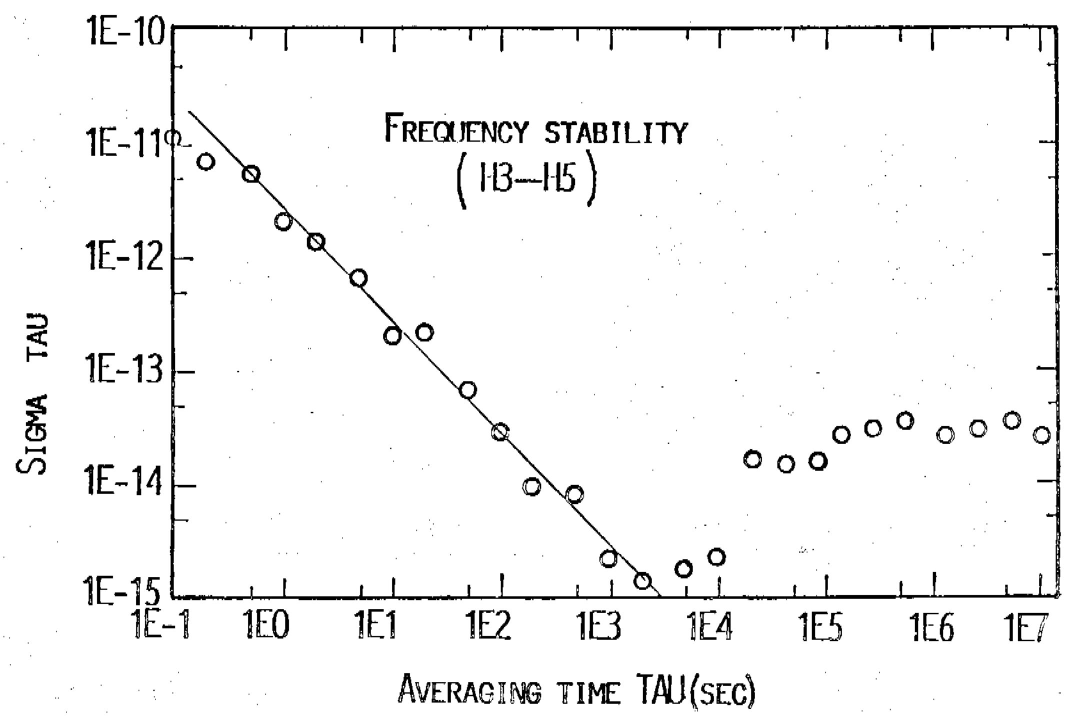

Fig. 4 Frequency stability of RRL hydrogen masers; with free-running cavities for tau less than 1E4 and automatically controlled cavities for tau larger than 1E4.

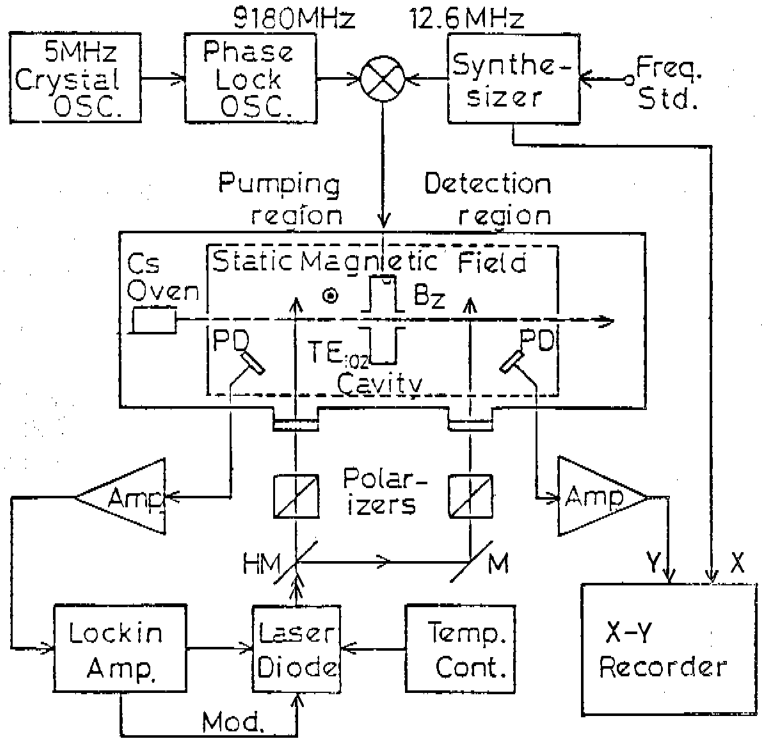

Fig. 5 Block diagram of the experimental setup for the Rabi resonance observation with the optically pumped Cs-beam frequency standard.

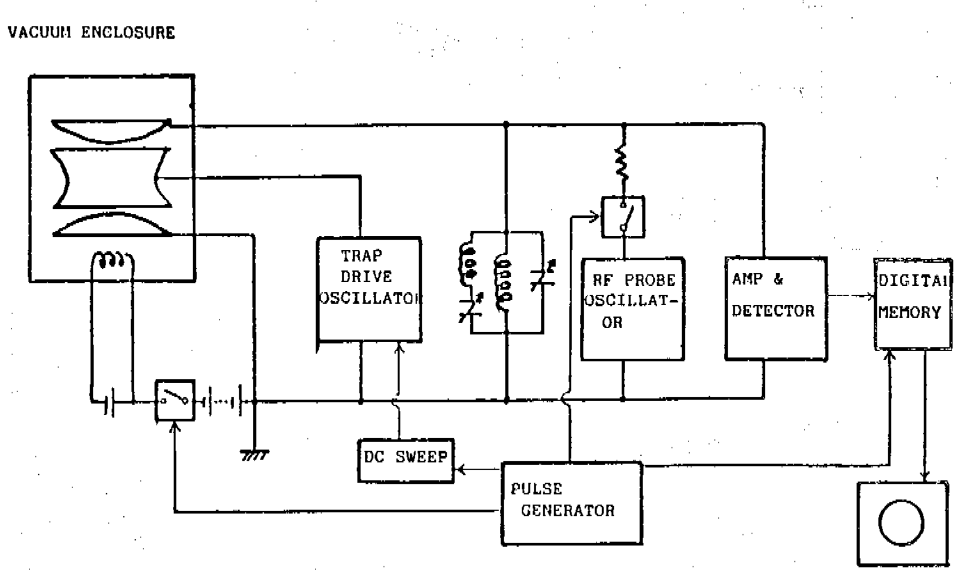

Fig. 6 Block diagram of the experimental setup of the ion storage frequency standard.

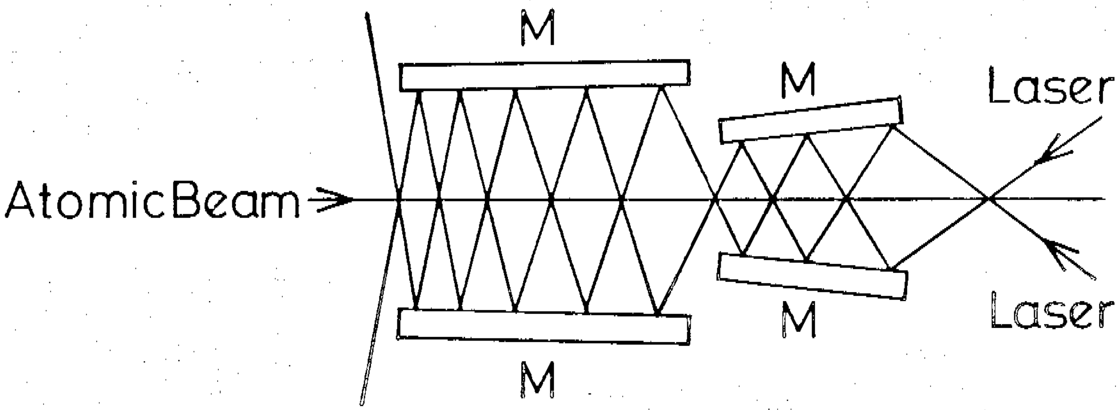

Fig. 7 Schematic diagram of the mirror configuration for the laser cooling of the atomic beam.

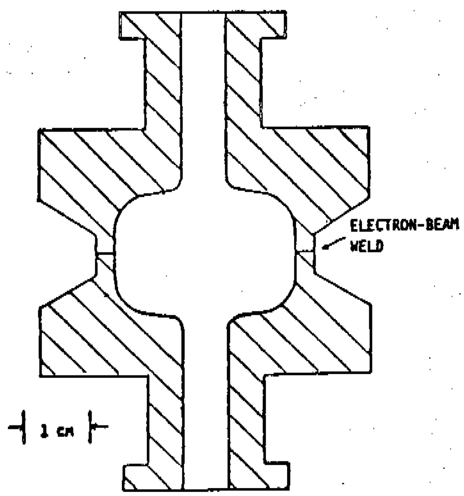

Fig. 8 Cross-sectional view of the 9.2 GHz niobium spherical cavity for the superconducting cavity stabilized oscillator.

Fig. 9 International/domestic time transfer links of RRL, using space links such as Global Positioning System (GPS), Very Long Baseline Interferometer (VLBI), Geostationary Meteorological Satellite (GMS-3), Communication Satellite (CS-2) and Broadcasting Satellite (BS-2).

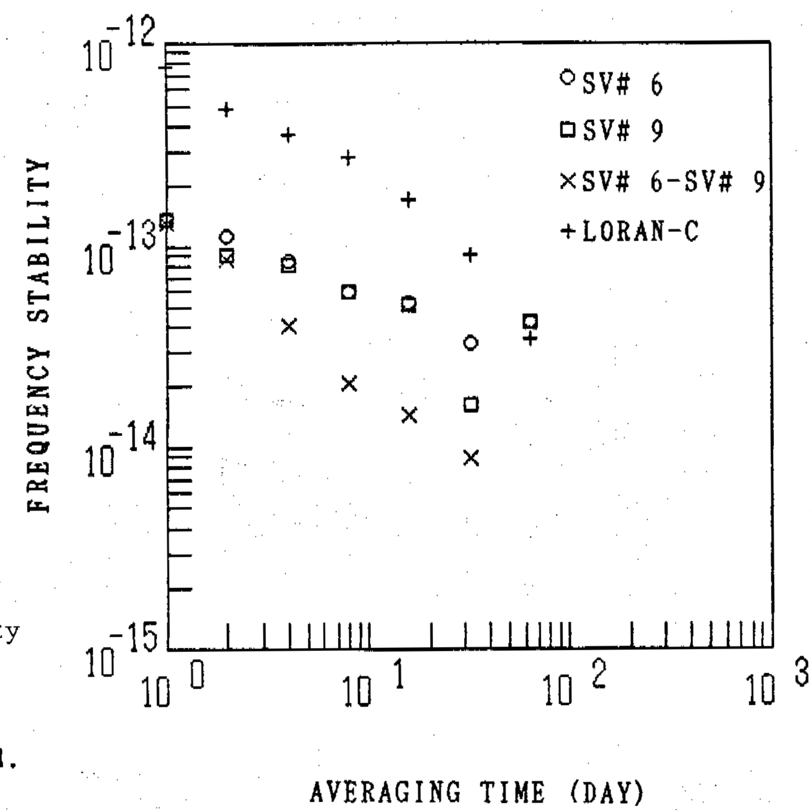

Fig. 10 Frequency stability of UTC(RRL) - UTC (USNO) compared via GPS satellite #6 & #9. Result via Loran C is also plotted.

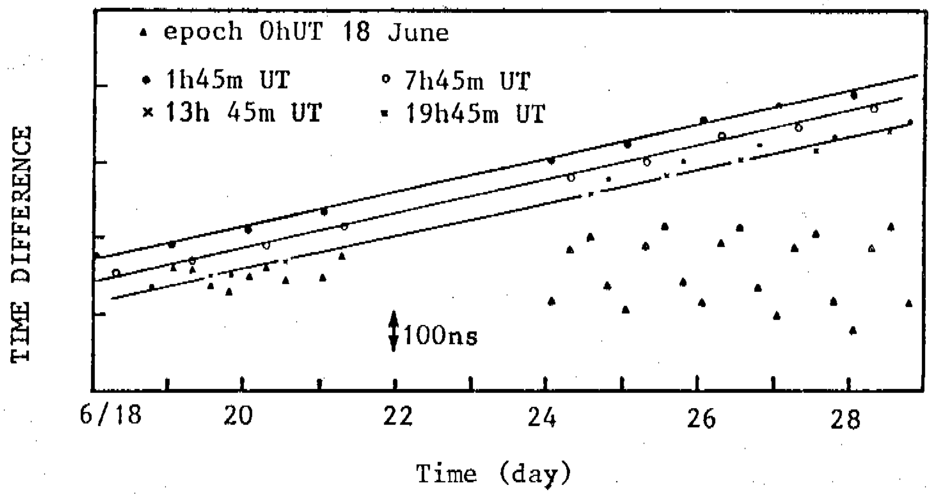

Fig. 11 Time comparison result of UTC(RRL) - UTC(NML) via GMS-3 obtained on June 18 to 28 in 1985. The triangle marks are calculated with only the ephemeris data at UT 0 on June 18, showing the error propagation due to the orbit determination error with time.

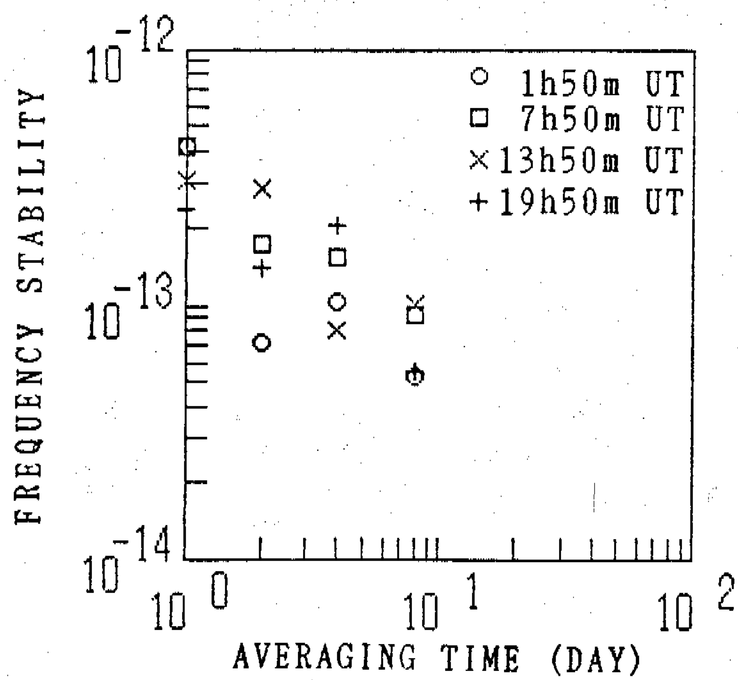

Fig. 12 Frequency stability of UTC(RRL) - UTC (NML) via GMS-3 obtained in July and August in 1986.