Vol. 32 No. 137 *Journal of the Radio Research Laboratory* *November 1985*
Printed in Tokyo, Japan *pp. 141–154*

THE TIME AND FREQUENCY STANDARD OF THE K-3 VLBI SYSTEM

By
Takao MORIKAWA, Tokuo SATO, Michito IMAE, Hitoshi KIUCHI,
Yasusada OHTA, and Noriyuki KURIHARA

(Received on April 2, 1985)

ABSTRACT

Radio Research Laboratory (RRL) has developed the K-3 Very Long Baseline Interferometer (VLBI) system, which is compatible with the Mark III VLBI system of NASA, for the VLBI joint experiments conducted by both RRL and NASA. As a part of this project the time and frequency standard of the K-3 system which is one of the most important parts of the K-3 system has been developed. It consists of two hydrogen masers, a commercial Cs clock, and the international and domestic time transfer links.

This paper presents the description of the developed hydrogen masers and the time transfer links, which have fully satisfied the requirements of the K-3 system and contributed to the VLBI experiments.

1. Introduction

As well known, it is the progress in the atomic frequency standards and the high precision time synchronization technology that has made it possible to conduct the Very Long Baseline Interferometer (VLBI) experiment with the baseline longer than 10000 km. Radio Research Laboratory (RRL) has long history of researches in the field of the time and frequency standard, on the basis of which the time and frequency standard system of the K-3 VLBI system[(1),(2)] has been developed. The time and frequency standard of the K-3 system consists of two hydrogen masers, a commercial Cs clock and the time transfer links, and has played an important role in the VLBI joint experiments conducted by both RRL and NASA[(3)].

Every VLBI station participating in a VLBI experiment has its own time and frequency standard which has the following two functions. The first function is to supply the local signal to the VLBI system. In a VLBI system a signal from a radio star, which is usually very weak, should be down-converted to the video frequency without any loss of the coherence. Therefore the phase noise of the local signal of the VLBI system must be exceptionally small. The phase stability required of the local signal depends on the noise temperatures of the VLBI system and the signal source as well as the sample time. In the K-3 system the phase fluctuation below $\pi/8$ radian for the sample time of 600s at the observation frequency of 8 GHz was projected.

The second function is to supply the clock signal to the formatter of the VLBI system, which is recorded in the magnetic tape together with the received signal from a radio star. In a VLBI experiment several radio stars are observed to measure the delay time in each observation. Therefore the fluctuation of the clock signal during the experiment must be smaller than the precision of the delay time measurement. In the K-3 system the precision of subnanosecond was projected.

The above functions require the time and frequency standard of the K-3 system to satisfy the following frequency stability.

$$\sigma_y(\tau) < 1.0 \times 10^{-14} \qquad \tau = 600\text{s}$$

$$\sigma_y(\tau) < 2.8 \times 10^{-14} \qquad \tau = 18000\text{s}$$

In order to meet the above specification two field operable hydrogen masers have been developed(4). The achieved frequency stability of such masers is 2.4×10^{-15} for the averaging period of 830s and 1.4×10^{-14} for 10^5 s, which fully satisfies the required specification.

For the cross-correlation processing the time and frequency standard of each VLBI station should coincide with each other within the limits of a certain precision. The required precision of clock synchronization in the K-3 system is 1μs. In an international VLBI experiment the stations participating in the experiment are worldwide located. Therefore it is reasonable and realistic to synchronize the clock of each station with the UTC of each country. The RRL Headquarters (RRL HQ) keeps UTC (RRL) which is linked by Global Positioning System (GPS) and portable clocks with the other UTC's maintained at the major time keeping institutes such as US Naval Observatory (USNO). The Cs clock of Kashima station is synchronized via a 7 GHz microwave link with UTC (RRL), and resets the clock signal of the formatter supplied by the hydrogen maser before each VLBI experiment.

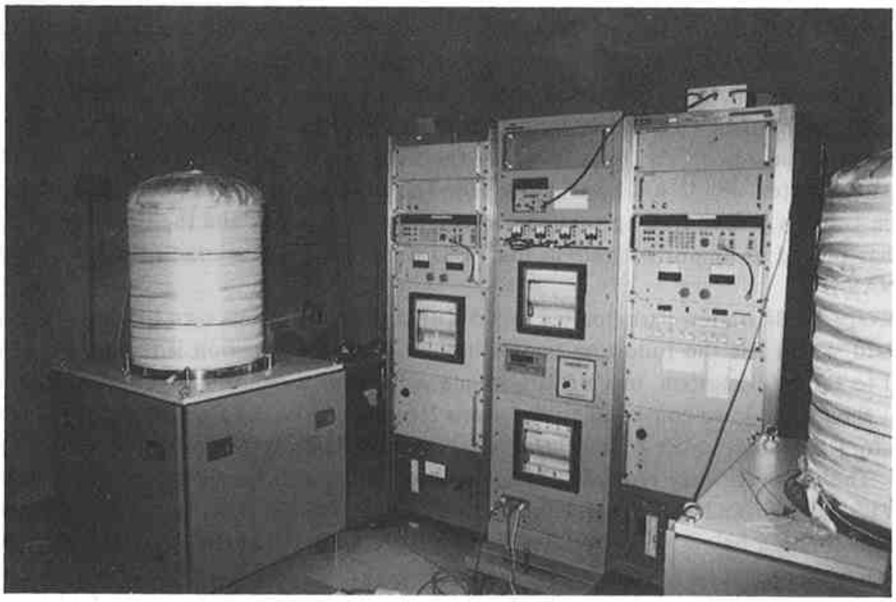

Fig. 1 The hydrogen masers for the K-3 system

2. Hydrogen masers

The maser consists of a physics package and an electronics package. Fig. 1 shows the physics and the electronics packages which are placed in the maser room of Kashima station. One maser supplies the local and the clock signals to the K-3 system as the main maser, while the other maser is used as the sub maser which usually monitors the main maser. In case of trouble of the main maser, the main maser is replaced by the sub maser, which makes the system highly reliable.

2.1 Physics package

The physics package is 84 cm wide, 94 cm deep, 160 cm high and 550 kg in weight. In Fig. 2 the structure of the physics is shown.

2.1.1 Magnetic shielding

The maser has four permalloy magnetic shields, all of which are 2 mm thick and set in a vacuum chamber. This structure has the following two advantages.

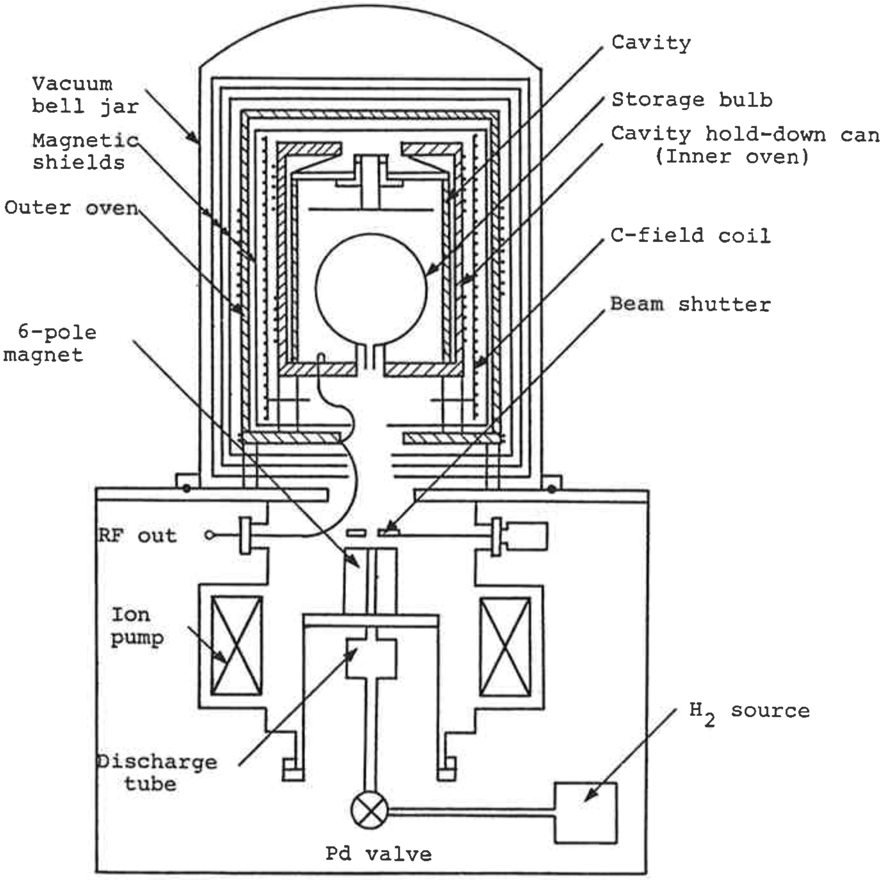

Fig. 2 The physics package of the maser for the K-3 system

One is that the conduit pipe which connects the ion pump and the resonant cavity can be eliminated. This structure results in the smaller aperture of the magnetic shields for the hydrogen beam path, and also in no heat-flow through the conduit pipe, which give better magnetic shielding and thermal insulation.

The other is that the magnetic shields function also as the thermal radiation shields, which contribute to improving the thermal isolation.

2.1.2 Resonant cavity

As well known, the fluctuation of the resonance frequency of the cavity (f_c) disturbs the oscillation frequency of the maser (f_m) (pulling effect[5]). The main causes of the fluctuation are the thermal expansion of the cavity material, the mechanical distortion of the cavity material, and the thermal fluctuation of the dielectric constant of the storage bulb.

Fig. 3 shows the structure of the resonant cavity. The cavity cylinder and the upper end-plate are made of glass ceramics (NEOCERAM) with a low thermal expansion coefficient of -5×10^{-7}. Silver conductive composition is painted on the inner surface of the glass ceramics. The measured loaded quality factor is 50000. The coarse tuning is carried out by moving the upper end-plate. The screwed axis for adjusting the upper end-plate is made of molybdenum which has a relatively low thermal expansion coefficient of 5×10^{-6}[6].

The cavity cylinder is fixed by the cavity hold-down can, which gives a stress onto the ceiling plate. This stress distorts the ceiling plate, which holds the coarse tuning axis, and changes the distance between the cavity end-plates. In order to achieve the maser frequency stability of 1×10^{-14}, the fluctuation of the distance should be below 0.3 nm. Therefore the cavity material should be highly rigid and the stress should be stable. The flexural rigidity of a plate depends on its Young's modulus and the third power of its thickness[7]. The ceiling

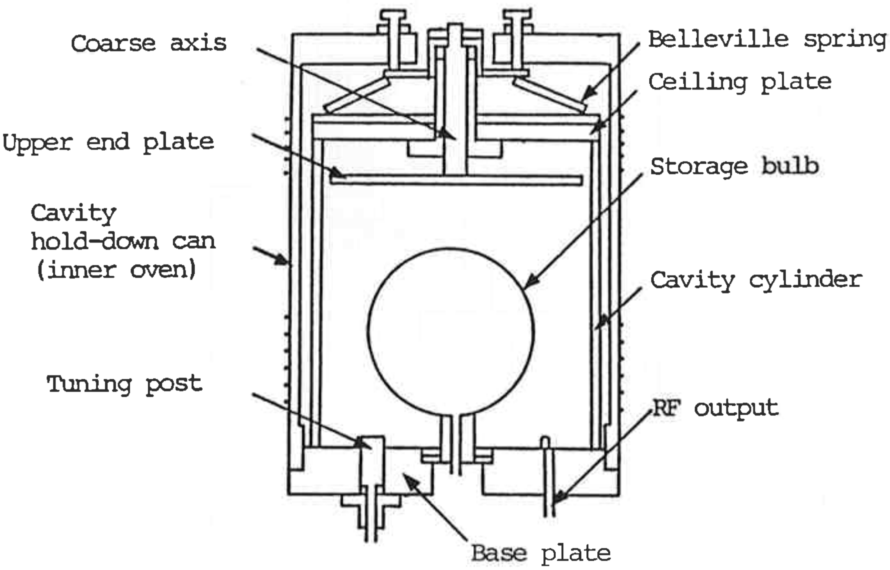

Fig. 3 The structure of the resonant cavity

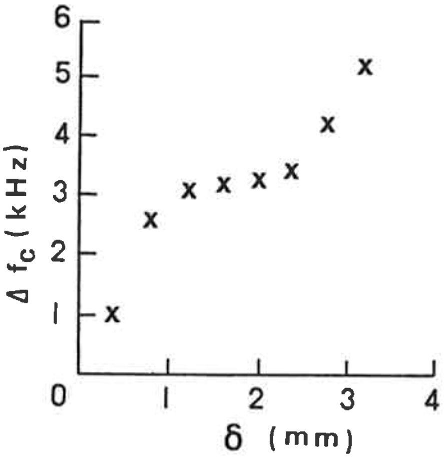

Fig. 4 Cavity stabilization by the Belleville spring

plate is made of alumina which has high Young's modulus of 3×10^6 kg/cm^2. The base plate is 29 mm thick and made of aluminium. The fluctuation of the stress is mainly caused by the thermal expansion of the cavity hold-down can. This stress change is absorbed by a titanium Belleville spring(8). Using the constant-load characteristic of the Belleville spring the stress on the ceiling plate can be stabilized. As shown in Fig. 4 the change in the cavity frequency becomes much smaller when the spring distortion is between 1 and 2 mm. The cavity can be stabilized by setting the spring in this region.

The effect of the thermal change in the dielectric constant of the storage bulb can be reduced by using a light storage bulb(9). The storage bulb is spherical and made of quartz glass. Its diameter is 180 mm and the weight is 260 g. The overall thermal coefficient of the cavity frequency is 500 Hz/K.

2.1.3 Thermal control

The stability of the cavity temperature should be better than 1 mK to achieve the maser frequency change of less than 1×10^{-14}. The thermal control is carried out by double ovens. The cavity hold-down can to which heaters and thermistor control sensors are attached is used as the inner oven. The oven is divided into two zones, each of which is independently controlled to minimize the thermal gradient. The outer oven is made of a thick aluminium cylinder with heaters and sensors and placed on the outside of the innermost magnetic shield. It is also divided into the cylinder zone and the base zone, each of which is independently controlled. Since there is no conduit pipe and the thermal radiation is shielded by the magnetic shields, the residual heat-flow paths are the cables and the standoffs which support the cavity, C-field coil, magnetic shields and the ovens. The standoffs are made of polyimide (VESPEL) with a low thermal conductivity of 0.28 kcal/m.hr.K. The cables are thermally connected to the base of the outer oven to prevent the heat from flowing directly into the cavity. Thus the cavity temperature stability of 1 mK is achieved without any other thermal insulators.

2.2 Electronics package

The electronics package consists of a phase-lock receiver, a cavity auto-tuner, oven and ion pump controllers, and monitor circuits. It is mounted in a rack which is 175 cm high and 57 cm wide.

2.2.1 Phase-lock receiver

Fig. 5 shows the block diagram of the phase-lock receiver. The output signal of the maser is amplified by the low noise amplifier, which is preceded by the varactor diode for the cavity auto-tuning and the 60 dB isolator. The noise figure of the low noise amplifier is 2.2 dB and the overall noise figure of the receiver is 4.5 dB. The signal is then mixed with the 1.40 GHz local signal from the phase-locked multiplier in the image rejection mixer. The resultant 1st IF signal (20.405 MHz) is again down-converted to 405 kHz. The 2nd IF signal is phase-compared with the reference signal from the synthesizer (hp3336A). The resultant error signal is filtered by the low-pass amplifier and used to tune electronically the 10 MHz voltage-controlled crystal oscillator (VCXO) to the maser frequency. The 10 MHz output signal of the VCXO is distributed to the multipliers, the synthesizer, the second pulse generator, the cavity auto-tuner and the VLBI system, via the distribution amplifiers with an isolation of 120 dB.

The front end, which is enclosed by the broken line in Fig. 5, is thermally controlled by the peltier module in order to improve the phase stability. The stability of the temperature is 5 mK. The front end is mounted in the physics package.

In the VLBI experiment the frequency difference between the local oscillators of the VLBI stations should be less than 1×10^{-12} in order to suppress the phase rotation of the corss-correlation spectrum. Therefore the frequency of a 10 MHz output signal is required to be finely adjusted. This can be carried out by the synthesizer whose setting resolution is 7×10^{-13}.

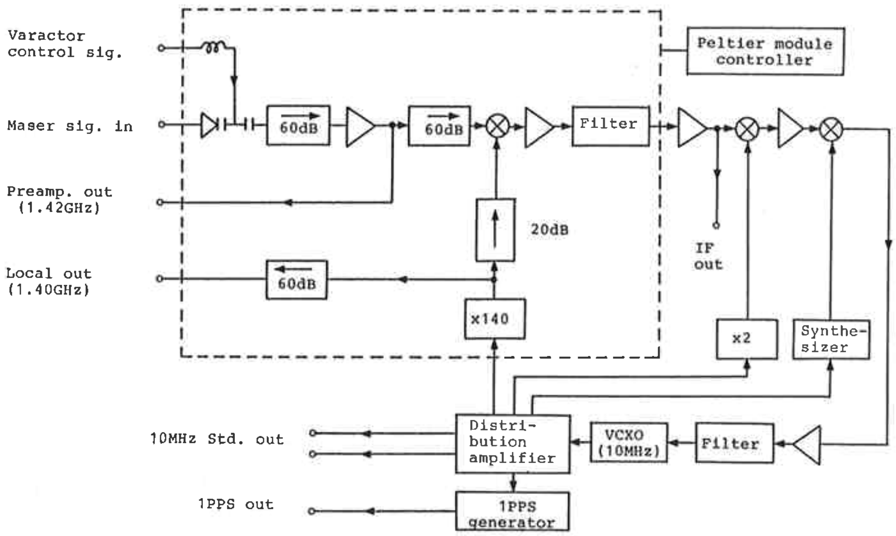

Fig. 5 The block diagram of the phase-lock receiver

2.2.2 Cavity auto-tuner

Due to the pulling effect, the maser oscillation frequency f_m shifts from the transition frequency of the hydrogen atom (f_0) if the cavity frequency f_c differs from f_0. Therefore the maser is equipped with the cavity auto-tuner(10) to tune f_c to f_0, whose block diagram is shown in Fig. 6. The output signal of the low noise amplifier of #1 maser (1.42 GHz) and the output signal of the phase-locked multiplier of #2 maser (1.40 GHz) are mixed in the image rejection mixer. The resultant IF signal (20.405 MHz) is mixed with the IF signal of #2 maser to obtain the beat signal between the masers, whose period is measured by the counter. The hydrogen beam is modulated by the mechanical shutter, which is driven by the pulse motor. The CPU (Z80) calculates the difference between the beat periods at Hi beam and Lo beam, and generates the varactor control signals and the shutter control signals. The CPU also controls the loop gain, the measurement mode and the other measuring parameters of the cavity auto-tuning.

A miscount of the beat period may cause a great change in the varactor control voltage, which will result in a great change in the cavity frequency. To avoid this miscount the CPU monitors the difference between the new and the old values of the varactor control voltages. If the difference exceeds the preset limit, the CPU rejects the new value as abnormal and holds the varactor control voltage at the old value. Then the measurement is repeated.

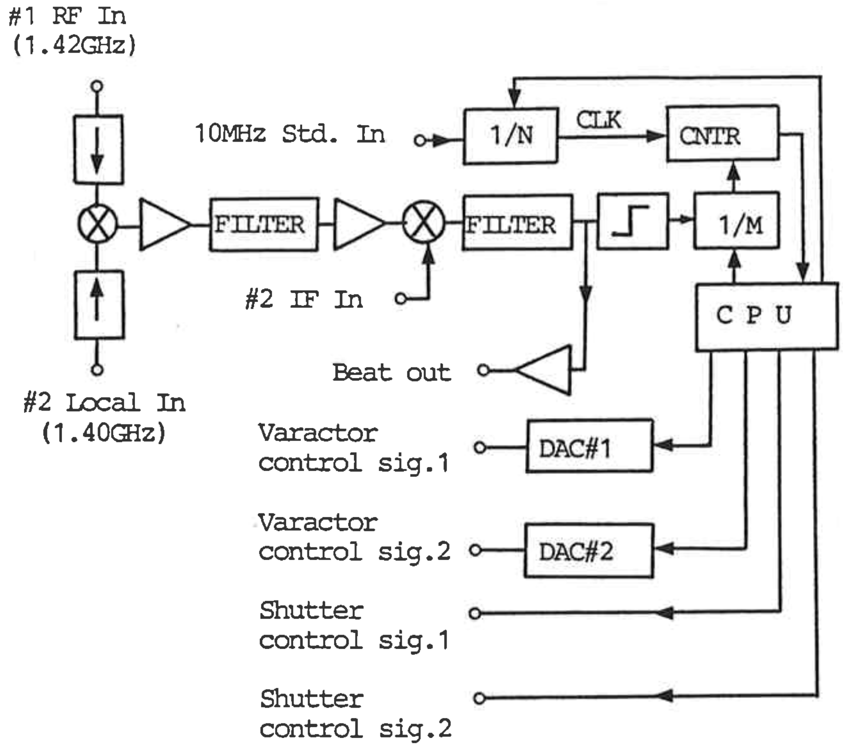

Fig. 6 The block diagram of the cavity auto-tuner

2.3 Frequency stability of the masers

The frequency stability of the free running masers was measured. The bandwidth of the measuring system was 2 Hz. A C-field of 2μT was added to one of the masers to offset the maser frequency by 1.2 Hz. During the frequency stability measurement both masers were placed in the same thermal and magnetic environment. The room temperature was controlled within ±1 K and the control cycle was about 1000 to 2000s.

Fig. 7 shows the frequency stability obtained. It shows the τ^{-1} characteristic between the averaging time of 1 and 20s and $\tau^{-1/2}$ characteristic between 20 and 1000s. In a VLBI experiment the observation period of a radio star is between about 10 and 20 min. and the frequency stability in this region is the most important. The frequency stability obtained is higher than 3×10^{-15} for the averaging period between 500 and 5000s and is 2.4×10^{-15} for 830s, which is enough for a VLBI experiment.

The long term frequency stability gradually deteriorates for the averaging period of more than 3000s, and is 1.4×10^{-14} for 10^5s. The main reason for the deterioration may be the relatively high C-field of 2μT, which is added to one of the masers, and the inadequate stability of the C-field current source. The specification of stability of the current source is 5×10^{-5}/day. This corresponds to the maser frequency stability of 7.8×10^{-14}/day for the C-field of 2μT, though the measured stability is 1.0×10^{-14} for one day. The real performance of the current source may be better than the specification, which explains the discrepancy between the values. However, it is very probable that the long term frequency stability is limited by the stability of the current source. In VLBI experiments the maser which distributes the standard frequency and time signal to the K-3 system is operated under the C-field of 20nT and the fluctuation of the current source can be neglected. Fig. 8 shows the monitor record of the beat period between the two masers and the 10 MHz phase comparison between any two of the masers and a commercial Cs clock.

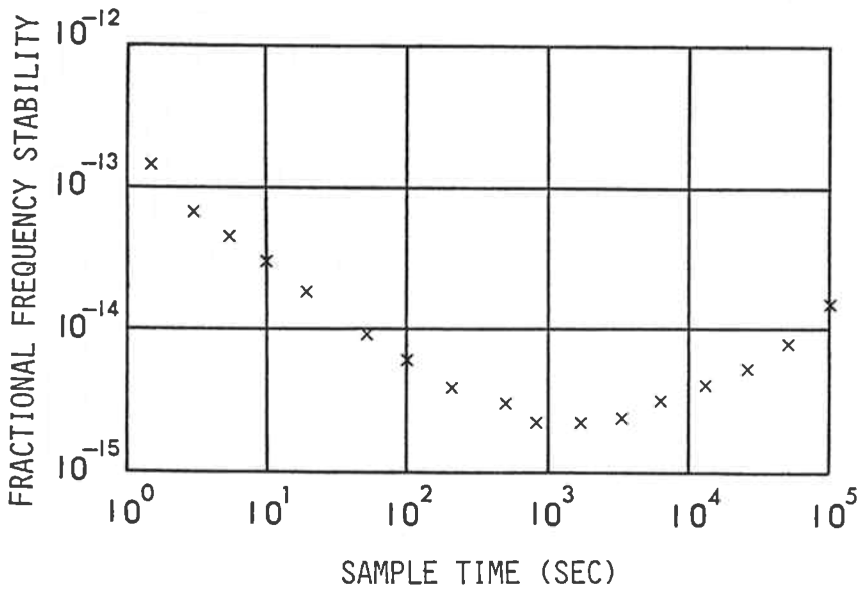

Fig. 7 Frequency stability of the free running masers

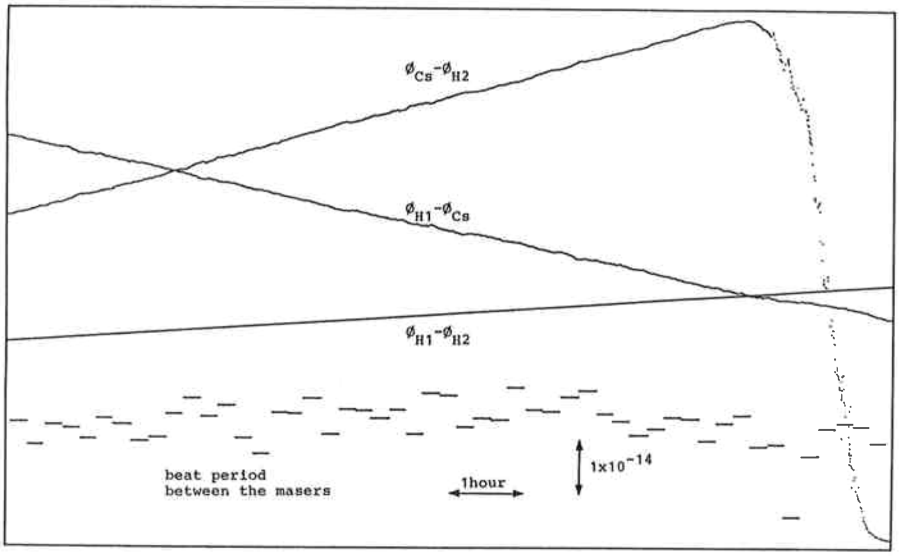

Fig. 8 The beat period and 10 MHz phase comparison between the masers and a commercial Cs clock

2.4 Sensitivity to the environment

The frequency of a maser is disturbed by several environmental factors. They are the room temperature, the external magnetic field, the barometric pressure and the mechanical vibration. The influence of the last two factors could not be evaluated because the measurement facilities were not available.

As stated above, the temperature of the room where the masers are placed is controlled within ±1 K and the control cycle is about 1000 to 2000s. The maser frequency is not significantly disturbed by this temperature control, but is disturbed by a slower temperature change. In order to evaluate this influence the room temperature was changed by 6.5 K and the change of the beat frequency was monitored. The time constant of the temperature change was 3.9 hours. During the measurement the auto-tuned laboratory type maser which was placed in another room and independent of the temperature change was used as the reference maser. The change in the beat period was measured 24 hours after the temperature had been changed. It was 1.5×10^{-13}, and the temperature sensitivity of the maser is 2.3×10^{-14}/K.

In order to evaluate the influence of the external magnetic field, a Helmholtz coil was wound on the vacuum bell jar and a vertical magnetic field of 0.1mT was added. The maser was operated under the 100nT C-field during the measurement. The measured magnetic sensitivity is 2.5×10^{-9}/T, and the magnetic shielding factor is 15000.

The above measurement was carried out at the RRL HQ, where the masers had been developed, and the measured value was considered to be good enough for the VLBI experiment under the usual geomagnetic circumstances. However, after the masers had been transported to Kashima station, where the VLBI station of RRL is located, frequency fluctuation of $4{\sim}5 \times 10^{-14}$ was observed during the VLBI experiments. During the VLBI

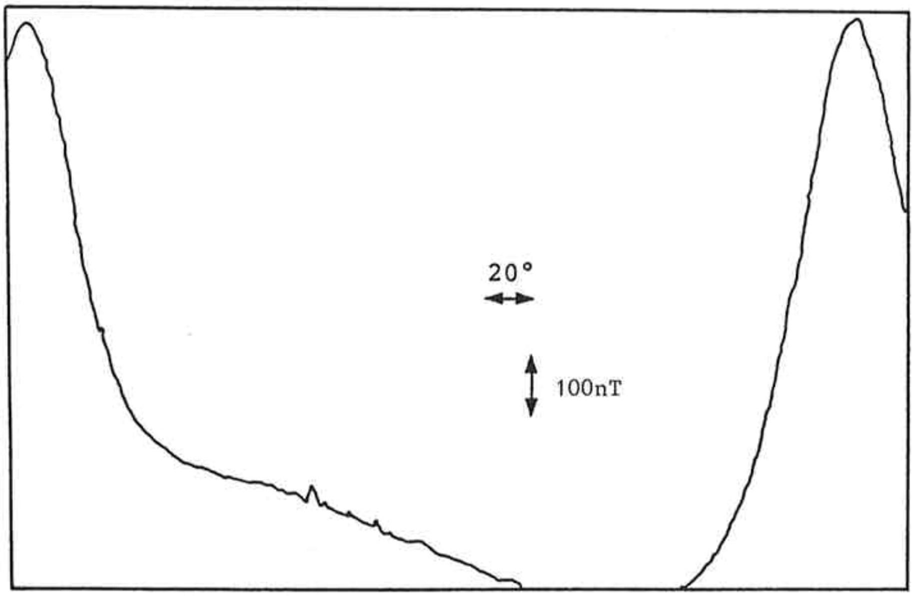

Fig. 9 Change of the external magnetic field when the azimuth of the antenna is swept

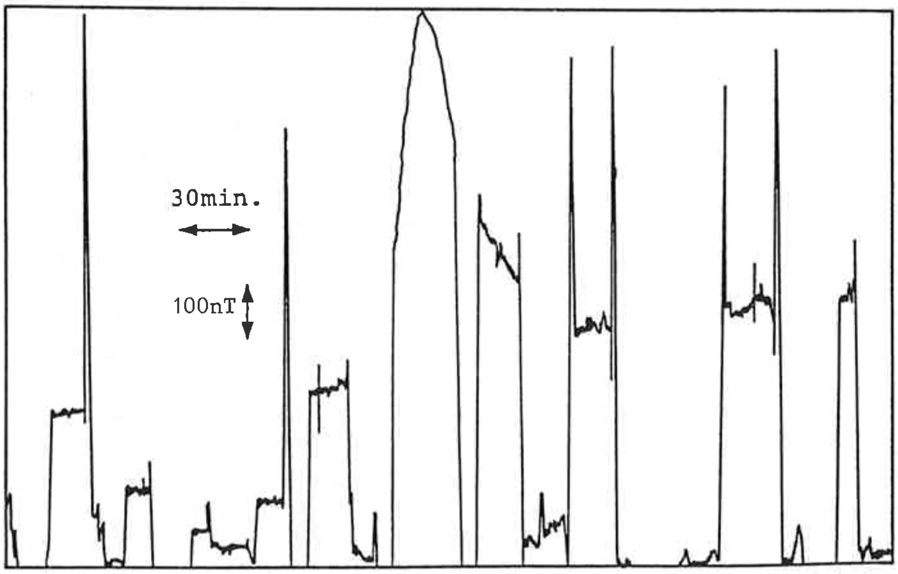

Fig. 10 Change of the external magnetic field during the VLBI experiment

experiments a large parabolic antenna, 26 m in diameter and 160 t in weight, was swung to track the radio stars. This movement of the antenna disturbed the environmental magnetic field. The fluctuation of the magnetic field in the maser room, which is located about 20 m distant from the basement of the antenna, has been measured by using a magnetic flux gate meter. The results are shown in Fig. 9 and Fig. 10. Fig. 9 shows the variation of the magnetic field in the maser room when the azimuth of the antenna is swept. Fig. 10 shows the fluctuation of the magnetic field in the maser room during the VLBI experiment which was carried out at the end of August 1984. The external magnetic disturbance amounts to more than 1μT. During the VLBI experiment one maser was operated under the 20nT C-field and used as the time and frequency standard of the K-3 system, while the other maser was operated under the 2μT C-field and used as the reference maser. The magnetic variation disturbed the reference maser. Later the C-field of the reference maser was set to 600nT and the fluctuation of the maser frequency reduced to 1×10^{-14}.

Therefore it should be recommended to check the external magnetic field variation and to operate the maser under low C-field at VLBI stations. Especially at mobile VLBI stations the magnetic disturbance of the antenna can be larger because the maser may be placed very close to the antenna.

3. Time transfer links

As stated in the Introduction, the clock of each VLBI station which is worldwide located should be synchronized with UTC within 1μs. The time transfer links for this purpose can be divided into the international and the domestic links. The former synchronizes UTCs which are maintained at the major time keeping institutes such as RRL and USNO, while the latter synchronizes the clock of a VLBI station with a UTC maintained at a time keeping institute.

3.1 International link

For a long time the Loran-C chains have played an important role for the international time comparison, especially among the USA and European countries with a precision of about 100ns(11). However, the Loran-C chain of the northwest Pacific region, whose signal RRL receives, is linked indirectly to that of the north Atlantic region. Because of this situation, the area in which the time comparison is feasible is limited and the regular calibrations by portable clocks are required. The time comparison by portable clocks in the northwest Pacific region are carried out by USNO once or twice a year, and the precision of the calibration is 100~200ns. Table 1 shows the results of the time comparisons by the portable clocks. The accuracy of the time comparison by the Loran-C at RRL is 100~200ns just after the calibration by the portable clock, but deteriorates to a few μs after one year. Therefore

Table 1 The time comparison by the portable clocks

	UTC(RRL) - UTC(USNO)
21 Aug 1981	5.0 ± 0.1 μs
18 Oct 1982	6.5 ± 0.2 μs
20 Nov 1983	5.80 ± 0.04 μs

this traditional link system is insufficient for the VLBI experiments.

However, the recent progress in the space technology has made it possible to make the time comparison with a high precision by using the satellites such as GPS(12). RRL has also developed two GPS receivers, one for the RRL HQ and the other for Kashima station, and has been making the routine calculations of UTC(RRL)-UTC(USNO) via GPS under the common view schedule to send them to Bureau International de l'Heure (BIH) since August 1984(13). The GPS has enabled the atomic clocks of RRL to contribute to the TAI and UTC for the first time. The achieved precision of the GPS time comparison at RRL is 10ns or better and the accuracy seems to be about 100ns.

The VLBI itself gives a precise and accurate time and frequency transfer method. RRL and USNO have conducted the international time transfer experiment since October 1984, which will be carried out regularly once a month. The expected accuracy is better than 10ns. The VLBI time transfer will calibrate the GPS link. Thus the combination of VLBI and GPS will play a very important role in the modern time comparison system.

3.2 Domestic link

The current synchronization technology offers several possibilities for the synchronization of the clock of Kashima station and UTC(RRL) with an accuracy of 100ns. They are Loran-C, TV link, satellite link, portable clock and wideband microwave link.

Among these methods the 7 GHz microwave link between the RRL HQ and Kashima station is used for the synchronization on a routine basis, as well as the irregular calibration by portable clock. Fig. 11 shows the block diagram of the synchronization system of RRL. The measurement system at the RRL HQ controls the channel switching and the measurement every 4 hours. The microwave link has one high speed data channel whose bandwidth is 5 MHz and 24 low speed data channels. The high speed channel is used for the synchronization.

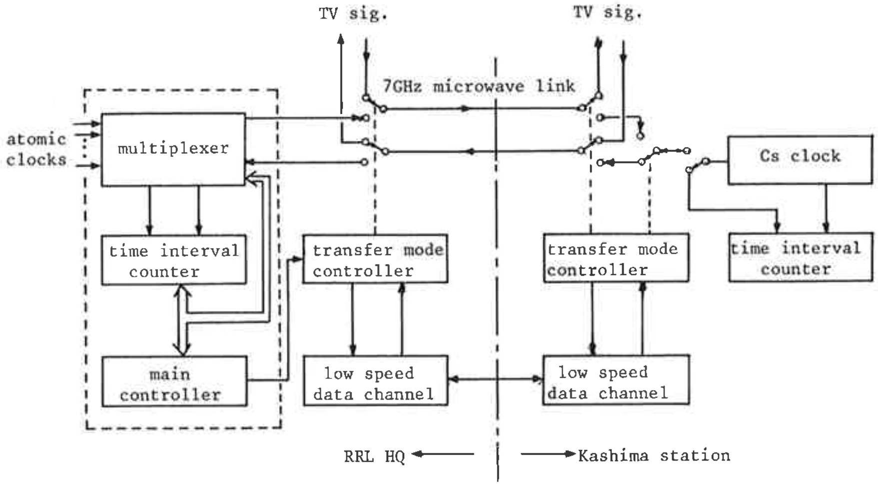

Fig. 11 The block diagram of the clock synchronization system of RRL

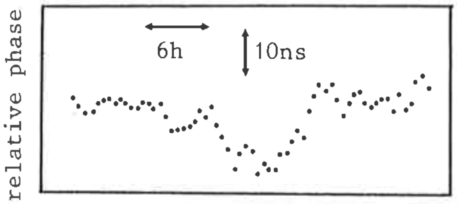

Fig. 12 Fluctuation of the delay time of the link between RRL HQ and the Kashima station

In order to measure the stability of the delay time of the microwave link, a signal of 5 MHz was sent through the link from the RRL HQ to Kashima station and then returned. The phases before and after the round trip between the RRL HQ and Kashima station were compared for 3 days. As shown in Fig. 12 the fluctuation of the delay time of the link is below 30ns.

The absolute value of the delay time of the microwave link was measured several times by the portable clocks and also by sending the clock signals to each other between the RRL HQ and Kashima station. The results obtained in both cases agree within 20ns. The accuracy of 20ns is sufficient for the VLBI experiments for geodetic survey. However, as well known, the VLBI can be used also for the international time comparison. RRL and USNO has conducted the time comparison experiment by the VLBI since October 1984, of which the accuracy is expected to be higher than 10ns. For this purpose the accuracy of the domestic link is insufficient. For a higher accuracy the calibration by the domestic Communication Satellite (CS) using spread spectrum technique(14) is planned between the RRL HQ and Kashima station. The accuracy of the calibration is expected to be higher than 1ns.

4. Conclusion

Two field operable hydrogen masers have been developed as the time and frequency standard of the K-3 system. The measured performance fully satisfies the requirements of the K-3 system, and they are now playing an important role as the time and frequency standard of the K-3 system at Kashima station.

The magnetic disturbance by the VLBI antenna tracking, which has been observed at Kashima station, suggests that it is necessary to check the magnetic environment in the maser room and to operate the maser under low C-field for VLBI experiments.

For the VLBI experiments the Cs clock at Kashima station is linked to UTC(RRL) via the microwave link whose accuracy is 20ns. While UTC(RRL) is linked to the major time keeping institutes by both the GPS receivers developed by RRL and regular portable clocks. The accuracy of the GPS link seems to be 100ns.

Acknowledgements

The authors wish to thank Mr. Saburi, the former Associate Director General of RRL, and Dr. Yoshimura, Section Chief of Standard Frequency and Time Research Section of RRL, for valuable suggestions and support in the development of the masers. They are also very grateful to the staff of VLBI project of the RRL HQ and Kashima station.

References

(1) Kawaguchi, N., Sugimoto, Y., Kuroiwa, H., Kondo, T., Hama, S., Amagai, J., Morikawa, T., and Imae, M.; "The K-3 Hardware System Being Developed in Japan and its Capability", NOAA Technical Report NOS 95 NGS 24 Proceedings of Symposium No. 5: Geodetic Applications of Radio Interferometry, pp. 163–176, May 1982.

(2) Takahashi, F., Yoshino, T., Murakami, H., Koike, K., Kunimori, H., and Kondo, T.; "K-3 VLBI Software Development for International Experiments", NOAA Technical Report NOS 95 NGS 24 Proceedings of Symposium No. 5: Geodetic Applications of Radio Interferometry, pp. 177–183, May 1982.

(3) VLBI Research Development Group, RRL; "The First US-JAPAN VLBI Test Observation by Use of K-3 System of the Radio Research Laboratories", J. Radio Res. Labs. **31**, 132, pp. 31–37, March 1984.

(4) Morikawa, T., Ohta, Y. and Kiuchi, H.; "Development of Hydrogen Masers for K-3 VLBI System", Proceedings of the 16th Precise Time and Time Interval Meeting, Nov. 1984.

(5) Kleppner, D., Goldenberg, H.M. and Ramsey, N.F.; "Theory of the Hydrogen Maser", Phys. Rev. 126, 2, pp. 603–615, Apr. 1962.

(6) Sabisky, E.S. and Weaklin, H.A.; "An Operating Development Model Spacecraft Hydrogen Maser", Proceedings of the 32nd Annual Symposium on Frequency Control, pp. 499–505, 1978.

(7) Timoshenco, S.; "Strength of Materials Part II: Advanced Theory and Problems", Third Edition 1956 D. Van Nostrand Company Inc., New York.

(8) Levine, M.W., Vessot, R.F., Nystrom, G., Hoffman, T. and Blomberg, E.; "A New Generation of SAO Hydrogen Masers", Proceedings of the 31st Annual Symposium on Frequency Control, pp. 525–534, 1977.

(9) Levine, M.W., Vessot, R.F., and Mattison, E.F.; "Performance Evaluation of the SAO VLG-11 Atomic Hydrogen Maser", Proceedings of the 32nd Annual Symposium on Frequency Control, pp. 477–485, 1978.

(10) Brousseau, R. and Vanier, J.; "An Electronic System for the Tuning of Masers", IEEE Trans. IM-22, 4, pp. 367–375, Dec. 1973.

(11) Potts, C.E. and Wierder, B.; "Precise Time and Frequeny Dissemination via the Loran-C System", Proc. IEEE vol. 60 No. 5 pp. 530–539, May 1972.

(12) Spilker, J.J. Jr.; "GPS Signal Structure and Performance Characteristics", J. Navigation, 25, pp. 121–146, 1978.

(13) Yoshimura, K., Imae, M., Urazuka, M., Morikawa, T., Yoshino, T., Kobayashi, S., and Igarashi, T.; "Research Activities on Time and Frequency Transfers Using Space Links", Special Issue for Proc. IEEE "Radio Measurement Methods and Standards" Nov. 1985 (to be published).

(14) Imae, M., Okazawa, H., Sato, T., Urazuka, M., Yoshimura, K. and Yasuda, Y.; "Time Comparison Experiments with Small K-Band Antennas and SSRA Equipments via a Domestic Geostationary Satellite", IEEE Trans. Instrum. Meas., IM-32, 1, pp. 199–203, March 1983.