THE FREQUENCY AND TIME STANDARD AND ACTIVITIES AT THE BEIJING INSTITUTE OF RADIO METROLOGY AND MEASUREMENTS

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Abstract

The Beijing Institute of Radio Metrology and Measurements (BIRMM), as a calibration center and a research division of radio metrology and measurements and frequency control devices for the system of space technology in China, has made some progress in PTTI research work in recent years. This paper will review some of PTTI activities briefly.

Frequency measurement is one of the routine jobs of BIRMM. Now there have been three kinds of frequency measuring systems: a system of frequency comparison, a system of phase comparison and a system of time comparison.

In cooperation with other organizations from 1978 to the second quarter of 1979, two experiments on time synchronization were carried out. With the help of the portable cesium clock in determining the time delay between two stations, one experiment of time synchronization, chiefly sponsored by the Central Bureau of Metrology, of China, between Nanjing (China) and Raisting (West Germany) by using the "Symphony" satellite, has achieved a result with an accuracy of 30 ns and an uncertainty of about 10 ns. The other experiment, applying the television pulse technique for time synchronization, has yielded a result with an error of about 0.5 μs in 24 hours.

In order to measure the short-term frequency stability of crystal oscillators or other frequency sources, BIRMM, in cooperation with the Wuhan Institute of Physics, developed a rubidium maser atomic frequency standard about two years ago. BIRMM has developed a short-term stability measuring system with a time-domain stability resolution $\sigma_y(2, \tau) < 1 \times 10^{-12}/\tau$ (sec) and a frequency-domain stability resolution $S_\phi(f) \approx 10^{-12}/f + 10^{-15}$.

Additional new PTTI items under consideration will be mentioned briefly, too.

I. Frequency measurement

BIRMM began its PTTI activities not long ago. The basic frequency standard founded in BIRMM is a commercial cesium beam atomic frequency standard (2 sets, type 3200, imported from Switzerland). Its frequency accuracy has been checked with the Loran-C receiver and has proved to be 1×10^{-11}. A crystal oscillator of type XSD with a time aging rate less than 1×10^{-10}/day is used as a working standard for frequency calibration. There have been set up the systems of frequency comparison, phase comparison and time comparison. The operation of these systems will be described below.

A. System of frequency comparison

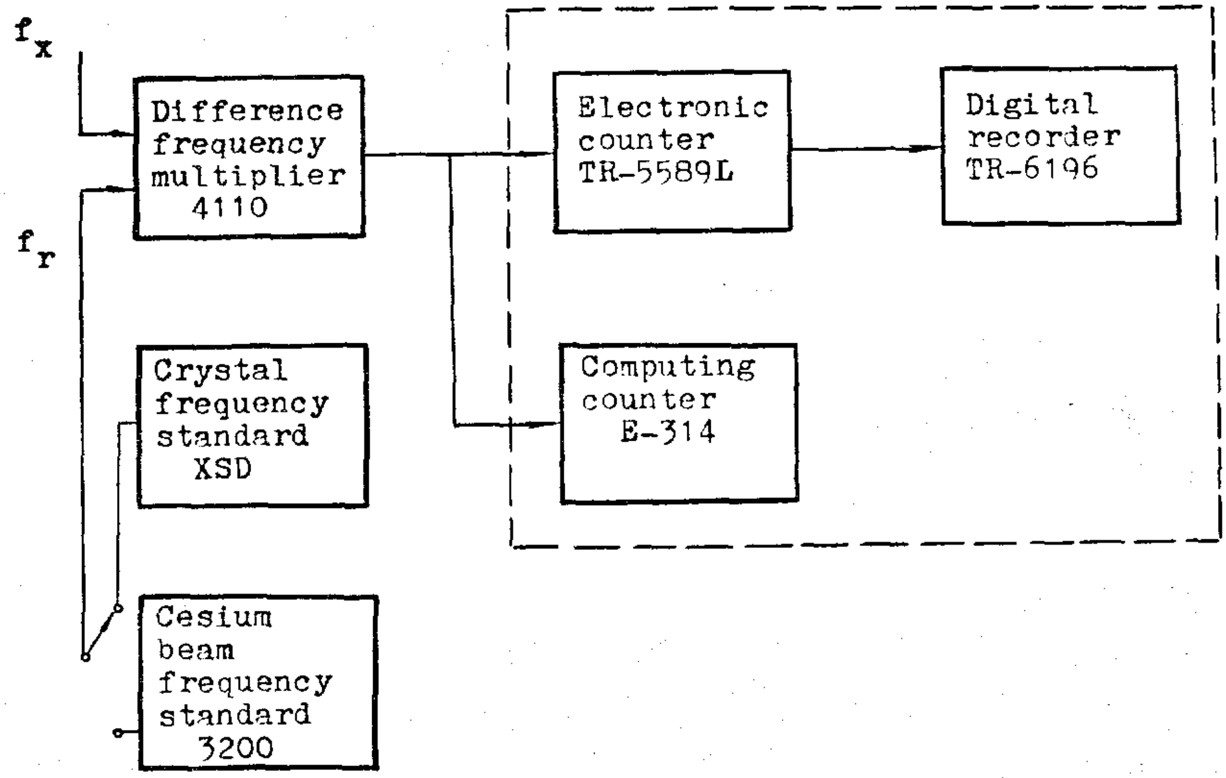

Figure 1. Functional block diagram of the system of frequency comparison

The limit sensitivity of the system is not only dependent on the uncertainty caused by the noise of the difference frequency multiplier 4110 itself, but on the resolution of the system. There exist experimental data for the former. The latter may be calculated as follows:

Frequency resolution $R_f = 1/Mf_o\tau$ where M is an effective multiplying factor, f_o is the nominal value of the frequency measured and τ is the sample time.

Sample time	Uncertainty caused by 4110 itself	resolution of the system	The limit sensitivity of the system
1 sec	$<4 \times 10^{-12}$	1×10^{-11}	$\approx 1 \times 10^{-11}$
10 sec	$<3 \times 10^{-12}$	1×10^{-12}	$\approx 3 \times 10^{-12}$
100 sec	$<5 \times 10^{-13}$	1×10^{-13}	$\approx 5 \times 10^{-13}$

Uncertainties caused by reference sources are given below.

Type of reference source	Drift-rate/day of the reference source	Error introduced by short-term stability of the reference source		
		1 sec	10 sec	100 sec
Crystal oscillator XSD	5×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}
Cesium frequency standard 3200	$10^{-14} \sim 10^{-15}$	3×10^{-11}	1×10^{-11}	3×10^{-12}

It can be seen from the above table that when XSD is used as a reference source in measuring long-term stability or aging rate/day, a 10 sec sample time can be applied to calibrate the frequency standard below 5×10^{-10}/day. But when 3200 is used as a reference source in measuring long-term stability or aging rate/day, in order to calibrate the frequency sources below 3×10^{-11}/day, 100 sec sample time must be applied due to the limit of the short-term stability of 3200 cesium frequency standard, so that the calibration error will be one order of magnitude lower than the error of the calibrated equipment.

B. System of phase comparison

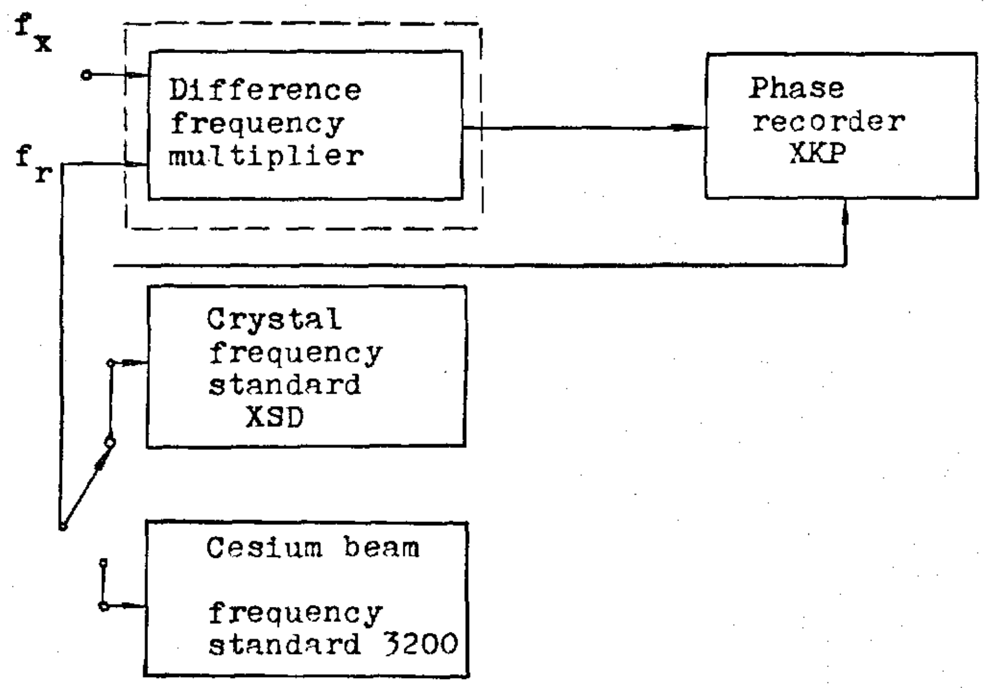

Figure 2. Functional block diagram of the system of phase comparison

The dashed line in the block diagram indicates that a measuring equipment can be added to increase the resolution of the system, if necessary.

The resolution of the system of phase comparison can be calculated by:

$$R\phi = \frac{1}{M\ f_o\ \tau N}$$

where M is the multiplying factor of the difference frequency multiplier, f_o is the nominal value of the frequency measured (in Hz), τ is the sample time (in sec) and N is the number of division in the width of the recording paper.

According to the above equation, the resolution of the system (when M = 1, i.e. without use of a difference frequency multiplier) is the function of the sample time and the input frequency as shown in the following table.

Sample time \ Resolution of the system \ Input frequency	100 KHz	1MHz	5MHz
10^3 sec	2×10^{-10}	2×10^{-11}	4×10^{-12}
10^4 sec	2×10^{-11}	2×10^{-12}	4×10^{-13}
10^5 sec	2×10^{-12}	2×10^{-13}	4×10^{-14}

Calibration error of the system of phase comparison: the calibration errors for various sample times are given below, assuming the input of the phase comparator to be 1 MHz.

Sample time τ	Resolution of XKP	Measurement error due to accumulated difference time of XKP	error Introduced by XKP in measuring sample time	error of XKP
10^3 sec	2×10^{-11}	5×10^{-11}	1×10^{-9}	1×10^{-9}
10^4 sec	2×10^{-12}	5×10^{-12}	1×10^{-10}	1×10^{-10}
10^5 sec	2×10^{-13}	5×10^{-13}	1×10^{-11}	1×10^{-11}

It can be seen from the above table that in order to reduce the error of the system an external standard clock should be used in measuring sample time.

3. System of time comparison

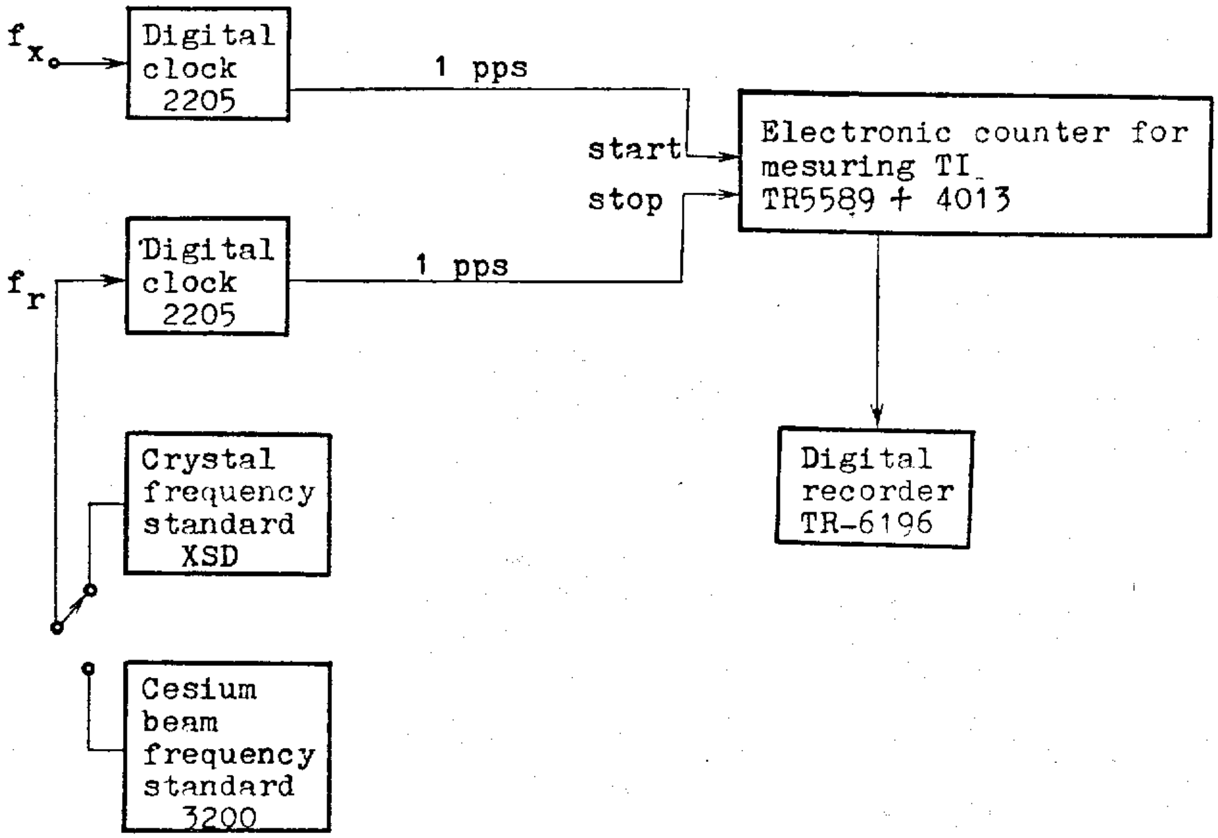

Figure 3. **Functional block diagram of the** system of time comparison

The resolution of the system of time comparison can be calculated by:

$$R_t = \frac{\tau_0}{\tau}$$

where τ_0 is the time base for time measurement and τ is the sample time. The resolution of the system is given below.

Time base / Sample time	1μ s (10^{-6} s)	0.1μ s (10^{-7}s)	10ns (10^{-8}s)
10^3 sec	1 10^{-9}	1 10^{-10}	1 10^{-11}
10^4 sec	1 10^{-10}	1 10^{-11}	1 10^{-12}
10^5 sec	1 10^{-11}	1 10^{-12}	1 10^{-13}

The calibration error of the system of time comparison depends on the phase jitter and phase jump caused by the frequency divider of digital clock 2205 and on the resolution of the system. Generally speaking, the phase jump of the phase divider is recognizable and the phase jitter is very small. Thus the calibration error of the system is chiefly dependent upon the resolution of the system.

The items for calibration and comparison BIRMM can deal with and the accuracy BIRMM can obtain are given in the following table.

Type of the frequency standard being calibrated or compared	Items for calibration and comparison and their accuracy				
	Stability (1 sec)	Stability (10 sec)	Stability (day)	Drift rate/day	Accuracy
Crystal frequency standard	2×10^{-12}	5×10^{-12}	$1\times10^{-9}\sim 3\times10^{-11}$	$1\times10^{-9}\sim 3\times10^{-11}$	1×10^{-10}
Rubidium gase cell frequency standard	2×10^{-12}	5×10^{-12}	3×10^{-13} (intercomparison)	1×10^{-12} (phase comparison method)	1×10^{-10}
Commercial cesium beam frequency standard	2×10^{-12}	5×10^{-12}	3×10^{-13} (intercomparison)		1×10^{-11} Receive Loran-C

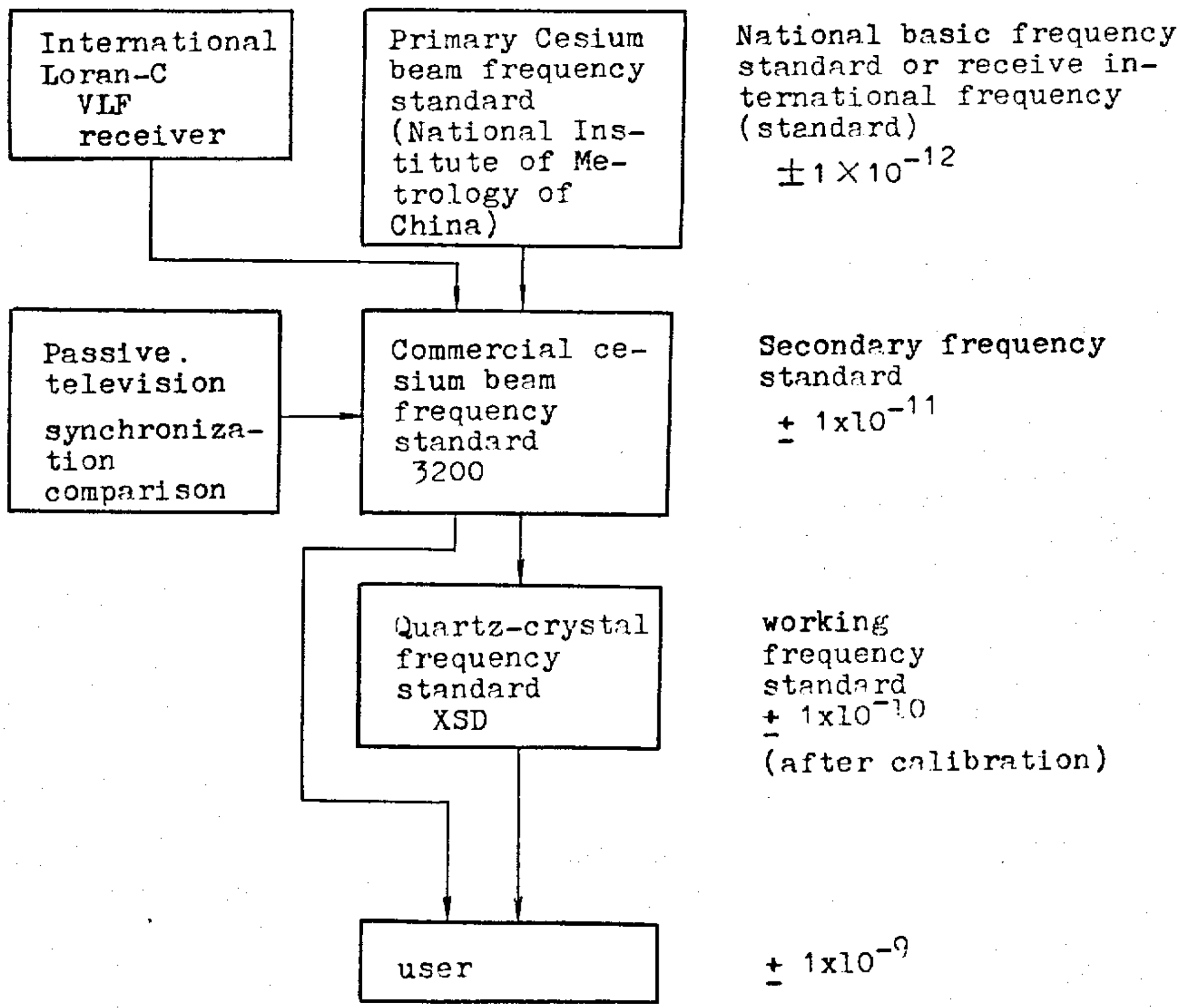

Figure 4. Schematic diagram of the hierarchy of frequency accuracy

II. Measurement of short-term frequency stability and a survey of the research work

Short-term frequency stability of precision frequency sources is a problem to solve urgently, which the system of space technology has been dealing with recently. BIRMM has undertaken some research work in this area with the following achievements:

A. Principal technical characteristics

(1) Frequency measurement range
1 MHz, 2.5 MHz, 5 MHz, 10MHz, 100 MHz,
M x 100MHz (M=45 to 70)

(2) Form of input signals
Continuous sinusoidal wave

(3) Resolution of the measuring system

a. Resolution of time-domain stability
Allan variance $\sigma_y \ (2, \tau) < 1\text{x}10^{-12}/\tau$
τ is in sec. f_h (bandwidth) is 10KHz

b. Resolution of frequency-domain stability
phase noise power spectral density
$S\phi(f) < 10^{-12}/f+10^{-15}$
f is Fourier frequency in Hz.

B. Standard reference sources

(1) Rubidium maser atomic frequency standard (active rubidium frequency standard)

To increase the measurement accuracy of short-term frequency stability, BIRMM in cooperation with the Wuhan Institute of Physics under the Academy of sciences of China has developed a rubidium maser atomic frequency standard as a reference source for the test of short-term frequency stability. The maser was developed by the Wuhan Institute of Physics, while the electronic circuits (including a phase-lock receiver, a 100MHz quartz-crystal oscillator and a 311KHz frequency synthesizer) were developed by BIRMM.

The schematic diagram of the maser, the functional block diagrams of the phase-lock receiver and 311KHz frequency synthesizer are given below.

Two models were successfully developed in 1977, with the maser having a copper cavity. The short-term frequency stability of these two models of the maser proved to be $5\text{x}10^{-13}/\tau$. (τ is in sec.)

For further improving the characteristics three new models have been developed recently. Some modification has been made in the maser and the electronic circuits.

The maser has a microcrystalline glass cavity instead of the copper cavity. The low-noise elements and components being used, the noise of the electronic circuits has been reduced and the operation reliability has increased.

The following technical characteristics are obtained after the preliminary test.

a. Output frequency stability of the maser is indicated in the following table and the curves.

b. Output power of the maser $(1.5\text{-}2) \times 10^{-10}$W)

(2) Besides the rubidium maser atomic frequency standard, 100MHz and 5MHz quartz-crystal oscillators have been developed as reference sources for the test of short-term frequency stability.

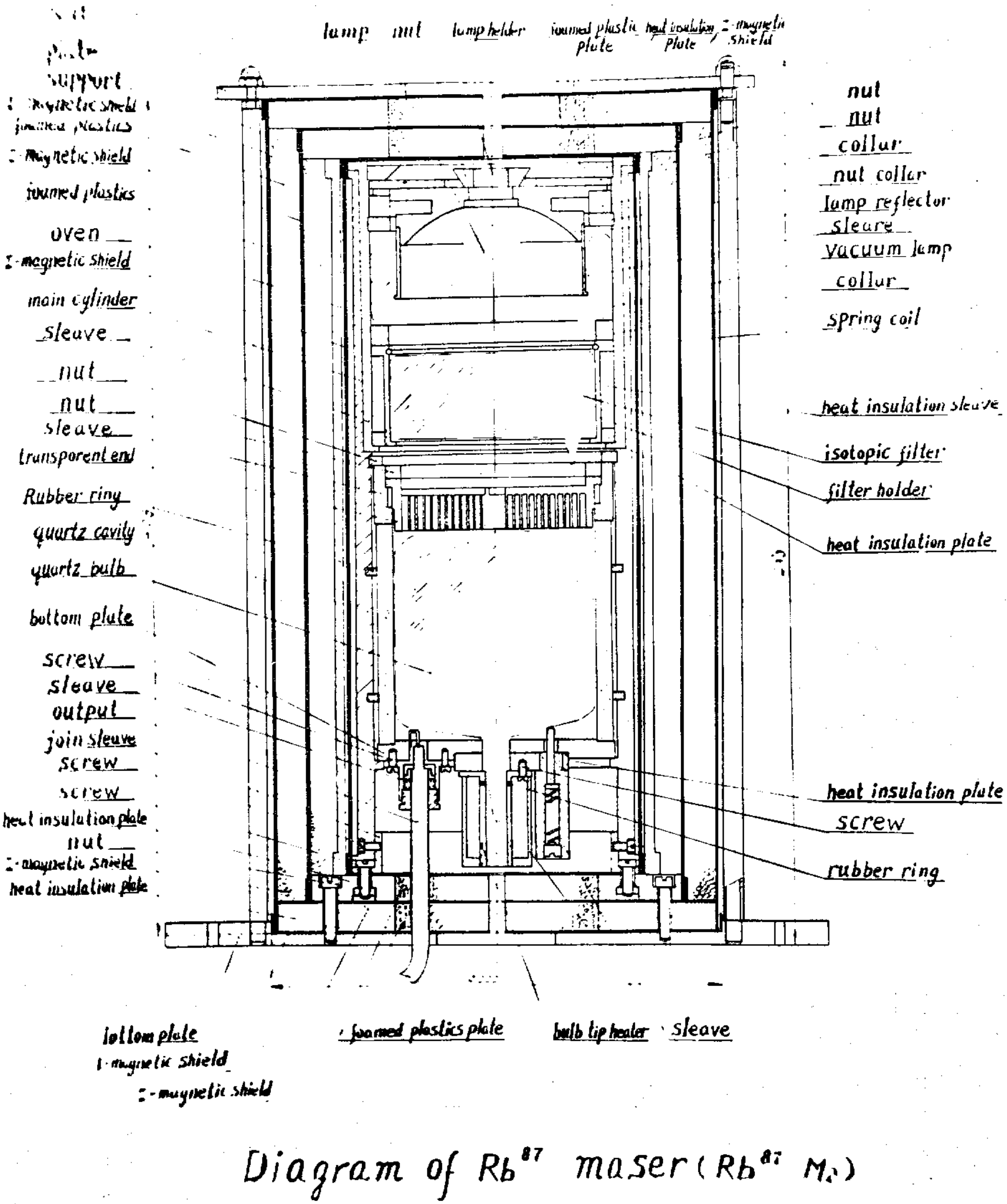

Figure 5. The structural scheme of the rubidium maser

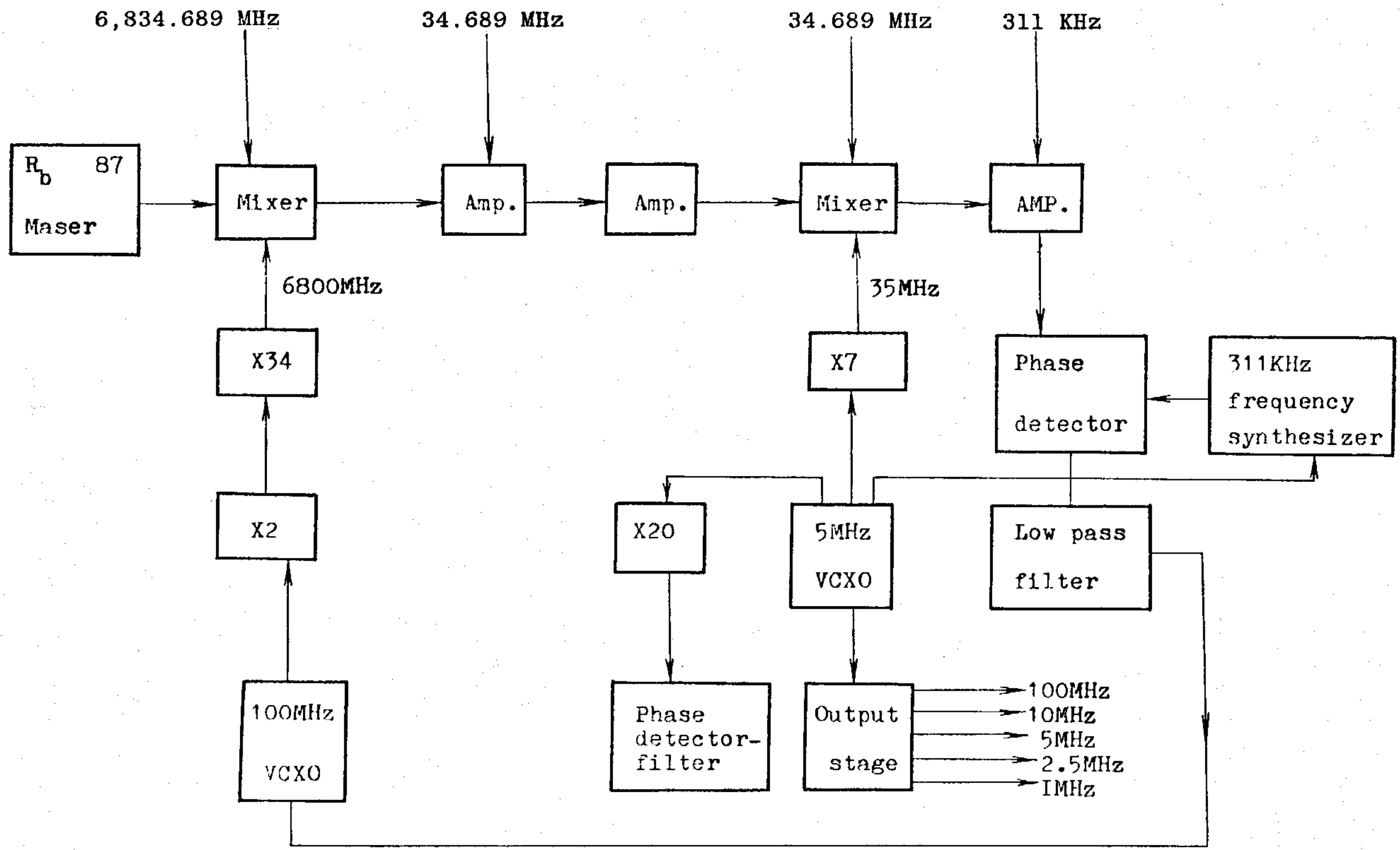

Figure 6. Functional block diagram

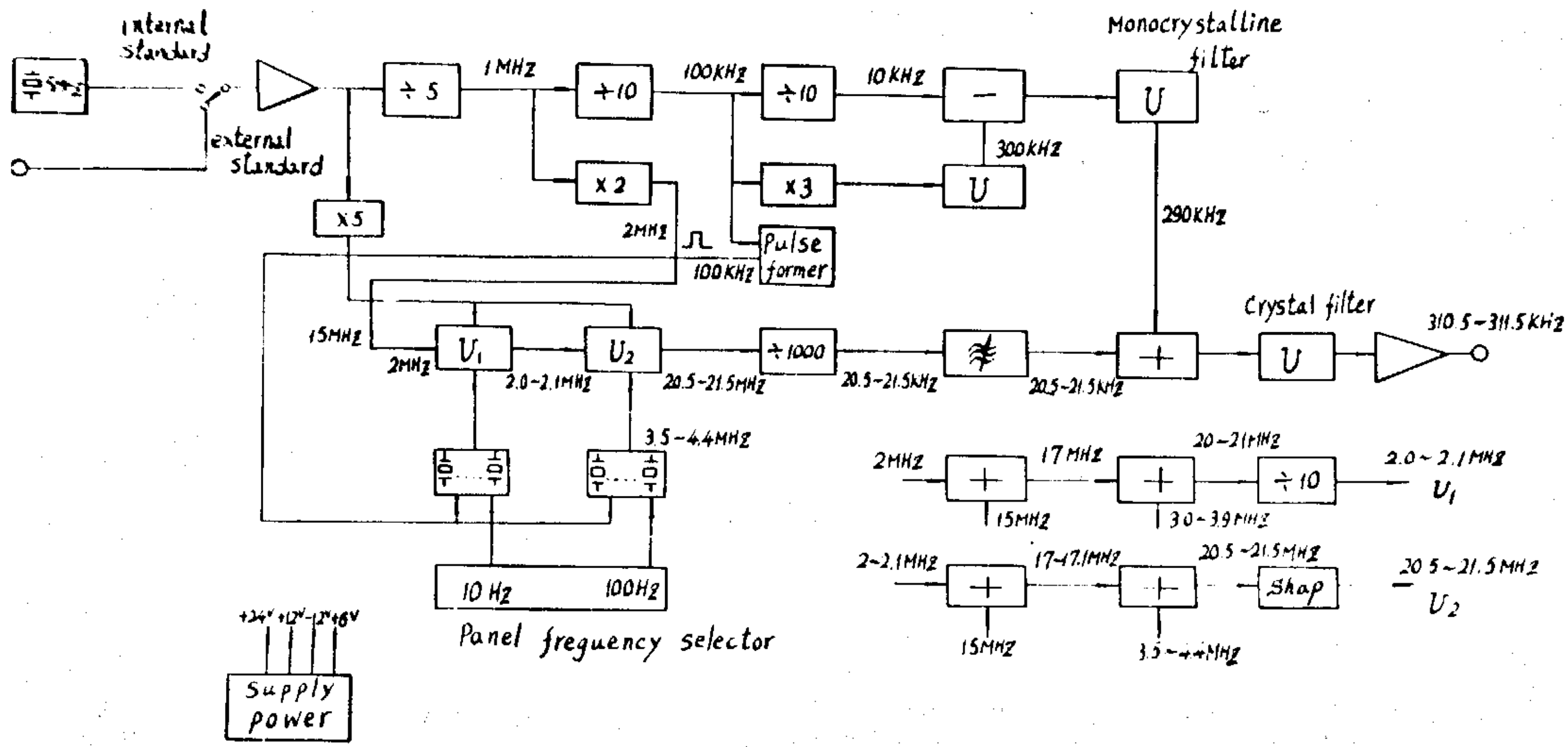

Figure 7. Functional block diagram of frequency synthesizer

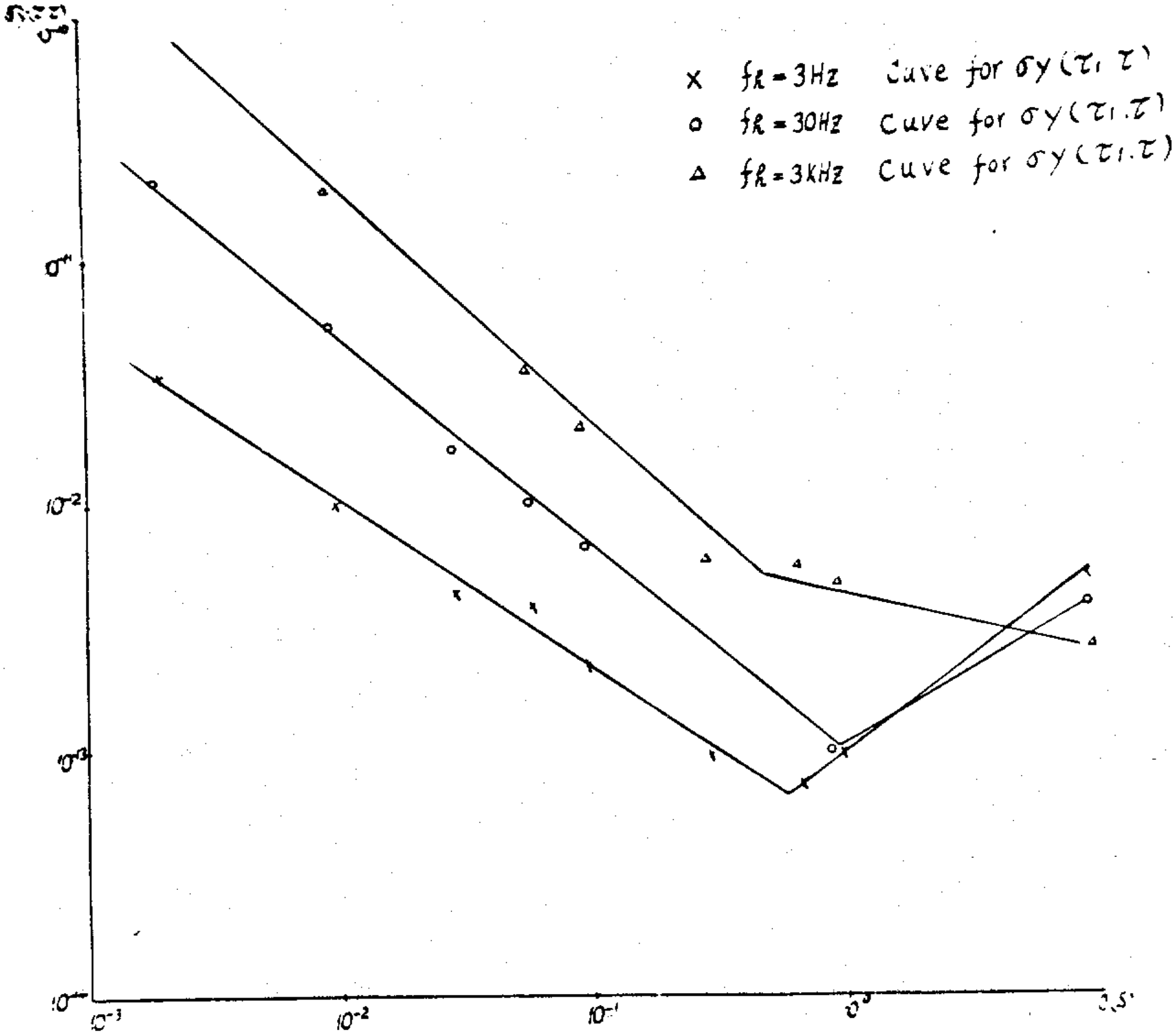

Figure 8. Characteristic curves obtained in test of the short-term frequency stability of PBR-MII maser

3. Comparators

A. Time-domain comparator

A multi-period measuring system was used to meet the requirements of measurement of short-term frequency stability with 1 ms—1 sec sample time.

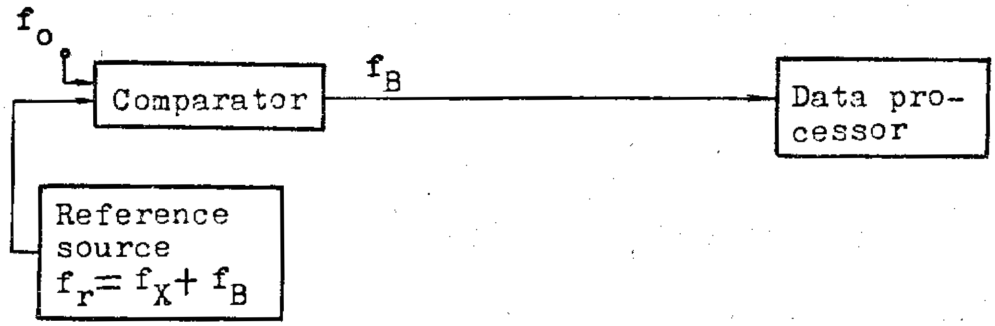

Figure 9. Functional block diagram of the multi-period measuring system

The limit sensitivity of the measuring system depends on the uncertainty caused by the noise in the comparator and on the resolution of the system. The former is determined by experiments. The latter is calculated by

$$R_T = \frac{f_B}{Mf_o} = \frac{\tau_o}{\tau}$$

where f_B is the beat frequency, τ_o is the time base of the counter, τ is the sample time, M is the error multiplying factor and f_o is the frequency measured.

(100MHz + 1KHz) crystal oscillator serves as the reference source of the comparator. With the help of a low noise frequency multiplier the frequencies of various sources being measured can be multiplied up to 100 MHz, then the beat frequency period (or multi-period) of mixed frequency can be measured and processed with the computing counter.

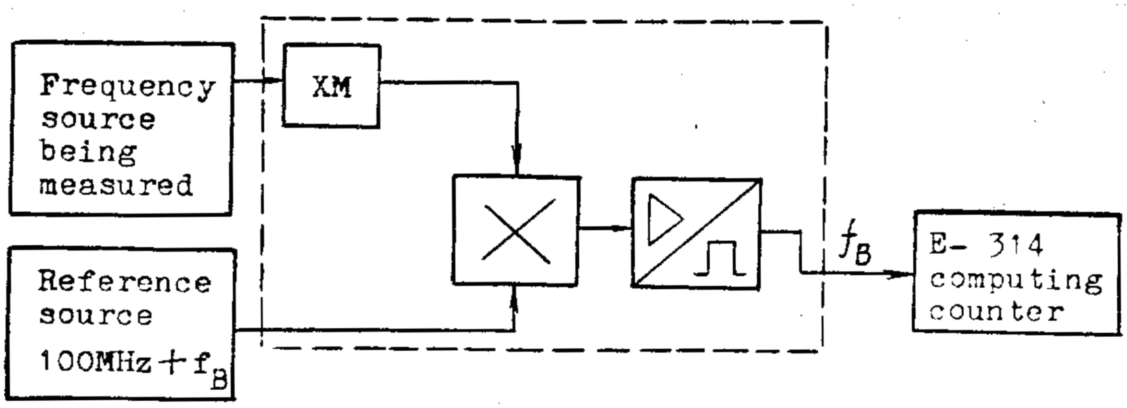

Figure 10. Functional block diagram of the time-domain stability comparator

The possible measuring accuracy for various frequency sources being measured is given in the following table.

Frequency being measured f_o	1 MHz	2.5 MHz	5 MHz	100MHz
Frequency multiplying factor M	5×20	2×20	20	1
Measuring Accuracy (τ in sec.)	$5\times 10^{-12}/\tau$	$1\times 10^{-12}/\tau$	$5\times 10^{-13}/\tau$	$5\times 10^{-13}/\tau$
Test band-width (f_b)	10KHz	10KHz	10KHz	10KHz

B. Frequency-domain comparator

The frequency-domain comparator developed by BIRMM uses a correlative zero beat method, in other words, two-channel zero beat method, based upon the single-channel beat zero method. With the help of two identical single-channels it measures the correlative components, thus improving its resolution and reducing residual noise of the phase-detecting amplifier. The block diagram is given below.

5MHz or 100MHz quarts crystal oscillator is used as reference source. The time constant of the phase lock loop is changeable. The phase noise levels of various Fourier frequencies are analyzed by the narrowband analog spectrum analyzer. The results are post-processed later on.

The narrowband analog spectrum analyzer has the following characteristics:

frequency range	from 5 Hz to 50 KHz
bandwidth	1 Hz, 3 Hz, 10 Hz, 30 Hz, 100 Hz, 300 Hz
sensitivity	30nv
dynamic range	80db

The residual phase noise $S_{\phi R}$ (f) of the measuring equipment is shown in the table.

Fourier frequency f (Hz)	10	100	1,000	10,000
Residual phase noise $S_{\phi R}$ (f) (db)	-135	-145	-155	-155

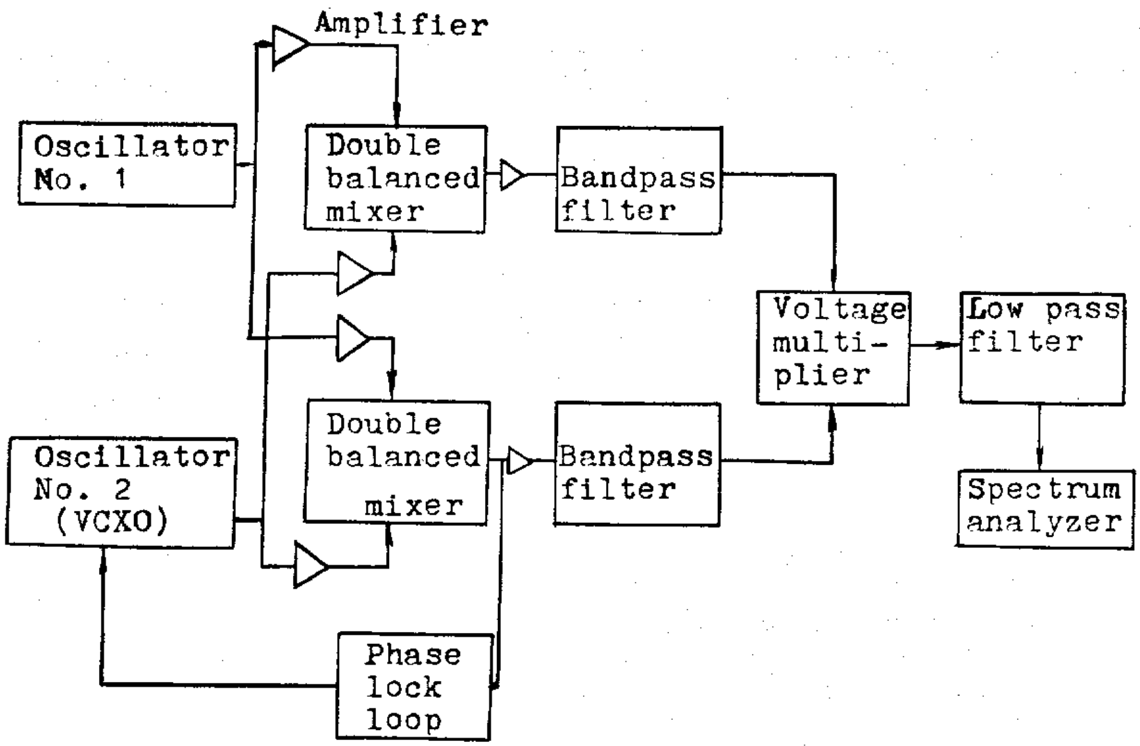

Figure 11. Functional block diagram of the frequency-domain comparator with a correlative zero beat method

The use of television signals for precision time and frequency comparisons

A. BIRMM has undertaken the work of **precision time and frequency comparisons** using the passive television method in order to compare its atomic frequency standard with atomic frequency standards of other institutes of our country at a remote distance.

B. The principle of operation and the functional block diagram of the TV line-6 synchronizing system:

The television system of our country is a system with 25 frames per second and 625 lines per frame and with interlaced scanning. Its vertical scanning frequency is 50 Hz, where as the horizontal scanning frequency is 15625 Hz. Passive television synchronization is based on the measurement of the time difference between the arrival of a certain television synchronizing reference pulse and a local clock second pulse. The clock difference between two locations and the frequency accuracy are determined by means of the post-exchange of the data. The first horizontal synchronizing pulse after the vertical and equalizing pulses of the odd field (the first field) is chosen as a reference pulse, i.e. line-6 of the odd field. Since the television frame frequency is 25 Hz, the clocks at two locations must be synchronized so that there would be no multivalence. This can be easily done by comparison with the BPV time signals (short-wave time signals transmitted by the Shanghai Observatory of China). The functional block diagram of the measuring system is shown below.

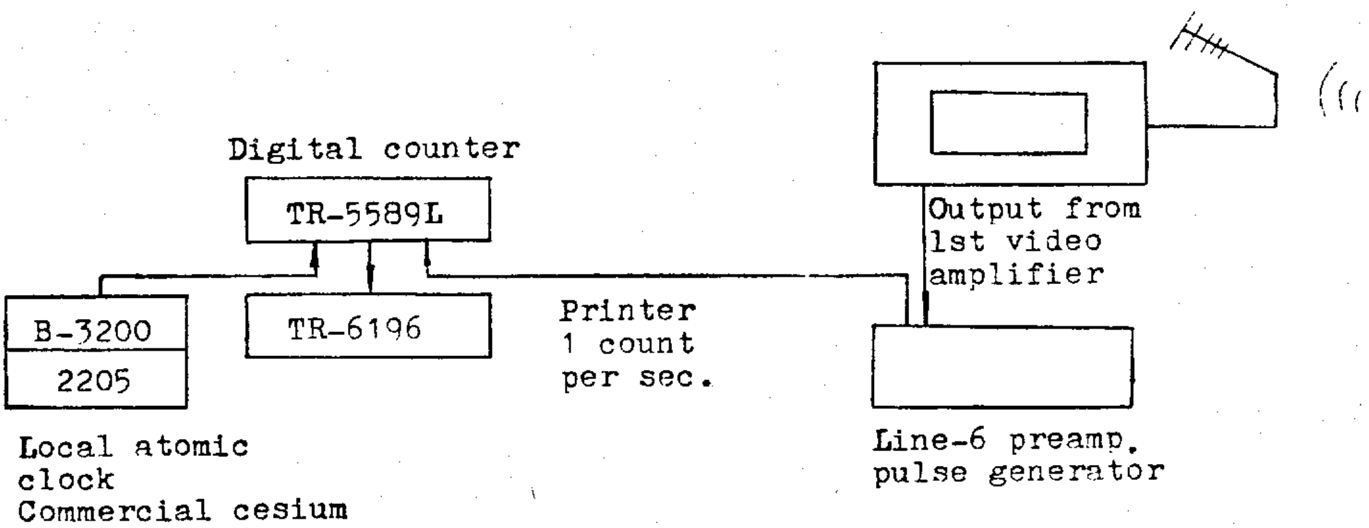

Figure 12. Functional block diagram of the TV line-6 synchronizing system

We have made it a rule to make two comparisons every day from 19 o'clock 15 minutes 0 second to 19 o'clock 15 minutes 45 seconds and from 20 o'clock 15 minutes 0 second to 20 o'clock 15 minutes 45 seconds (Beijing time). Each comparison lasts 45 seconds, and one value is taken in every second. Two average values are calculated every day, i.e. one at 19 o'clock, the other at 20 o'clock.

C. The result of the test:

(1) Stability of the relative time difference between the Beijing Institute of Radio Metrology and Measurements and the Beijing Observatory

$$\text{Standard deviation } \sigma = \sqrt{\frac{\Sigma(\Delta\tau_i - \Delta\bar{\tau}_i)^2}{N-1}}$$

ΔT_i denotes the relative time difference

N denotes the number of measurements

at 19 o'clock $\sigma = 0.32 \mu s$

at 20 o'clock $\sigma = 0.3 \mu s$

Allan variance

at 19 o'clock $\sigma = 0.23 \mu s$

at 20 o'clock $\sigma = 0.24 \mu s$

(2) Accuracy of the frequency calibration

The relative frequency deviation of the BIRMM commercial cesium clock during two months in comparison with the portable rubidium clock of the Beijing Observatory is shown below.

$$\frac{\Delta f}{f} = \frac{\sigma}{\tau} \qquad \tau = 86400 \text{ sec.}$$

Standard variance at 19 o'clock $\frac{\Delta f}{f} = 3.7\ 10^{-12}$

at 20 o'clock $\frac{\Delta f}{f} = 3.4\ 10^{-12}$

Allan variance at 19 o'clock $\frac{\Delta f}{f} = 2.4\ 10^{-12}$

at 20 o'clock $\frac{\Delta f}{f} = 2.6\ 10^{-12}$

(3) Determination of the time-delay difference between the Beijing Observatory and BIRMM by using a portable clock:

The portable clock is a commercial cesium one imported from Switzerland. It took sedan four hours to transport the clock (to go and to come back).

The result of the comparison is as follows.

The' serial number of the transportation	1	2	3	4	5
Time-delay difference (μs)	44.7	44.4	44.6	44.8	45.2

Uncertainty $0.3 \mu s$ (standard deviation)

(4) Conclusion

The following conclusion can be drawn from the two-month continuous comparison.

a. The different readings of the counter after the two continuous measurements which have been made every twenty four hours will approximately give the relative clock difference between two stations. The stability is $\sigma < 0.5\mu s$, in other words, the two measurements separated by twenty four hours have achieved the 5×10^{-12} accuracy of frequency calibration.

b. Time-delay difference between two stations can be measured with an accuracy within $0.3\mu s$ using a portable clock. Therefore the BIRMM clock can be precisely synchronized with the clocks of the Beijing Observatory or other remote places within $0.3\mu s$ (UTC).

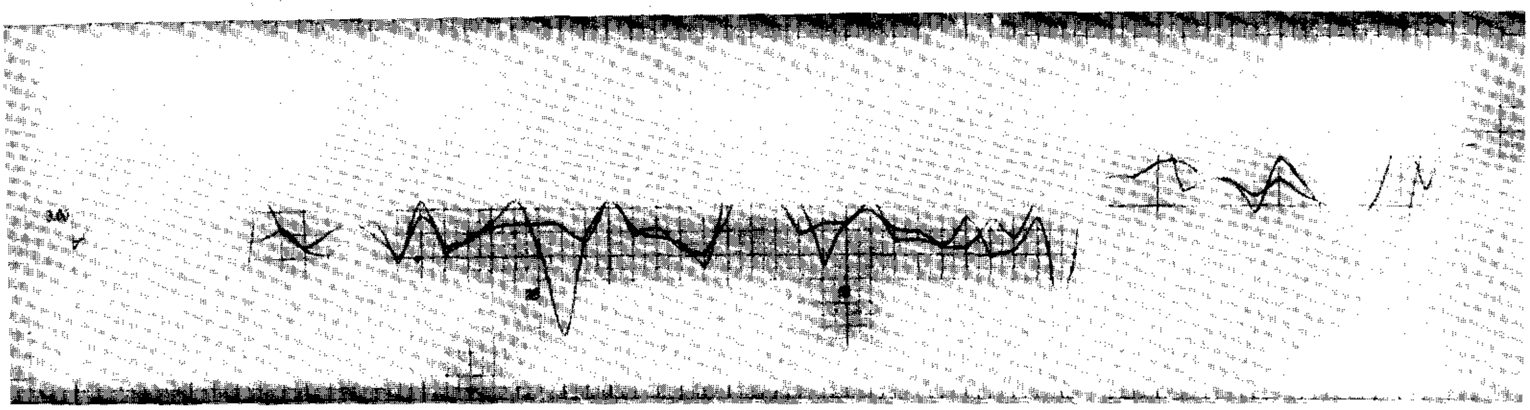

Figure 13. Curves obtained in the test of stability of the relative time difference

4. Time synchronization test by using satellites

Time synchronization via satellites is an advanced technique under development generally recognized in the world. The technique provides high accuracy, large coverage, long transmission distance and short comparison time and requires low cost for building the station. BIRMM took part in the experiment of time synchronization by using the "Symphony" satellite organized by the Central Bureau of Metrology of China.

Three experiments were carried out. Two of them were conducted in China from March 1, 1979 to March 10 and from March 21 to March 31. The other experiment was conducted with a foreign country from June 18 to June 27. The comparison test with the portable clock was made in the period of all the experiments.

From March 1 to March 10 the experiment was conducted between Beijing and Shanghai.

From March 21 to March 31 the experiment was conducted between Shanghai and Nanjing.

From June 18 to June 27 the experiment was conducted between Nanjing (China) and Raisting (West Germany).

The experiment version by using the noncoherent two-way method (or simultaneous two-way method) and the results obtained are presented.

A. Principle of noncoherent two-way method (simultaneous two-way method) for time synchronization test.

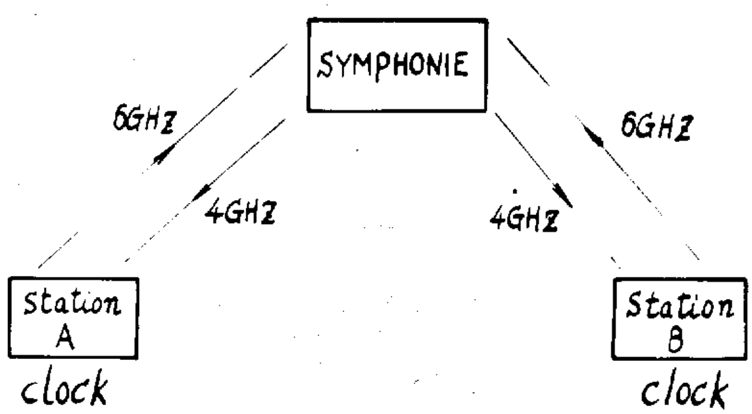

Fig 14

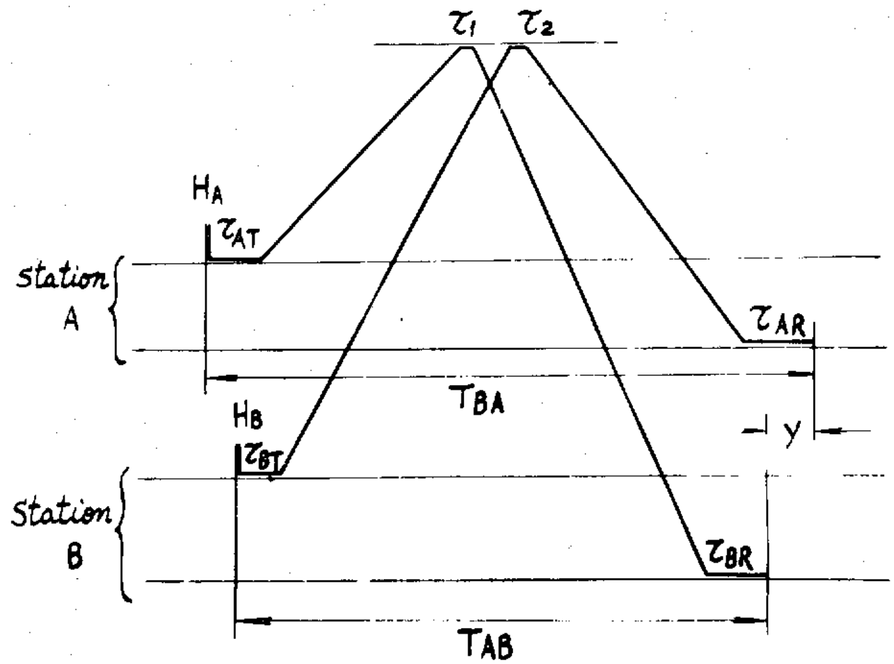

Fig 15

Simultaneous two-way method can be expressed as follows: two ground stations transmit standard time signals to each other at the same moment and receive the standard time signal transmitted by each other. To test the method is one of the important purposes of the experiment. The functional block diagram and the principle of operation are given above in Figures 14 and 15. With the help of the above-mentioned method it is quite easy to obtain T_{BA} and T_{AB}. T_{AB} is the time difference between the standard time signal transmitted by station A and the clock time of station B which is measured by the time interval counter of station B. T_{BA} is the time difference between the standard time signal transmitted by station B and the clock time of station A which is measured by the time interval counter of station A.

If we express the clock difference between station A and station B by Δt

$$\Delta t = H_1 - H_2 = \frac{T_{AB} - T_{BA}}{2} - \left[\frac{t_{AT} - t_{AR}}{2} + \frac{t_{BR} - t_{BT}}{2} + \frac{t_1 - t_2}{2} \right]^2 \qquad (1)$$

$$\text{Let } M = \frac{t_{AT} - t_{AR}}{2} + \frac{t_{BR} - t_{BT}}{2} + \frac{t_1 - t_2}{2}$$

then (2)

$$\Delta t = \frac{T_{AB} - T_{BA}}{2} - M$$

B. Parameters used in the experiments in China

$$\Delta t = H_1 - H_2 = \frac{T_{AB} - T_{BA}}{2} - \left[\frac{\tau_{AT} - \tau_{AR}}{2} + \frac{\tau_{BR} - \tau_{BT}}{2} + \frac{\tau_1 - \tau_2}{2} \right]^2 \quad (1)$$

Let $M = \frac{\tau_{AT} - \tau_{AR}}{2} + \frac{\tau_{BR} - \tau_{BT}}{2} + \frac{\tau_1 - \tau_2}{2}$,

then

$$\Delta t = \frac{T_{AB} - T_{BA}}{2} - M \quad (2)$$

A transponder was employed in the experiment to carry out the test of two-way method. The transmission power of the ground station was restricted in order that the satellite transponder could work in the allowable range.

C. Parameters used in the experiment with West Germany

	Uplink	Downlink	EIRP
Shanghai ground station	6096 MHz	3905 MHz	78dbW
Nanjing ground station	6130 MHz	3865 MHz	79dbW
Beijing ground station	6130 MHz	3865 MHz	79dbW

Two satellite transponders were used in this experiment, thus the transmission power of the ground station increased and the synchronization accuracy improved.

D. Results of the experiments

Places for the experiment	Antenna elevation and carrier-noise ratio	Test method	Stability (ns)	Accuracy (ns)
Shanghai Beijing	6.4°/8.6° 9~11db	two-way	70	71
Shanghai Nanjing	6.4°/8° 9~12db	two-way	70	75

Nanjing Raisting	8°/23° 16~18 db	two-way	9	29

E. Determination of the clock difference by the clock transport

The accuracy of the portable clock (stability and accuracy) depends on the quality of the clock and the time interval between trips. The shorter the time interval, the higher the accuracy. In general, the accuracy lies within 10~200 ns. The portable clock we used for the experiment is a 3200 commercial cesium clock. It was transported by air. The transport test was carried out on purpose to determine the value M and the accuracy of satellite time synchronization by using the two-way method.

The result of the transport test is as follows.

From . . . to	Number of the trips	Time interval	Stability (ns)
Shanghai-Beijing	10	Once a day (24 hours)	14
Shanghai-Nanjing	7	Every two days (48 hours)	28
Nanjing-Raisting	4	Different for each case. In the first case to go and to return took 12 days. In the second case to go and to return took 13 days.	30

It can be seen from the equation (2) that the value M must be measured accurately, besides the calculation after post-exchanging T_{AB} and T_{BA}, when the clock difference Δt is found by using the two-way method. There are two approaches to determine M. One approach is to measure precisely $\tau_{AT} - \tau_{AR}$, $\tau_{BR} - \tau_{BT}$, $\tau_1 - \tau_2$, then to calculate M. It is a quite complicated and difficult job. And it still remains one of the problems to solve in satellite time synchronization research. The more precise the value M, the higher the accuracy of time synchronization. Thus there should be a very precise measurement for time delay of the ground station. The other is to determine the value M by using the portable clock.

5. New PTTI items under consideration

A. To set up a hydrogen maser atomic frequency standard

In order to improve the accuracy and stability of frequency standard of this institute, BIRMM has completed installation of the hydrogen maser atomic standard developed by the Shanghai Institute of Metrology and Measurements. BIRMM expects the frequency accuracy to be improved to $(1 \sim 5) \times 10^{-12}$ in 1980. (by using the hydrogen maser atomic standard).

B. To set up the BIRMM local atomic time scale as a part of the atomic time scale of our country.

A clock group made up of two hydrogen maser atomic standards and two cesium clocks (and more clocks will be added in 1980) is used for time keeping to set up at (BIRMM).

C. To further improve the characteristics of the rubidium maser atomic frequency standard and to increase its reliability. The performance of the short-term frequency measuring system will be further improved too.

D. To deal with the research work of transfer from frequency domain to time domain in the area of short-term frequency stability measurement and to undertake the development of automatic measuring equipment.

E. To study frequency calibration technique by using the colour television subcarrier frequency method.

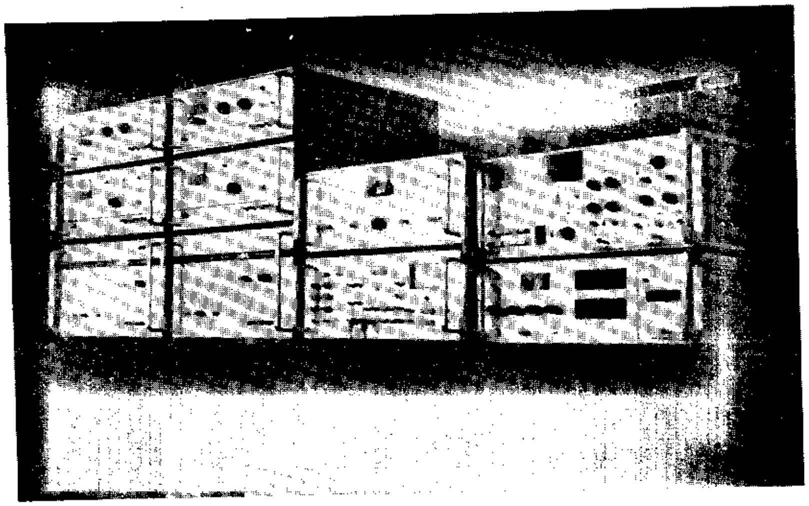

Figure 16. Short-term frequency stability measuring system
Two rubidium atomic frequency standards
(far left and the second from the left)
Reference frequency source
(the second upper one from the right)
Comparator
(the second lower one from the right)
Computing counter (far right)

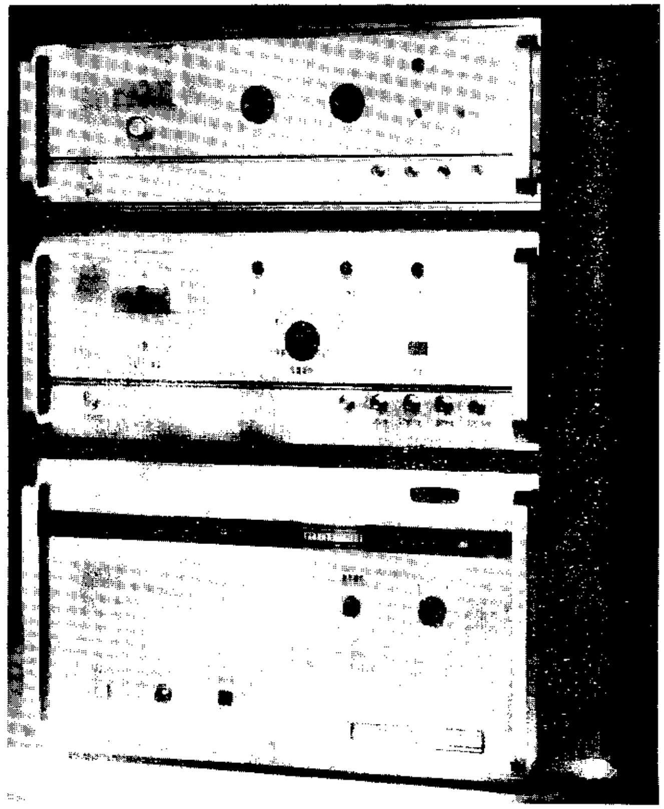

Figure 17. Rubidum maser atomic frequency standard 311 KHz frequency synthesizer (above). Phase-lock receiver (center). Rubidium maser (below).

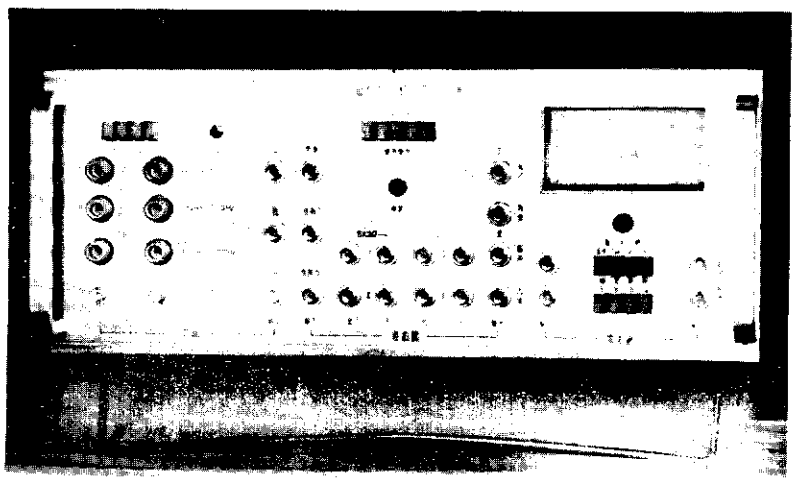

Figure 18. Short-term frequency stability comparator, the time-domain comparator and the frequency-domain comparator are mounted in one unit.

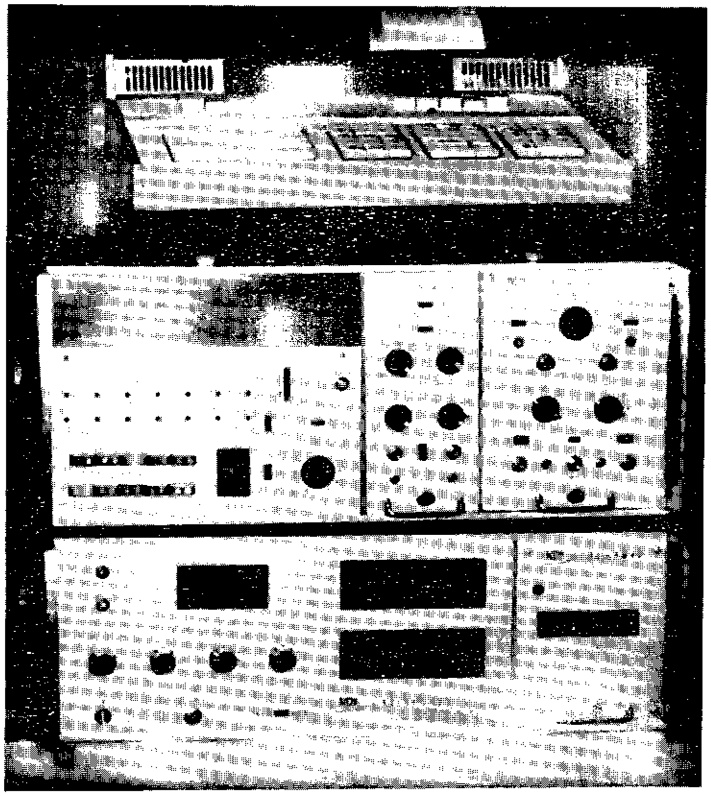

Figure 19. Data processor. (E-314 computing counter produced by the Nanjing Communication Instruments Factory)

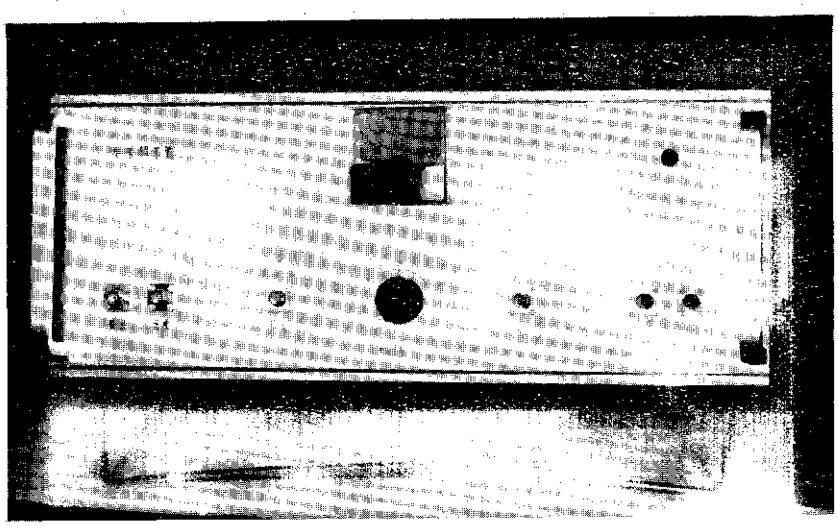

Figure 20. Short-term stability reference frequency source

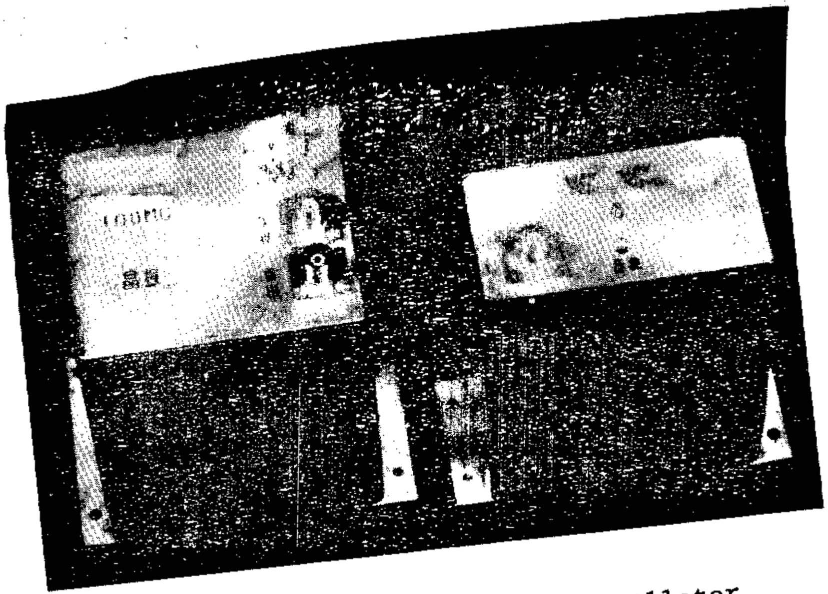

Figure 21. 100 MHz crystal oscillator
5 MHz crystal oscillator

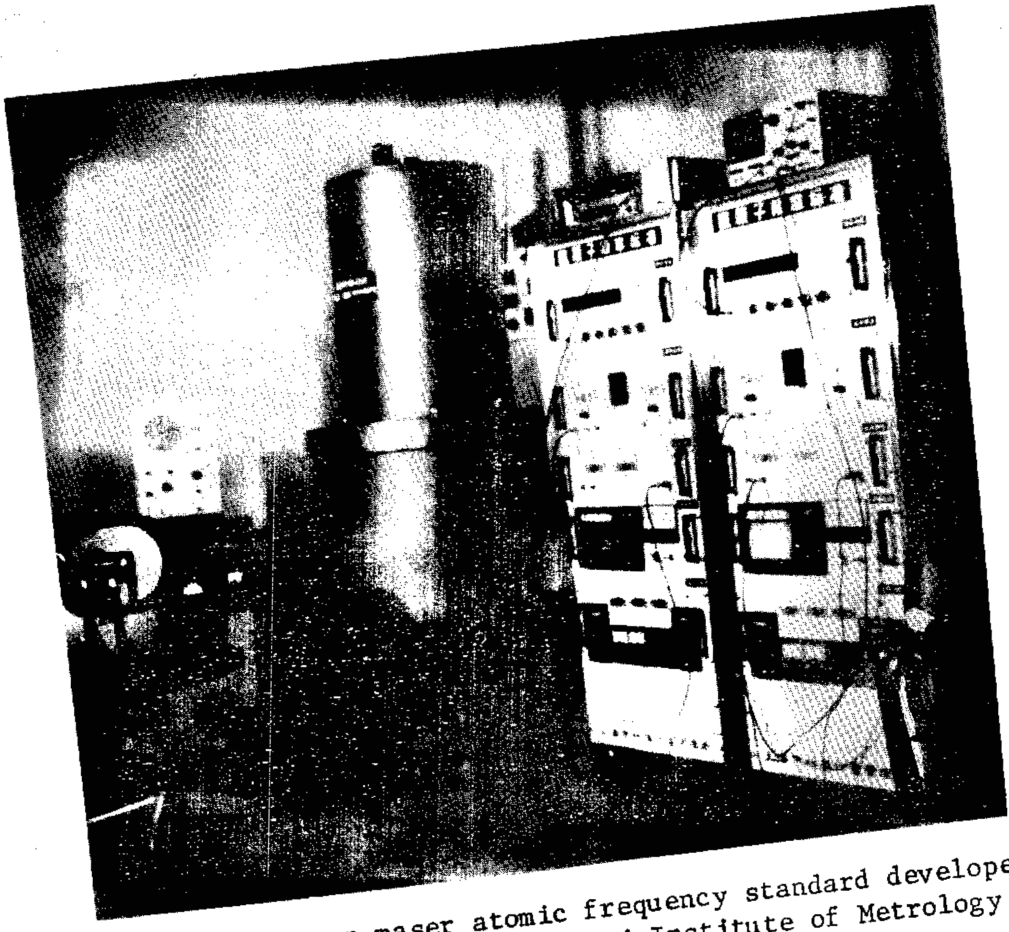

Figure 22. Hydrogen maser atomic frequency standard developed for BIRMM by the Shanghai Institute of Metrology and Measurements