PRECISION FREQUENCY SOURCES

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INTRODUCTION

Program of F.T.S.

Frequency and Time Systems, Inc., is organized to supply state-of-the-art precision oscillators based upon internal development programs, advanced developments of affiliates in Switzerland, and precision oscillators available to us on the basis of distribution agreements when such opportunities complement the line of products.

Applications

With regard to applications we recognize that frequency and time interval standards, whether they are used in the laboratory or in the field, constitute only one important need for precision oscillators. Throughout the historical development of radio technology, there has been an increasing need for precision oscillators in communications and navigation. Densely packed communications channels have expanded toward higher frequencies and the development of time ordered communications has increased. Radio aids have been extended to larger regions of navigable space and higher levels of accuracy. For these reasons the need for precision oscillators of more and more advanced performance continues. In this connection it is essential to regard precision oscillators as subsystems which must be chosen and designed to meet the requirements of the larger systems into which they will be integrated. We, therefore, recognize that no single kind of precision oscillator and no particular configuration can be developed for the growing diversity of applications.

Scope of Paper

In this paper we will outline briefly the status of our internal development of new cesium beam stabilized oscillators. We will also discuss the status of the advanced state-of-the-art quartz oscillator soon to be available, and we will describe a new, very advanced and extremely practical rubidium stabilized oscillator which we are now in a position to supply. We will confine our discussion to application oriented information relating to these cesium, quartz and rubidium oscillators, and we will not go into operating principles which are thoroughly discussed in the literature and are not germane to this meeting.

With regard to performance data, our cesium development program has not yet reached the point at which typical results can be published. Likewise, the evaluation of production models of our new quartz oscillators has not been completed to the point of comparison with already published measurements of the engineering prototype. In the case of the

Table 1
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	Oscillators			Resonators		
	Quartz	Rubidium			Cesium	Cesium
	B-5400	FRK	FRT		FTS-1	FTS-2
Output (MHz)	4 - 7	10	10 5 1 0.1			
Stability				Length	12.5 in	21 in
Short-Term	7×10^{-13} (1 sec)	5×10^{-11} (1 sec)	2×10^{-11} (1 sec)	Volume	110 in^3	412 in^3
Long-Term	1×10^{-10}/day	1×10^{-10}/mo	1×10^{-10}/mo	Weight	9 lbs	21 lb.
Temp. Range	-60°C +60°C	-25°C +65°C	-10°C +50°C	Accuracy	1×10^{-11}	1×10^{-13}
Power	2.4W (25°C)	13W (25°C)	50W (25°C)	Short-term Stability	5×10^{-11} (1 sec)	3×10^{-12} (1 sec)
Warm-up	30 min (2×10^{-7})	10 min (2×10^{-10})	10 min (2×10^{-10})			
Volume	50 in^3	72 in^3	780 in^3			
Weight	1.6 lbs	2.9 lbs	27 lbs			

miniature rubidium oscillator, performance information has been included in an earlier paper of this meeting.

While two of the precision oscillators which I will describe were developed and are presently manufactured outside the United States, I want to say at the outset that in addition to our role as distributors of such technologically advanced products, we also include in our plans licensed manufacturing, as required, to meet the conditions imposed by the Buy American Act.

PRECISION FREQUENCY SOURCES

Overview

Table 1 summarizes some of the characteristics of the quartz and rubidium oscillators and two cesium resonators which we will review in this paper. While two prototype cesium tubes have been constructed and operated in the course of our development program, it is still too early to make a direct comparison of the characteristics of oscillators based upon these tubes with the characteristics of quartz and rubidium oscillators. Such a comparison has been made in the case of the quartz and rubidium, however, and the significant characteristics are apparent. It may be noted here that the difference in size and weight between the rubidium and quartz oscillators is not particularly great as reflected by the new development I will discuss below. They are both very compact and power requirements, while different, are very small.

B-5400 Quartz Oscillator

The model B-5400 quartz oscillator is a refinement of new developments reported by Brandenberger, et al.[1] in 1971. These advancements involve the control of noise characteristics of critical circuit components in order to minimize their effects upon short term stability. In the sideband frequency range from 1 to 100 Hz the power in the frequency spectrum of the phase fluctuations, as reported at that time, was decreased by more than 10dB below that of earlier state-of-the-art 5 MHz oscillators. In the time domain, stability values were measured to be better than 1×10^{-12} from 0.1 seconds to averaging times well beyond 100 seconds.

The B-5400 has been designed at Groupe des Etalons de Frequence of Ebauches Company by Mr. Brandenberger. It incorporated the advances in short term stability and, at the same time, it is reduced in size to a very compact unit having a minimum power requirement.

A small preproduction group of B-5400 oscillators has been manufactured by Oscilloquartz, a subsidiary of Ebauches in Switzerland, in order to determine the practical limitations of

[1]H. Brandenberger, et al., "Proceedings of the 25th Annual Symposium on Frequency Control," (1971), p. 226.

factory processing. The evaluation of these units is in progress and we expect production oscillators of this type to be available within a few months. They will reflect the advances demonstrated by the development prototypes. Figure 1 illustrates one of the preproduction B-5400 units.

Cesium Resonators

Two cesium atomic beam resonator developments are in progress at Frequency and Time Systems. The FTS-1 Cesium Tube has been designed as a resonator for oscillators which will meet the requirements of the specification MIL-F-28734 Types 2 and 3. The second development, the FTS-2, is based upon the research carried out under the direction of Dr. Peter Kartaschoff at the Swiss Laboratory for Watch Research (Laboratoire Suisse de Recherches Horlogères). This work included the basic design of a high-performance cesium tube. The LSRH resonator uses a very effective system of atomic beam optics utilizing a hexapole deflection magnet at the source end and a double dipole deflection magnet at the detector end. FTS-2 is the first prototype which incorporates the LSRH design principles. It has demonstrated an excellent level of performance and we consider it to be the appropriate cesium tube to meet the requirements of MIL-F-28734 Type 1 frequency standards, as well as other high-performance laboratory instruments.

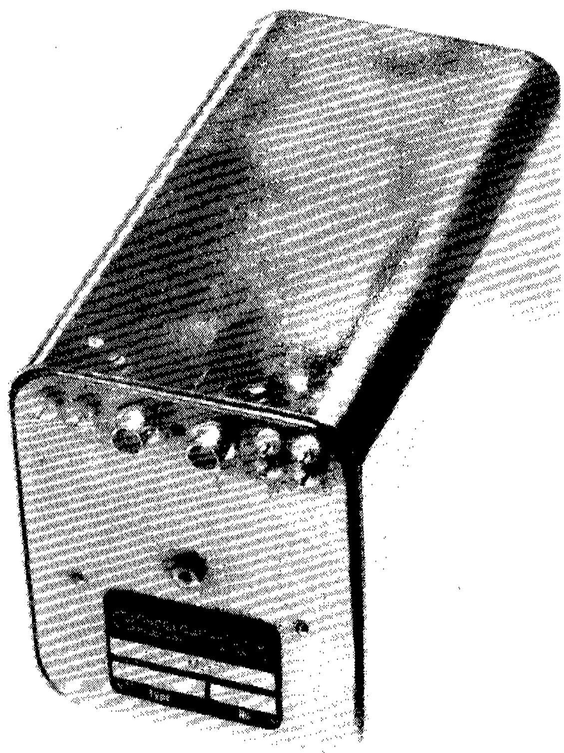


Figure 1. B-5400 high-performance quartz oscillator.

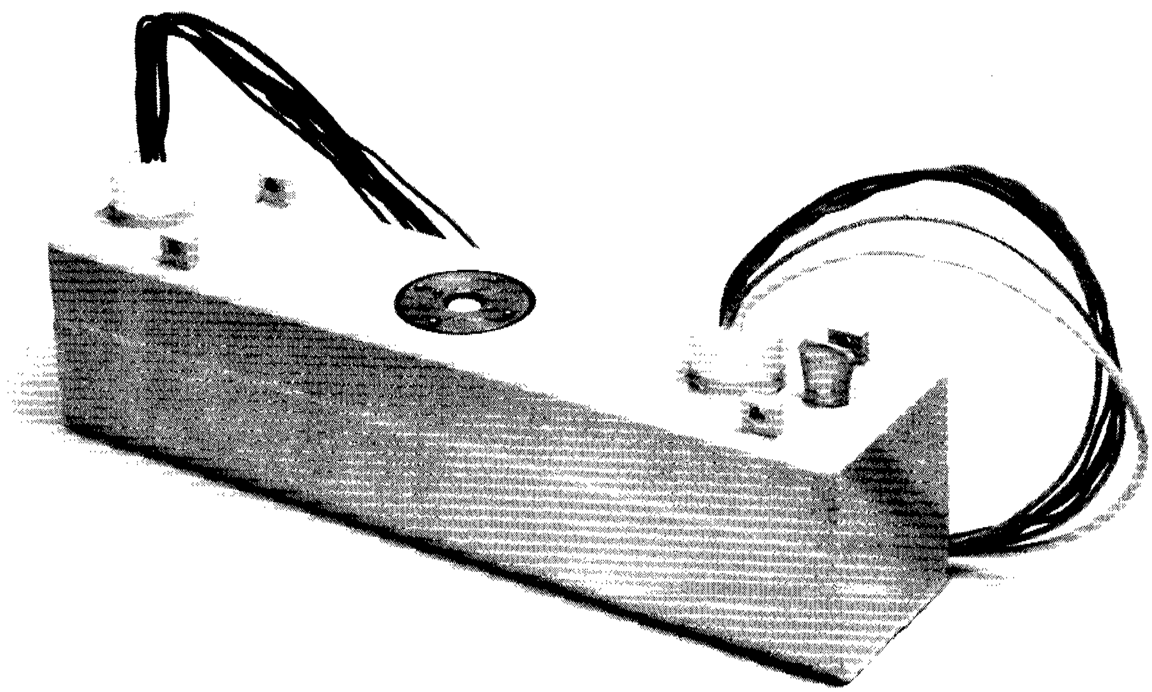
This tube also demonstrates new efficiency principles which are important in terms of cost per unit of operating time, a consideration which will certainly come into sharper focus.

The FTS-1 is illustrated in Figure 2. This tube is an advanced prototype which reflects most of the final design details which will be included in the production tubes. The design of a basic electronic system utilizing this tube is also in progress on the basis of coordinated work by Frequency and Time Systems, Groupe des Etalons de Frequence of Ebauches and Oscilloquartz.

The relationship between the two FTS cesium tubes and the requirements of MIL-F-28734 is illustrated graphically in Figure 3. The expected performance of the B-5400 quartz oscillator is also illustrated in this graph, and it is evident that this unit will also be an important component in high-performance atomic frequency standards.

Rubidium Oscillators

In the United States and Canada, Frequency and Time Systems distributes rubidium frequency standards manufactured by Efratom Elektronik in Munich, Germany. One of these units, the model FRK, is a modular oscillator which functions not only as a frequency standard, but also as a basic building block for systems that require highly stabi-



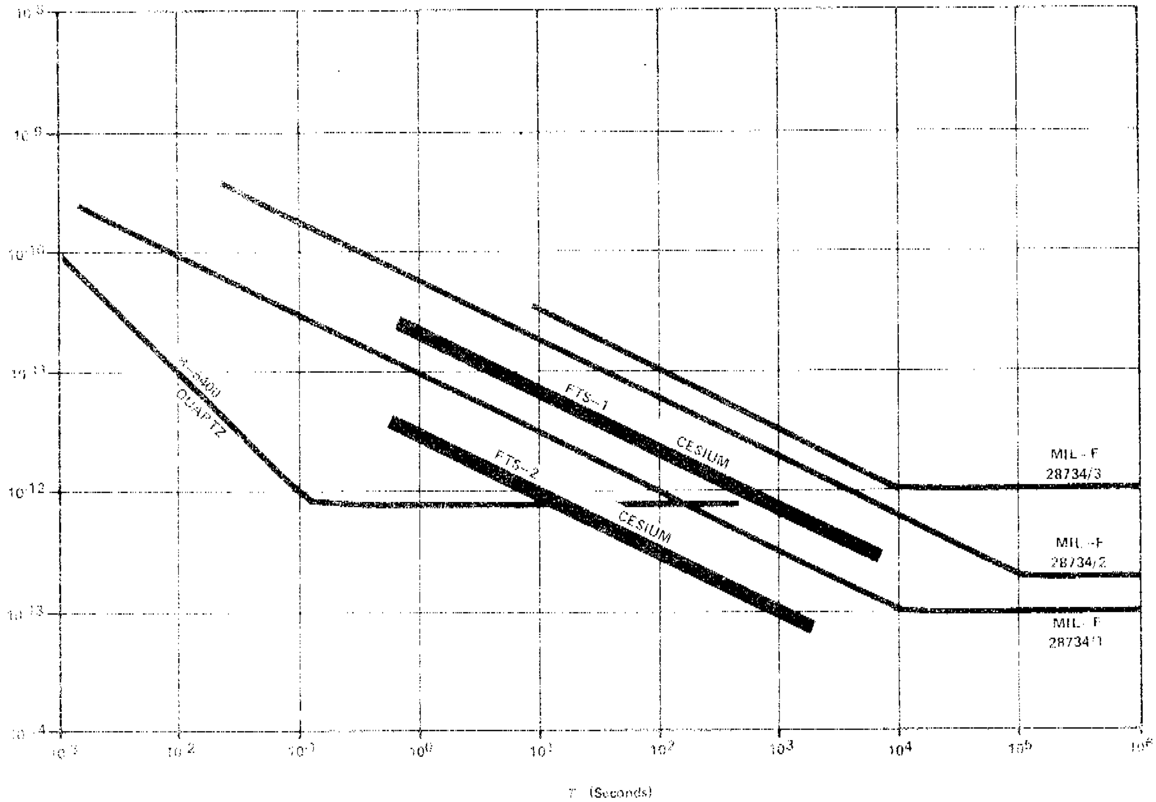


Figure 3. Precision frequency sources.

lized oscillators. The FRK is certainly the most compact atomic oscillator ever made and, while the specifications are conservative, its performance characteristics are equivalent to the most advanced devices of this type. Operating power requirements are minimal at 13 watts and, perhaps as important as the compact size, the warm-up and settling time following power turn on is extremely short. Following the application of power, the FRK locks up and delivers signal in about six minutes at 25°C. In ten minutes the frequency is well within the specified nominal value of 1×10^{-9}. This warm-up characteristic and the relative absence of the effects of shock and acceleration make it possible to utilize the FRK rubidium oscillator in field applications for which precision quartz oscillators could never be considered. The small size and power requirement assures that no significant system penalty will result.

The model FRT is a laboratory frequency standard based upon the miniature FRK. The FRT includes a power supply for operation from utility power lines and a stand-by battery with two hours reserve capacity. This instrument is well suited, therefore, to portable time transfer applications as well as reliable laboratory operation in the event of power failure. The commonly used standard frequencies are available with buffered dual outputs in each case.

Figure 4 illustrates the system organization of the miniature FRK. The output of a voltage controlled crystal oscillator is multiplied and combined with a signal from a synthesizer to produce the 6834-MHz rubidium frequency. This signal is applied to an Rb 87 resonance cell through which the light from a rubidium lamp also passes. When the signal frequency corresponds to the rubidium atomic resonance, the absorption of rubidium light in the cell increases. This effect is sensed in a photo detector and a control signal is generated which steers the frequency of the voltage controlled oscillator.

Figure 5 illustrates the FRK with the cover removed showing the voltage regulator circuit card nearest the cover, and the multiplier/synthesizer circuit card on the adjacent face.

Figure 6 is a view of the rubidium cell along with the microwave cavity into which it fits. The windings illustrated produce the magnetic "C" field which is necessary to the operation of atomic standards.

Figure 7 illustrates the FRK modular oscillator installed as a component in the Efratom Model FRT portable rubidium frequency standard. The heat sink may be used when there is no adequate heat transfer surface available for mounting. The stand-by battery shown in Figure 7 provides for two hours operation in portable applications and uninterrupted ser-

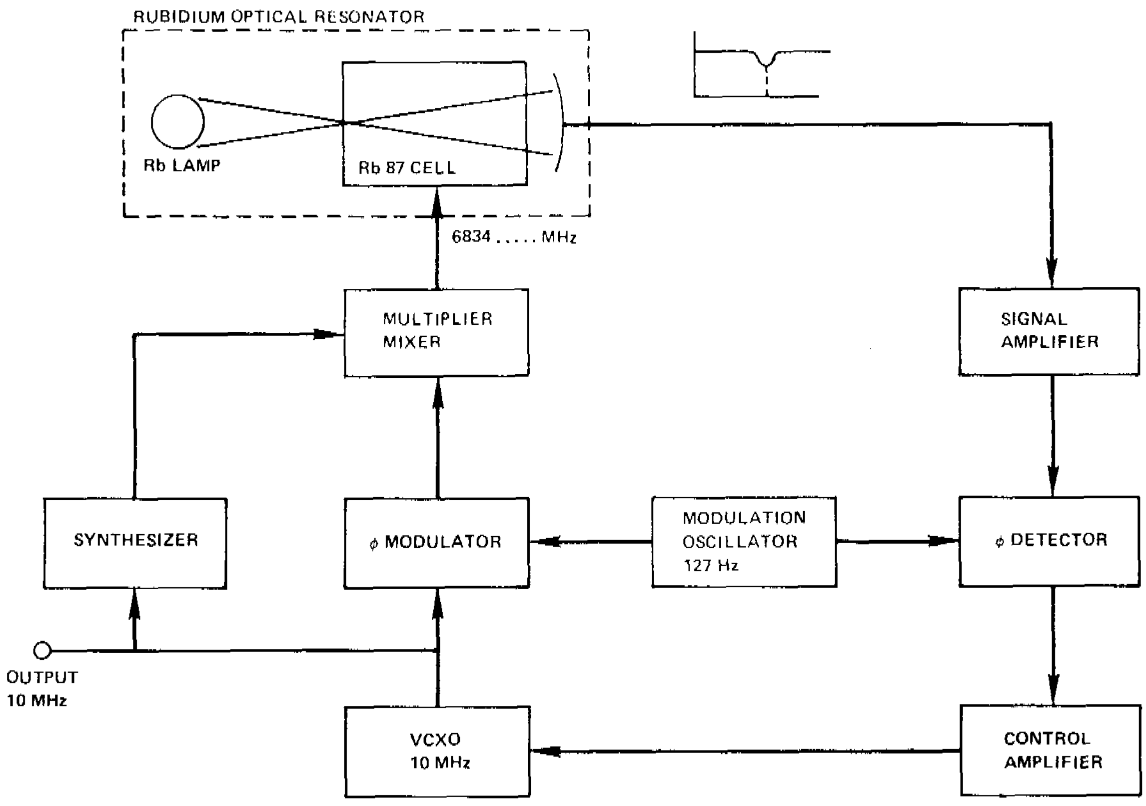


Figure 4. Block diagram of the FRK rubidium oscillator.

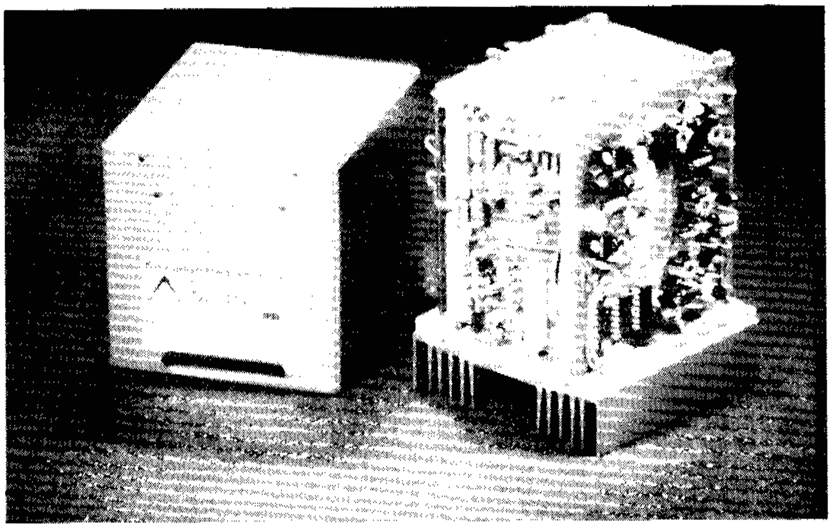


Figure 5. FRK rubidium oscillator.

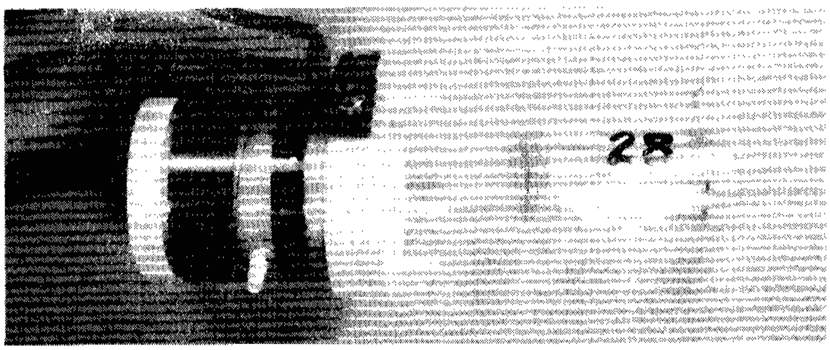


Figure 6. Rubidium cell in the FRK rubidium oscillator.

vice in the case of power failure. The power supply automatically charges the battery and provides all power to the unit while connected to utility lines.

The front view of the complete FRT is illustrated in Figure 8. Four commonly used standard frequencies are available from independent dual outputs at the front and rear of the unit. A meter and switch permit the important functions to be monitored and the frequency trim control is also available on the front panel.

CONCLUSION

Performance measurements of the FRK have already been discussed by Professor Alley and it is not necessary to repeat them here. The new rubidium frequency standards are available at the present time. In just a few months the new quartz oscillator will also be available.

Figure 2 also shows the results of the three-month frequency measurement between the NP-3 hydrogen maser and the six-clock NBS cesium ensemble in 1969–1970. An Allan variance analysis for 20-day sampling time gave a relative fractional frequency stability of seven parts in 10^{14}. The internal estimate of the variation in the NBS time scale was 4.5 parts in 10^{14}.

At both the USNO and NBS, the NASA masers operated in an average air-conditioned environment. The cavities of the masers were automatically tuned continuously with respect to a good crystal oscillator; for this mode of operation the automatic tuning system should limit cavity-related frequency excursions to less than one part in 10^{13}.[1] The variation of NP-4 with respect to A.1 (USNO) was approximately three times that expected, due to cavity-related frequency changes.

As discussed above, the algorithm used to compute A.1 (USNO) was designed to generate as uniform a time scale as possible. A.1 (USNO) has been evaluated from internal considerations to be stable to a few parts in 10^{14} for measurement periods from 10^6 to 3.10^7 seconds. However, estimation of frequency stability from internal consistency alone would be too optimistic if there were some unknown frequency shifts which were common to most cesium standards in an ensemble.[7] One effort to evaluate the stability of A.1 (USNO) against external standards has been made by B. Guinot and M. Granveaud.[9] Compared to IAT, A.1 (USNO) was found to have a stability of 0.6 to 1.3 parts in 10^{13} for averaging times of 60 days. (IAT, however, was not truly external to A.1 (USNO) since 25% of IAT was derived from the USNO time scale.) If this stability estimate were valid for the 240 day period in which A.1 (USNO) and NP-4 were compared, then the variation of A.1 (USNO) with respect to NP-4 was approximately three times that expected.

That time scales based on cesium ensembles do vary with magnitudes greater than expected from internal estimates of stability may be seen from Figures 3 and 4. Here the frequency variations of NP-4 and the contributors to the IAT time scale are plotted against IAT. (While the deviations in frequency between NP-4 and A.1 (USNO) shown in Figure 2 were definitely real, some of the frequency variations in Figures 3 and 4 were probably due to poor reception of LORAN-C signals, which were used to link the various time scales. This coordination error has been calculated as $\pm$ 1 part in 10^{13} on a 30 day basis.[9]) The variation of NP-4 against IAT was comparable to the variations of the contributing time scales against IAT. The NP-4 maser and the independent cesium ensembles agreed to within several parts in 10^{13} for the eight-month period.

Thus there was no clear, unambiguous conclusion as to the relative stabilities of a hydrogen maser and a system of cesium clocks. It would be of interest to conduct further comparisons which would involve more than one hydrogen maser of the NP type. Hopefully such comparisons would provide further data to evaluate the stability properties of hydrogen masers and cesium clock ensembles.

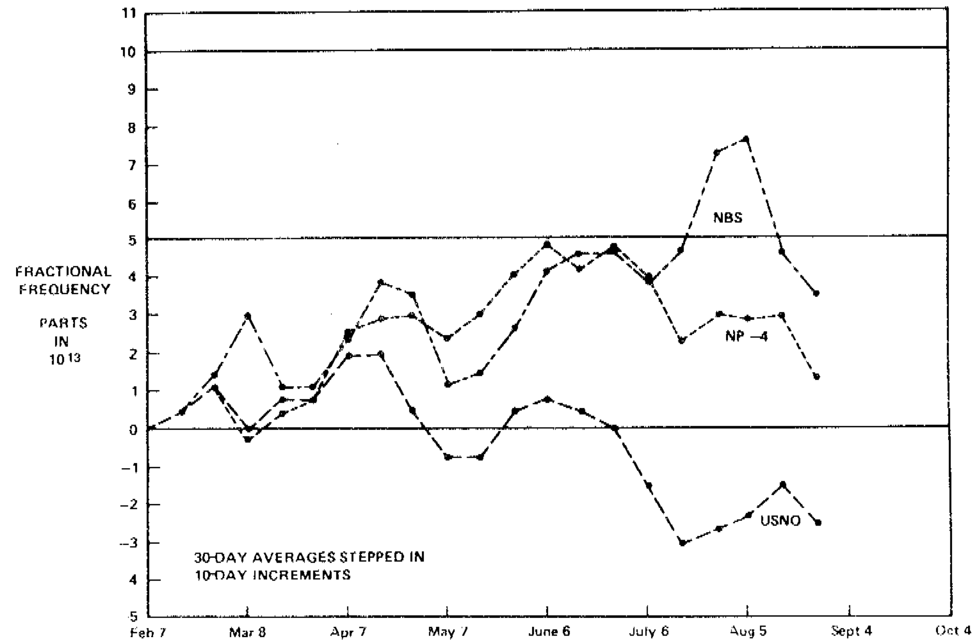


Figure 3. USNO, NBS and NP-4 maser frequency versus IAT.

III. MEASUREMENTS BETWEEN MASERS

Figure 5 shows frequency comparisons of the NASA prototype masers against the NX-1 maser in 1969 and 1972. The data have been corrected for second order doppler shift (with an error estimate of ±.0004 Hz), magnetic field measurement (±.0000013 Hz), and wall shift (± .0024 Hz). The errors associated with cavity tuning and the measurement technique were no greater than ± .00014 Hz. Since NP-5 was in Goldstone, California and was compared via traveling clock, VLF, and LORAN-C, there was an additional measurement error estimated at ± .0007 Hz.

Table 1 gives the 1972 absolute frequency of all of the NASA masers with respect to IAT. These values were referred to the 1972 NP-4 measurement reported previously.[8,9] The error estimate given for the average value of the absolute frequencies was that attributable to a single hydrogen maser since the major uncertainty, the wall shift, was a common systematic error. Table 1 includes a new value for the wall shift temperature coefficient associated with the hydrogen masers. The cavity temperature of NP-2 and NP-4 were lowered by 17°C. The resulting changes in the frequencies of NP-2 and NP-4 indicated that the previous value for the wall shift temperature coefficient was in error.*

*The value for f_H given herein differs by 0.0003 Hz from the value in Reference (8). This is due to the use of the present value of wall shift temperature coefficient, namely (0.008 ± 0.0003) Hz-in/°C. The previous value, assumed in Reference (8) to be (0.005 ± 0.0003) Hz-in/°C, was that given by Vessot et al. (12), and was only claimed to be valid for the temperatures from 25°C to 40°C, whereas the new value was measured for 35°C to 53°C. The 0.0003 Hz change is far less than the claimed error, so is not of great significance.

Due to operational requirements, immediate before and after measurements were not done, and the 1972 measurements were the first precise frequency comparisons of NP-2 and NP-4 and the other masers subsequent to the temperature changes.[12]

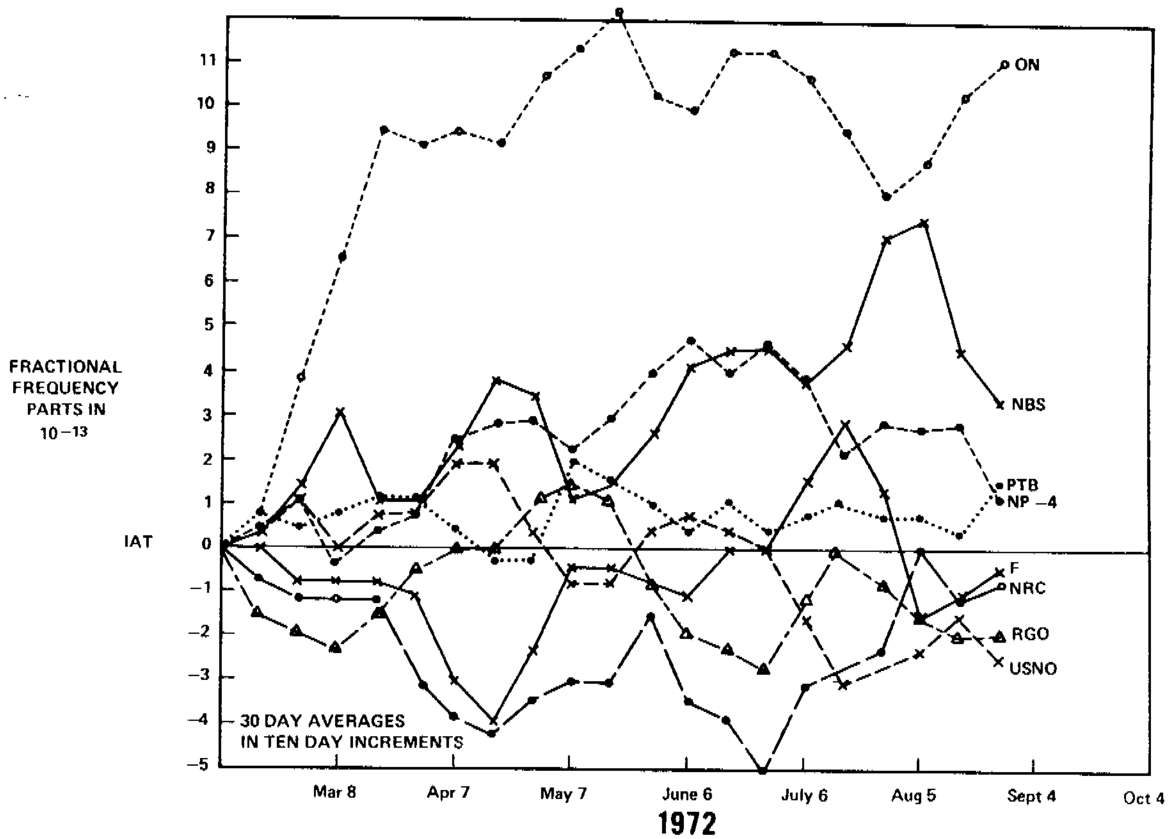


Figure 4. Frequency comparisons--International Standards Labs and NP-4 H-maser versus IAT.

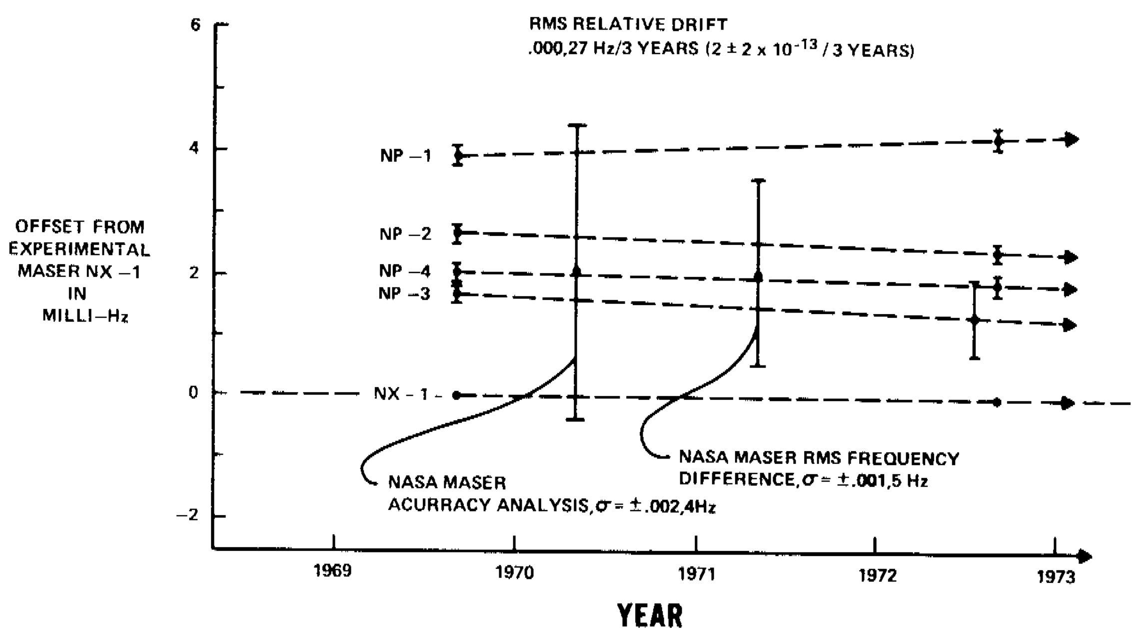


Figure 5. Frequency relationships—NASA NX-1 and NP-1, -2, -3, -4 atomic hydrogen masers.

Because of this temperature change, NP-2 and NP-4 in Figure 5 should only be compared to one another, and NP-1, NP-3, and NX-1 should only be compared to one another, in order to estimate the long term performance of the NASA masers.

Table 1

f_H = 1,420,405,751. + table value, Hz

Maser	NP-1	NP-2	NP-3	NP-4	NX-1
Value	.7782	.7764	.7753	.7758	.7740
Average value 0.7760 ± .0024 Hz					

The long-term stability inferred in Figure 5 should be valid if frequency variations due to magnetic field changes are either negligible or estimated by Zeeman frequency measurements. (In the 1972 NP-4/USNO measurement, the magnetic field was checked weekly. The variations in Zeeman frequency indicated an uncertainty in the maser frequency of ± .000014 Hz, with a negligible measurement error.) Under these conditions, a stability estimate for the NASA masers was 2 ± 2 parts in 10^{13} in three years.

An estimate of the intrinsic reproducibility of the NASA maser has been calculated from the RMS variation of all of the maser frequencies from their average frequency. The resulting value was 0.0015 Hz. Reproducibility may be improved significantly if the maser bulbs were removed and recoated; however, this was not done since these masers were in field usage for most of the three years. (For field applications, these absolute differences are easily removed or adjusted to any desired frequency by synthesizers.)

CONCLUSION

Hydrogen masers have already provided significant contributions to PTTI applications due to their excellent short-term stability. Their long-term stability, long operating life, and reproducibility demonstrate their usefulness in generating accurate, stable, and uniform time scales. The use of the hydrogen maser holds promise to improve time and frequency control with greater ease than presently possible with large ensembles of cesium clocks.

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