CLOCKS FOR AIRBORNE SYSTEMS*

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ABSTRACT

Because of the need for an accurate clock for future airborne systems such as IFF, MITRE has investigated the potential performance of compact oscillators. In particular, extensive testing of rubidium oscillators manufactured by Efratom has been performed for more than two years. The results indicate that an accuracy of better than 10 microseconds should be achievable in tactical aircraft provided that appropriate measures are adopted to counter the many environmental factors. In a favorable environment a stability of better than 5×10^{-13} for one day is achievable with present commercial units, but improvements are required to suit operation in an aircraft. Results of some vibration tests show promise, but further investigation is required.

With further development of rubidium controlled clocks the ultimate limitation on time accuracy in aircraft will probably be associated with time dissemination, maintenance difficulties and doctrinal hurdles.

INTRODUCTION

The design of a communications system and the study of an Identification Friend or Foe (IFF) scheme, both using absolute time,(1) have aroused the interest of the Air Force in the capabilities of small frequency standards. Preliminary investigation has led to the realization of the wide potential value of accurate airborne clocks, since accurate time can be used for many communication and navigational systems which, at present, are designed to use independent oscillators. Although there are now only a few AF systems in the development phase that require accurate time, the trend toward the use of coding to achieve security and the

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development of Time Difference of Arrival (TDOA) techniques for precise location suggest that an accurate clock may well be a vital part of the complex nerve center of future weapons of war.

The Navy has already taken action to coordinate the many systems in their service using precise time, and plans to provide a master clock (comprising three standard oscillators with cesium beam tubes) on Navy platforms.(2) Although a similar system cannot be implemented on aircraft, Air Force system requirements are not as onerous as those of the Navy in many respects. In particular, aircraft (unlike ships) are not required to operate autonomously for long time periods; some relaxation of independent clock performance should be tolerable. For Air Force needs, a unit must be light and compact.

When we learned that small rubidium cell units were being produced commercially, we decided to investigate the performance of this type of oscillator in some detail. Two commercial rubidium units were purchased from Efratom Systems Corporation in April 1979 and testing began that same month. Other units have been purchased for an experiment in which signals from aircraft were received at three sites and the times were recorded. The recorded results were then used to compute the positions of the aircraft. Consequently we have performed many tests on different versions of the commercial models. We have also tested an early version of the M-100 militarized model that was made available for Project SEEK TALK, and performed vibration tests on this unit and on one of the commercial units.

On the whole our results have confirmed the performance claims for these units and shown that there is a good prospect of achieving time accuracy of 10 microseconds for 10 hours. Many features of the present designs will require attention, and special procedures will have to be established before this accuracy in time keeping will be reliably obtained on tactical aircraft.

PRIMARY OBJECTIVES OF THE TEST PROGRAM

The immediate objectives of our preliminary testing were to establish, at first hand, the basic accuracy of the rubidium cell and to check the performance figures quoted by Efratom. We also needed to obtain more experience with precise time-interval measurements and accurate oscillators in order to be well-prepared for performing environmental tests on militarized versions of rubidium cells when they become available. Many measurements have been made to a higher resolution than would normally be required, in order to ensure satisfactory performance with our transportable units.

THE COMMERCIAL EFRATOM UNITS

Figure 1 shows a photograph of two Efratom units. These are both fitted with the optional finned heat sink. With the heat sink attached, the major dimensions are approximately 4 in x 4 in x 5.7 in and the weight is 3.5 lbs. The output is +7 dBm (1 volt in series with 50 ohms) at 10 MHz.

The input power required is approximately 15 watts at 24 volts dc, but is a function of the temperature and the supply voltage which should be kept within 22 to 32 volts dc.

The two available commercial units are designated FRK-L and FRK-H, the latter being the more expensive unit. The specifications for the two differ in some important features, as shown in Table 1.

TABLE 1 Major Specification Features of Efratom Units

	FRK-L	FRK-H
Long-Term Stability	$<4\times10^{-11}$/month	$<1\times10^{-11}$/month
Short-Term Stability	3×10^{-11} (τ=1sec)	1×10^{-11} (τ=1sec)
	1×10^{-11} (τ=10sec)	4×10^{-12} (τ=10sec)
	3×10^{-12} (τ=100sec)	1×10^{-12} (τ=100sec)
Trim Range	2×10^{-9}	1×10^{-9}
Environmental Effects:		
Voltage Variation	$<1\times10^{-11}$/10%	$<1\times10^{-11}$/10%
Temperature (Base Plate)	$<6\times10^{-10}$ from -40°C to +65°C	$<1\times10^{-10}$ from -25°C to +65°C
Magnetic Field	$<3\times10^{-11}$/oersted	$<3\times10^{-11}$/oersted
Pressure	$<1\times10^{-13}$/mbar	$<1\times10^{-13}$/mbar

The warm-up characteristics are specified as reaching within 2×10^{-10} frequency error in 10 minutes. The retrace is not specified but data supplied by Efratom shows a retrace of 1×10^{-11} in 60 minutes at 25°C. This retrace is defined as the difference from the frequency before switching off. However, the measurement accuracy claimed is only $\pm 1 \times 10^{-11}$.

Some other options available give improved magnetic shielding, optimized performance at desired temperatures, and improved short-term stability. One option fitted to MITRE-purchased units is external resistance-control of the frequency adjustment, with a range of 1×10^{-10}.

The FRK-L units we have tested are not strictly representative because they have been given special attention. After our early testing gave us a better appreciation of high-performance oscillators, our objectives were expanded to include assessment of the scope for further improvements in small rubidium oscillators.

A brief history of the units is given below.

FRK-H 3368 Received April 1979. Has been operated almost continuously. Installed in special unit with temperature control of the fan in August 1980. Subsequently used as local reference.

FRK-L 3311 Received April 1979. Returned to Efratom June 1979 to correct intermittent fault. Deficiency in magnetic shield corrected by clamping (August 1980). Temperature compensation modified April 81. Used in test as transportable clock.

FRK-L 3610 Received June 79. Returned to Efratom for improvement of temperature coefficent and other minor changes in Sept. 79. Used intermittently in 1980, and continuously in 1981.

FRK-H 4548 Fitted with extra mumetal shield. Received June 80 and returned to Efratom because of non-reproducible turnover effects. Particularly susceptible to phase-lock but otherwise has proved to be exceptionally stable. The temperature compensation was modifed in 1981.

FRK-H 3940 Ordered with special features. The mumetal shield was given special attention and the temperature coefficient adjusted for a heat sink temperature of 42°C. Received March 81. Operated continuously since April 81. Used for transportable clock.

FRK-H 5415 Ordered with the same features as H3940. The temperature coefficient was unsatisfactory and the unit was returned to Efratom for attention. Measurement since return to MITRE has shown that the short-term (minutes to hours) instability is about one order worse than for other units.

M100 018 Received March 1980 and returned to Efratom because of nonreproducible turnover effects caused by stray signal couplings between subunits. Returned to MITRE Aug. 80. Particularly susceptible to phase-lock. Tested through Oct. 80 and returned to Efratom for investigation.

MEASUREMENT CONDITIONS AND TECHNIQUES

The units have been operated in a widely used laboratory, and, on some occasions, room temperature changes which were not under our control affected the measurements significantly. Since the spring of 1981, three of the units have been mounted on vibration isolators with the optic axis vertical so that movement of their cabinets should not cause a change in the earth's magnetic field. The stabilized power supplies have a standby battery with capacity for about 30 minutes operation of the oscillators and their associated clocks. The resolution of the clocks is 100 ns. These three units are all fitted with a finned heat sink and a temperature-sensing thermistor to control the operation of a cooling fan.

Other units have been operated from a floating battery supply. The heat sink temperature can be monitored or recorded, and the temperature can be varied over a range of 10 to 20°C by control of the cooling.

Measurements have been purely relative with no attempt to obtain an absolute-time reference. The phase/time difference between two oscillators is recorded using an H-P 8405A Vector Voltmeter. For the more important measurements the differences between at least three oscillators have been recorded simultaneously.

From July 79 to August 80 we used an H-P 5062C Cesium Beam Reference Frequency* as the standard, and measured the long-term drift of unit FRK-H3368. We have also used an Arbiter 1011C Frequency Comparator with the ABC-TV signal. Unfortunately, reception at MITRE is not line-of-sight, and the signal-to-noise ratio is usually inadequate for accurate frequency measurements.

We have found it necessary to provide special shielding of the oscillators to avoid phase-lock effects. For bench testing we enclose the units in an aluminum box with decoupling fitted to the four leads that are brought out (power supply, crystal oscillator varactor voltage, rubidium lamp voltage).

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*This unit was kindly lent by N. F. Yannoni (RADC).

PHASE LOCKING AND STRAY COUPLING

All the units we have tested suffer from interaction effects when operated in the vicinity of other units. Some lock up to another unit even when the frequency difference is greater than 1×10^{-11}. The phenomenon is displayed as a constant phase-difference until the frequency difference exceeds the hold-in range, when the phase jumps. With proper shielding there is no evidence of phase lock.

An experiment in which the output of one unit was coupled into another showed that the signal required to achieve partial phase lock for a frequency difference of only 1×10^{-12} was 0.1 volt or 14 dB below the output level. Before proper shielding was fitted there were many false symptoms of coupling through the connections to the phase meter. Other experiments with unshielded units have shown that the frequencies of both units are affected.

When M100-018 was phase-locked to FRK-L 3610 the phase recording against an unlocked unit showed sinusoidal perturbations of 2 ns peak-to-peak at six periods per 100 ns of total change. Another small perturbation was detected at 42 periods per 100 ns of total change. Subsequent measurements of the output signal from another unit, H4548, showed harmonics of 60 MHz extending to the 21st (1260 MHz) and many harmonics of 10 MHz. The strongest harmonics were 20 MHz at 20 dB down and 240 MHz at 35 dB down. The 420 MHz component was 37 dB below the 10 MHz level. A non-harmonic output of 237.125 MHz was 39 dB below the 10 MHz output.

Many recordings have shown occasional cyclic phase changes in a period of approximately one to ten seconds without phase-locking and sometimes cyclic changes of only a few hundredths of a nanosecond or about one tenth of a degree. Some recent tests with H3940 and L3311 close together and inadequately shielded showed, in the phase comparisons against H3368, cyclic changes at 1/7 Hz and approximately 1/100 Hz. The effect on L3311 was the greater, with a peak to peak excursion of more than 3 ns. The 1/7 Hz was probably the difference between the frequencies of the two servo oscillators, indicating leakage of modulated signals between the two units. After refitting the shields at the rear of the cabinets, the leakage effects were no longer detectable.

The FRK-L units show noise of approximately 1/100 ns; for the FRK-H units the high frequency noise (>1 Hz, but noise bandwidth only ~5 Hz) displayed on the recorder is appreciably less. A recording of L3610 vs L3311 showed occasional cyclic modulation and occasional jumps of 1/10 ns.

For our time-keeping requirements, small modulation of the phase is of negligible concern. However, the evidence of leakage implies stray coupling between subunits. It is suspected that such coupling may cause changes in the frequency when a unit is subjected to mechanical stress. Although the turnover effects are usually reproducible, M100-018 as originally submitted was found to suffer from variable stray coupling.

CHARACTERIZATION RESULTS

Warm-Up and Retrace

Measurements of warm-up and retrace have been made on an ad hoc basis so that the results given in Table 2 show values measured at some convenient time, rather than a detailed record as a function of time.

Retrace is not exactly defined, and the measurement of the frequency was made within two to eight hours of switching on. The frequency difference is referred to the value before shutting down. The overshoot measured on some of the tests shows the difficulty of defining retrace. It apparently would be unwise to rely upon achieving the limiting stability until a unit has been operated for ten days, although on all our tests the frequency reached after two hours was within 2×10^{-11} of the previously established value.

A frequency accuracy of 1×10^{-10} should be attained with 15 minutes after switching on, but more experimental data will be required in order to assess the practicality of starting an airborne clock just prior to take-off.

Temperature Coefficient

M100-018 is the only unit we have measured over a wide range of temperature. Results are shown in Figure 2. The hysteresis indicates the difficulty of making accurate measurements of the temperature coefficient in the region of the minimum.

The unit was cooled from +37 to -30°C in two hours and then left overnight to reach the lowest temperature. The temperature was then raised to 60°C in three hours and again the unit was allowed to cool overnight. After settling at 37°C the frequency was in excellent agreement with the value measured at the start (1×10^{-12}). Following investigation of thermal transients in the region of 60°C the temperature cycle was repeated.

The compensation is well suited for a range of -50 to +55°C, giving a total change of only 6×10^{-11}. In the region of 30 to 45°C, corresponding to a range around normal ambient temperature with the large heat sink used for environmental testing, the coefficient is $+2 \times 10^{-12}$ per °C.

Table 2

Warm-up* and Thermal Effects

Unit	Temperature Coefficient (°C x 10^{-12})	Warm-up (x10^{-11})	Retrace		Overshoot	
			Off-Time (Days)	Frequency Change (x10^{-11})	Value (x10^{-11})	Recovery
FRK-L 3311	<-0.15 after adjusting R28 April 81	-6 @ 11 min	1	1	small	
			2	2	small	
			12	2	2.8	7 days
FRK-L 3610	+1.3 to 2.0, increasing at higher temp. (30 to 50°C) +5 before return.	-10@9 min -1 @ 60 min	14	2	4	not measured
FRK-H 3368	-0.5 (30 to 60°C)	-20@7 min -1 @50 to 90 min	1	0.5	small	
			14	-	6 @ 2 days	- 10 days
			18	0.5	2.6 @ 1 day	no record
FRK-H 4548	< + 0.5 (estimated .3 35 to 45°C) < - 0.2 after modification		10	-0.8	small	
FRK-H 3940	< +0.3 (30 to 50°C)	-6 @ 8 min	0.5	-0.7	small	
M100 018	+2 (37 to 47°C)	changed from + to - @ 13 min, -3 @ 20 min	3	<0.5	not checked	

*at ambient 23 ± 2°C

The other units have been measured over a limited region by cooling with a fan or raising the temperature by blocking the air flow. Following the example set earlier[3] the compensation of units L3311 and H4548 has been adjusted. We have found the value of the compensating resistor to be very critical; we are uncertain that results are reproducible. After reducing the value of R28 by 0.5% in unit H4548, the temperature coefficient was small, but measurement was uncertain, partly because the laboratory temperature varied appreciably and affected the frequency of the reference.

Effects of Magnetic Field

By placing the unit with the optic axis along the earth's horizontal component, H, reversal gives the effect of a change of 0.36 Oe (Bedford MA.) Since the change is instantaneous it can be measured with precision.

Our experience with L3311 is of special interest. When tested before its return to Efratom in 1979 the effect was 1.6×10^{-11}; after the return to MITRE the effect was small. Then in July 1980 the result was the same as originally measured. Inspection revealed an appreciable gap between two sides of the outer shield and the mumetal plate fixed to the heat sink. By clamping these two sides the effect of a reversal of H was again small. A plastic spacer of .010 in, inserted in one side, gave a consistent effect of 0.6×10^{-11}

Fitting a clamp to H3368 did not improve the magnetic shielding. Because we have used this unit continuously as a local reference we have not investigated further. However, the poor shielding resulted in problems from a choke in an adjacent power supply, and with one type of fan motor. The fan we finally fitted gave no detectable effect even at a spacing of only one inch.

The M100 is fitted with a folded lip on the heat sink mumetal and the results showed excellent shielding. However, after completion of vibration tests, measurements showed appreciable sensitivity to the earth's field.

Turnover (Constant Acceleration)

Most units display the largest turnover effect along the optic axis, possibly as a result of small physical movements of the "physics package" and is, perhaps, affected by inhomogeneity of the C Field[4]. Unit H4548 displayed small turnover effects, but appreciable change for a rotation of 90° around a horizontal axis which gave a maximum effect of 12×10^{-12}.

Table 3

Effects of Magnetic Field

	Fractional Frequency Change x10^{-11}	
Unit	Reversal of Horizontal Component of Earth's Field (H = 0.18 Oe)*	Estimated** Effect of Reversal with Optic Axis Vertical (Ƶ = 0.54 Oe)*
FRK-L 3311	small	small (see text)
FRK-L 3610	1.3†	4‡
FRK-H 3368	2.1†	6.5‡
FRK-H 4548	small (3 Mumetal shields)	small
FRK-H 3940	0.4†	1.2‡
M100 018	small (see text)	small (see text)

* Information from R. Hutchinson (RADC)
** The effect of a change of 2 Ƶ in magnetic field was calculated using the results for a change of 2H.
† Lower frequency with fins North
‡ Higher frequency fins at the top

Table 4

Turnover Effects (Gravitational Changes)
(parts x10^{-11} per 2g)

Unit	Fins Vertical* Optic Axis E-W	Fins Horizontal Optic Axis E-W	Optic Axis Vertical (corrected for magnetic field)
FRK-L 3311	0.4	0.2	1.8 ± 0.2[†]
FRK-L 3610	1.7	1.6	2.4[‡]
FRK-H 3368	0.9	0.5	4.0[‡]
FRK-H 4548	0.2	0.3	0.3[†]
FRK-H 3940	0.7	0.1	0.5[‡]
M100 018	<0.2	<0.2	1.0[‡]

* Fins Vertical is equivalent to Label Top/Bottom
† Higher frequency with fins at top
‡ Lower frequency with fins at top

Because measurements were made on L3311 for three different conditions of the magnetic shield we are more confident of the measured result for the optic axis than for other units, although the accuracy for all should be within ± 3 x 10^{-12}.

In view of the early experience with M100-018 and the evidence of stray coupling effects, we suspect that some of the turnover effects may be the result of changes in signal coupling, although measurements have given consistent results.

After vibration testing of M100-018 the turnover tests gave different results (cf magnetic shielding changes). The sense of the change along the optic axis was reversed and the magnitude was twice the previous value.

The excellent stability of H4548 along the optic axis was demonstrated by drop tests on the bench. Only very small (barely detectable) phase transients occurred (whereas the M100 displayed phase changes as great as 40° (11 ns), and output level transients of 1 dB when given less severe shocks).

Most units show monotonic phase jumps for shocks along the optic axis with reversal of sense for the opposite sense of shock. The effects on the frequency are small.

Crystal Tuning and Aging

A change in crystal tuning equivalent to a varactor bias change of more than 10 volts caused a frequency change of no more than 2×10^{-12} on H3368, and 8×10^{-12} on L3311.

The tuning of H3368 was set to give a varactor bias voltage of 14 volts on Aug. 79. The crystal aging had been compensated by a change to 7.2 volts by Oct. 81.

Pressure Effects

With M100-018 the frequency change for a change from atmospheric pressure to vacuum (10^{-3} atmosphere) was no worse than -5×10^{-11}. The temperature was kept constant within 1°C for this test.

Supply Voltage

Measurement on H3368 gave an average effect of $+2 \times 10^{-12}$ per volt of change over the range 20 to 30 volts. Correction for temperature change would make the coefficient slightly greater, but the value is about half that given in the specification.

Stability and Aging

Measurements of the stability for periods of hours have shown that the temperature changes are the main factor. A typical value for the six hour Allan variance (for the three units with fan control circuits) is 2.8×10^{-13}. However, in one week, the result for H3940 was 5.3×10^{-13} whereas L3311 and H3368 both gave 2.8×10^{-13}. In some tests the effect of an apparent drift was significant, but the calculation was not corrected because such drifts appear to be random.

Unit H4548 has been operated without temperature control and the six-hour variance is clearly affected by the changes in temperature. The value for the combined variance with H3368 was 3.5×10^{-13} for one week when the temperature was relatively stable. It increased to 7×10^{-13} for a week when the temperature rose to 30°C during the day. For the favorable week the six-hour variance for L3311 and H3368 combined was only 1.6×10^{-13}.

Results for the six, twelve and twenty-four hour variances for H3940 and H3368 over one period of ten days are given in Table 5. The effect of diurnal changes in temperature can be seen in the dependence of the 12 hour variance on the time of sampling. An assumption of a daily sinusoidal fluctuation of amplitude 5.5 ns would make the corrected values fit a $\tau^{1/2}$ dependence, but the two weekends would distort the diurnal effect.

Aging data were obtained on H3368 by referring to the cesium reference, starting after two months of prior operation. This unit showed negative aging in the first four months with the rate slowing to approximately -5×10^{-12} per month. After a three month gap the result for the subsequent five months was a positive change at an average rate of less than 5×10^{-12} per month. The records for other units are purely relative and mostly spoiled by interruptions. However, units H3940 and L3311 have recently been operated without interruption or adjustment. Their frequencies compared with H3368 four months after setting to a small difference were -4×10^{-12} and $+5 \times 10^{-12}$ respectively, although L3311 has changed as much as $+8 \times 10^{-12}$ in one ten-day period, and -5×10^{-12} in a five-day period. The clocks were resynchronized 10 weeks after the initial frequency adjustment, and the accumulated time differences after a further seven weeks were + 4.1 μs for H3940 and + 23.2 μs for L3311. One additional measurement with Unit H4548 showed a monotonic change of a total of -2.5×10^{-11} in three months, compared with H3368.

We have not made extensive calculation of the variance for shorter periods because this requires recording with enhanced resolution. One measurement for L3311 and H3368 combined gave the two-hour variance value of 2.3×10^{-13} and the one-hour value of 1.9×10^{-13}. Unit H3940 is distinctly less stable for the shorter periods, and the one-hour variance for it combined with L3311 was 3.7×10^{-13}.

Unit H5415 was put on test in October 1981 but the frequency instability is so much worse than for any other unit that accurate characterization would require extraordinary care. Frequency changes of 1×10^{-11} in ten minutes and 3×10^{-12} in one hour were observed.

TABLE 5

Combined Variances for 6, 12 and 24 Hour Intervals

Units H3940 and H3368. April 17 to 27, 1981

INTERVAL	STARTING TIME FOR INTERVALS								ALL TIMES
	1100	1300	1500	1700	1900	2100	··	0900	
6 Hour Variance x 10^{-13}	3.76	3.47	4.33						3.96
12 Hour Variance x 10^{-13}	4.9	4.46	3.73	3.28	3.83	5.09			4.28
24 Hour Variance x 10^{-13}	5.06	5.19	4.7	4.89	4.35	4.21	··	5.67	4.95

Unit H3368 has occasionally displayed a sudden positive jump in frequency lasting about half an hour and then returning to the previous value. The largest change seen was $+5 \times 10^{-11}$. Coincidentally, these changes have usually occurred at night or on weekends, although smaller changes have occurred while the recording was being observed.

On Sunday August 9, 1981, unit L3311 lost lock of three occasions in a six-hour period, operating in the search mode for approximately half an hour on the second occasion. Full recovery after regaining lock took five hours. The resultant effect was a time loss of 6 µs in 11 hours equivalent to a mean frequency difference of -1.5×10^{10}. This is the only occasion when loss of lock has occurred without power failure.

Various difficulties were encountered in the experiments with the portable clocks but not with the rubidium oscillators. Two successful experiments gave a maximum change of 75 ns between any pair after returning some 7 hours later. This change is less than the 100 ns resolution of the counters. The tests were made in hot weather and temperatures were higher than allowed for during transportation.

VIBRATION

The effects of vibration were measured using a Ling Model A300 shaker at the Air Force Geophysics Laboratory. Preliminary tests showed that the stray magnetic-field effect on M100-018 was negligibly small after a few minutes delay.

Resonance effects were explored with sine wave excitation over the range 20-2000 Hz. The frequency difference compared with a reference was set to a small value before testing and both the phase difference and the varactor voltage were recorded. The recorder response falls above 2 Hz to about one tenth amplitude at 20 Hz.

When vibrated at a frequency close to the servo carrier frequency (nominally 127 Hz) the 10 MHz output changes were dependent upon the excitation rate of sweep. Results of a slow sweep, with reversals in sense around 130.5 Hz, using unit H4548, are shown in Figure 4. The varactor voltage showed modulation of approximately 1×10^{-9} peak-to-peak, which was undetectable as phase modulation until the vibration frequency was close to that of the servo. The phase excursions for low beat frequencies became quite significant, and in many of the tests the units lost lock for vibration at this frequency, or even at some harmonic.

M100-018 was vibrated along the optic axis and the two axes designated A & B in Figure 5. The inclination of 22 1/2° with respect to the sides is a consequence of fitting the unit within the circle of bolt holes used on the shaker table.

The performance of M100-018 was clearly best for vibration along the optic axis, whereas the turnover effects were worst along this axis. Pronounced effects were produced in the frequency range 20 to 50 Hz, and 90 to 100 Hz, where the phase change averaged about 2 ns per second (2×10^{-9}) for excitation of 3g amplitude. There was no loss of lock, but strangely, there was as much effect when passing 250 Hz as when passing 125 Hz. The vibration frequency range of 20-2000 Hz was swept through in 13 1/2 minutes, i.e. at a rate of 1% per 2 seconds. When vibrated along axis A there were marked effects. At 3g peak amplitude the average frequency change was more than $+3 \times 10^{-9}$ when the vibration frequency was below 30Hz, but then changed sense to -5×10^{-10} for vibration in the range 40 to 110 Hz. In the vibration frequency range 375 Hz to 750 Hz the unit was out of lock for two minutes.

For axis B the frequency change was as large as 10^{-8} for vibration below 30 Hz. There was a phase transient at 125 Hz, a small effect at 250 Hz and loss of lock from 375 Hz to approximately 480 Hz (about one minute).

Unit H4548 performed much better, but when vibrated at 130 Hz along the optic axis the servo went out of lock for a vibration amplitude greater than 0.42g. Except for this problem, the phase changes were small although varactor voltage resonances were displayed at 105, 210, 330, 390, 1500 and 2020 Hz. Other effects were probably associated with vibration harmonics coinciding with 130 or 390 Hz. Only the resonance at 105 Hz caused a significant phase change, of about -12 ns with a vibration amplitude of 1g.

Tests on unit H4548 along the two axes normal to the sides showed that the axis normal to the labelled side was best, with only small changes in varactor voltage displayed at 130, 260 & 390 Hz. The biggest change of 0.2 volt occurred in the region 1950 to 2010 Hz. The only change in the 10 MHz phase was about 1 ns at about 45 Hz vibration.

Tests with noise excitation (white from 15 to 1000 Hz, falling by 6 dB at 2000 Hz, viz. MIL-STD-810C Figure 514.2-224) were made on M100-018, with the results summarized in Table 6. We suspect that the frequency change is mainly caused by the low frequency noise, in view of the effects observed with sinusoidal vibration.

Unit H4548 was tested for 15 minutes with noise excitation of $.04g^2$/Hz. This was the maximum time obtainable before the thermal overload switch of the shaker tripped open. Only brief tests with noise were made for the other two axes since our objective was to prove that the deficiencies of M100-018 were not endemic to the basic design.

Figure 6 shows the record of the five-minute run on M100-018 for noise vibration of 6.4g rms along the optic axis. Figure 7 shows a portion of the 15 minute record for noise vibration of 8g along the best axis for H4548. The frequency fluctuated by 'parts' in 10^9, but the average rate was only about 2×10^{-10} since the net change was less than 150 ns in 900 seconds, and should be compared with the results shown in Table 6.

Table 6

Noise Vibration M100-018

Noise Level		
Density g^2/Hz	rms 'g'	Average Frequency Difference
.0004	0.8	-3×10^{-11}
.0016	1.6	-11×10^{-11}
.0064	3.2	-30×10^{-11}
.0256	6.4	Approximately -100×10^{-11}

We believe that the difficulties encountered with vibration at the servo frequency will be overcome by using vibration isolators. However with units that are affected by vibration below 30 Hz, it will be necessary to use isolators having a very low resonant frequency.

FUTURE POSSIBILITIES

It is contended that, by the 1990s, there will be many avionics systems requiring accurate time and that the needs of all will be best satisfied by each aircraft carrying a master clock. We believe that clock should use a rubidium cell.

Many systems will be designed to operate from an internal standard that will, perhaps, be a common design of crystal oscillator.(5) However, with a master clock in the aircraft the systems could be designed so that when the master is available it automatically corrects all timing and provides a reference for the frequencies of internal oscillators. The planning of this conceptual use of absolute time will need to be flexible. We fear there is risk of encountering major difficulties before the operational stage is reached because of unforeseen, or ignored, human factors.

Some of the areas requiring special attention are:

- engineering design of a clock package to reduce the environmental effects of vibration, temperature, pressure, magnetic fields and power supply transients;
- choice of the technique that will best serve to ensure accurate synchronization before take-off;
- provision of redundant dissemination techniques in the many links between the USNO and tactical aircraft.

We believe that the best way to transfer time to an aircraft from the local time center will be to carry on a small clock rather than a signal transmission (although a laser system could satisfy the need for covertness). Consequently, we envision that a crew member will carry the master clock on board where it will be plugged into its special mounting. The internal battery will have a capacity of, perhaps, only 10 minutes. Use of the master, directly, should be superior to carrying out a clock to synchronize the on-board clock after warm up.

To provide this facility every base will need a Time Center in which an appropriate number of portable units will be kept in continuous operation. The portable master clocks can be monitored and adjusted periodically. Pick-up of a clock will become a part of the scramble drill.

On the basis of our experience with compact rubidium-controlled oscillators we believe that it will eventually be possible to achieve better than one microsecond accuracy on tactical aircraft with a unit that can easily be carried on a belt or by hand.

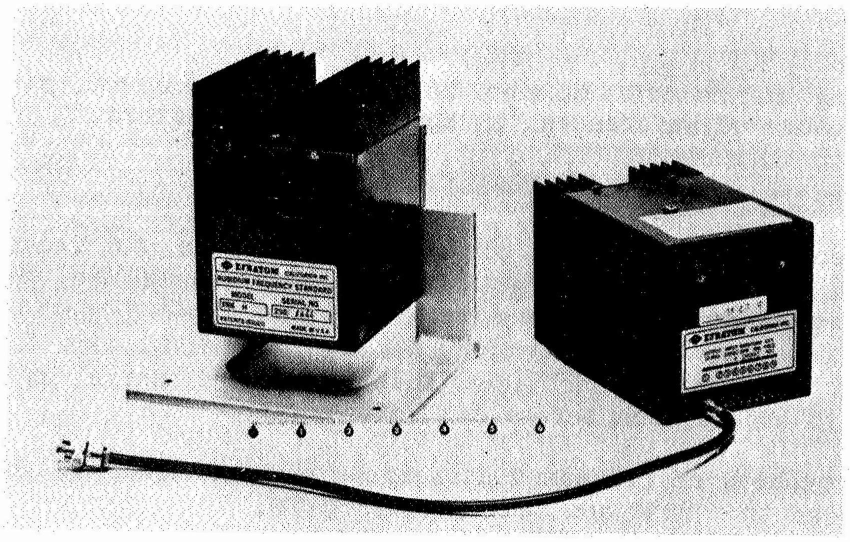

Figure 1. Efratom Units

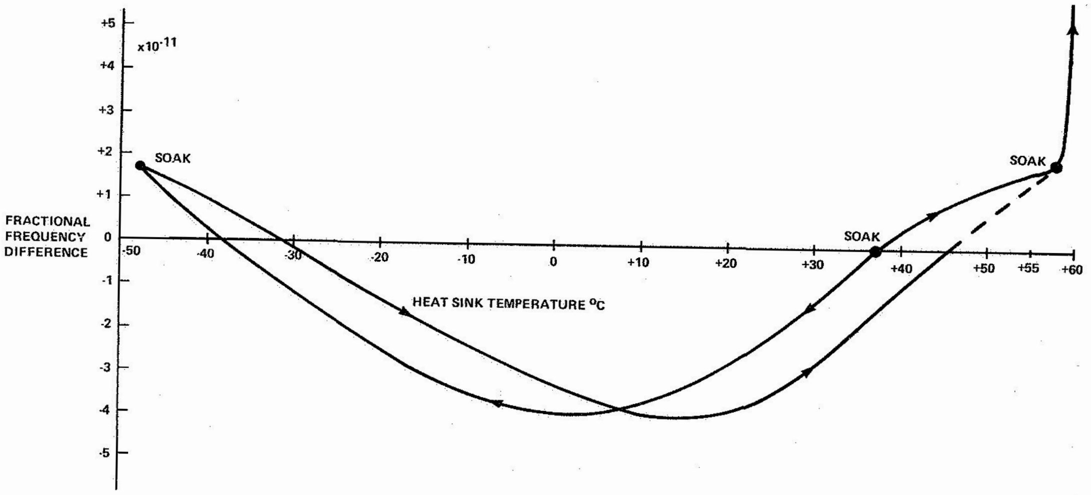

Figure 2. M100 Serial 018 Frequency Dependence On Temperature

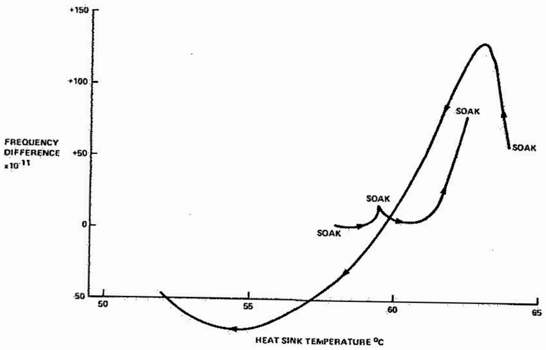

Figure 3. Thermal Transient Effects M100 Serial 018

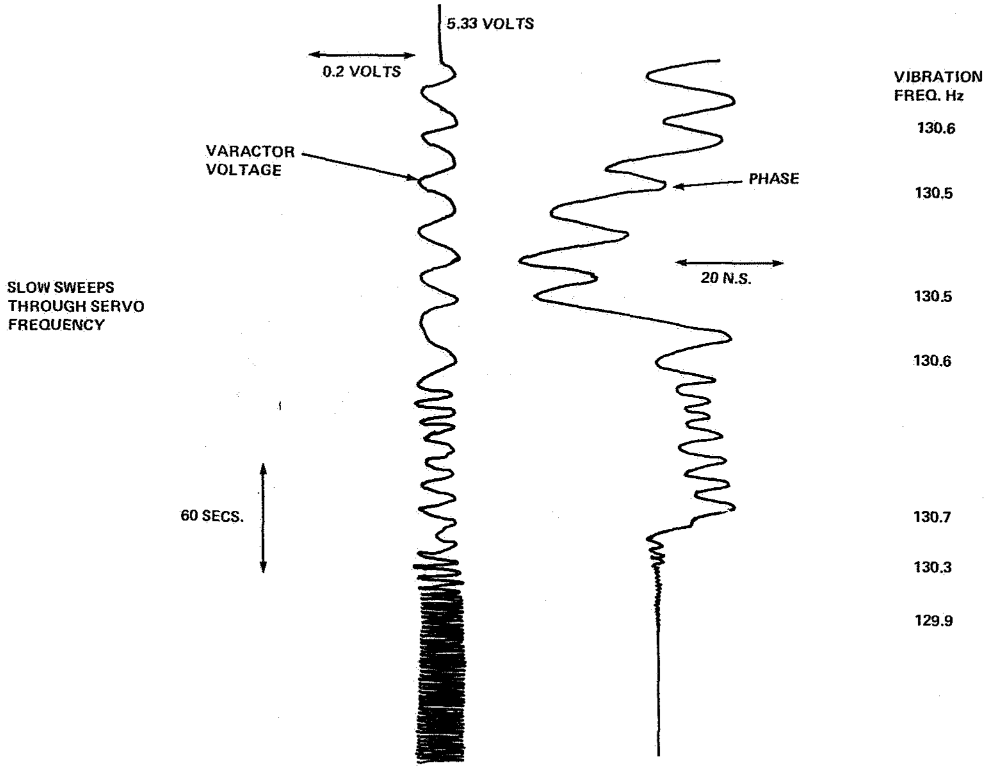

Figure 4. FRK-H 4548 Sine Wave Vibration 0.7g RMS Axis Normal To Labelled Side

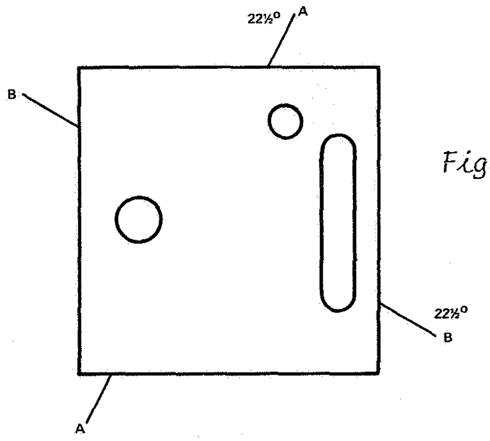

Figure 5. Vibration Axes M100

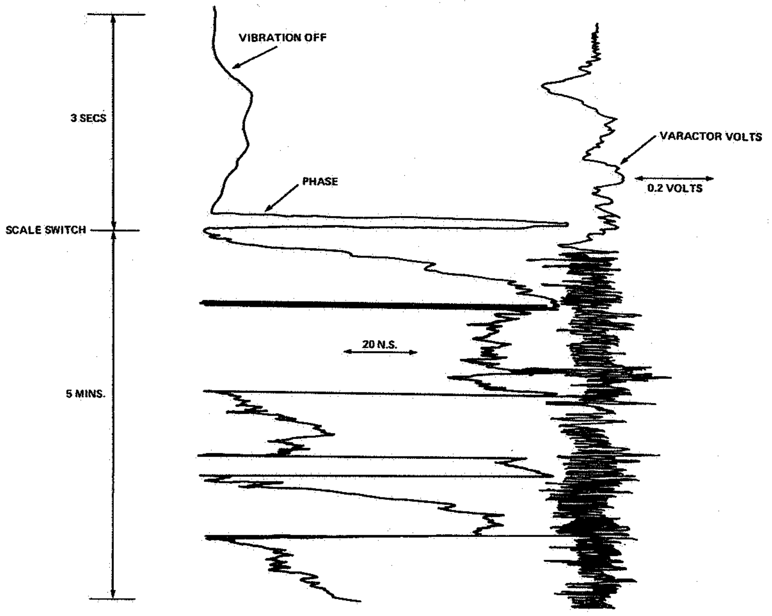

Figure 6. Noise Vibration M100-018.
$.026g^2$/Hz Optic Axis Oct. 20/80

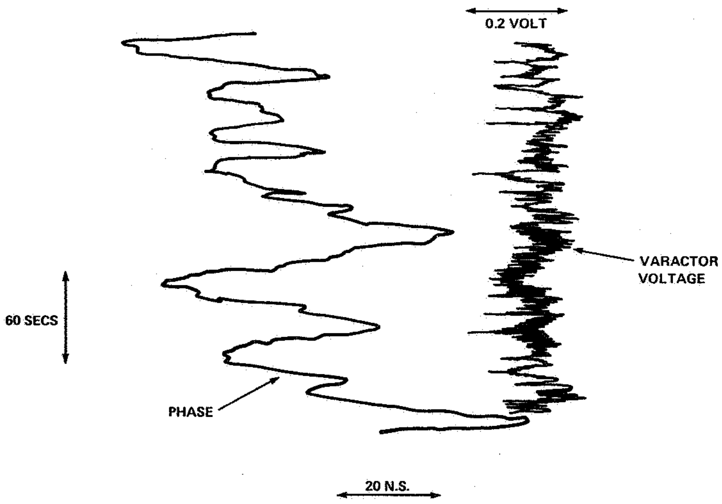

Figure 7. Noise Vibration FRK-H4548 Oct. 28/80
$.04g^2$/Hz Normal To Labelled Side

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