THE RUBIDIUM-CRYSTAL OSCILLATOR HYBRID DEVELOPMENT PROGRAM

by

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ABSTRACT

The rubidium-crystal oscillator hybrid (RbXO) will make precise time available to systems that lack the power required by atomic frequency standards. The RbXO consists of two subassemblies in separate enclosures. One contains a small rubidium frequency standard (RFS) without its internal oven-controlled crystal oscillator (OCXO), plus interface circuits. The second contains a low-power OCXO, and additional interface circuits. The OCXO is ON continuously. Periodically, e.g., once a week, the user system applies power to the RFS. After the few minutes necessary for the warmup of the RFS, the interface circuits adjust the frequency of the OCXO to the RFS reference, then shut off the RFS. The OCXO enclosure is separable from the RFS enclosure so that manpacks will be able to operate with minimum size, weight, and power consumption, while having the accuracy of the RFS for the duration of a mission.

A prototype RbXO's RFS has operated successfully for 4200 ON-OFF cycles. Parallel efforts on a Phase II RbXO development are in progress. Two sources for the RbXO are scheduled to be available during 1986.

INTRODUCTION

The rubidium-crystal oscillator hybrid (RbXO for short) is intended to satisfy the requirements of systems that need frequency (or clock) accuracies that are currently beyond the capabilities of crystal oscillators, but which cannot tolerate the high power consumption of atomic frequency standards.

Rubidium frequency standards (RFS) typically have about 100 times better long-term stability than the best oven-controlled crystal oscillators (OCXO's). RFS's, however, also consume about 100 times more power than the lowest-power-consuming OCXO. The RbXO will provide the best qualities of both types of oscillators, i.e., it will have the long-term stability of a RFS with only slightly more power consumption than the OCXO.

PRINCIPLE OF OPERATION OF THE RbXO

A RFS normally consists of an atomic (Rb) resonator, an oven controlled crystal oscillator (OCXO), plus multiplier and feedback circuits, in a single enclosure. The RbXO consists of two subassemblies in separate enclosures. One contains a small RFS, without the OCXO, plus interface circuits. The second contains a low-power OCXO and additional interface circuits. The OCXO is ON continuously. Periodically, the user system applies power to the RFS. After the few minutes necessary for the warmup of the RFS, the interface circuits adjust the frequency of ("syntonize") the OCXO to the RFS reference, then shuts off the RFS. For manpack applications, the OCXO subassembly will be separable from the rest of the RbXO so that the manpack can operate with minimum size, weight, and power consumption, while having nearly the accuracy of the RFS for the duration of a mission.

The following will illustrate how the RbXO is expected to operate. The RFS is expected to be able to maintain a frequency accuracy of $\pm 1 \times 10^{-9}$ for a period of ten years when operated in a duty-cycling mode (e.g., 5 minutes ON time per week). The OCXO can be expected to have an aging (or "drift") rate of better than 1×10^{-10} per day when operated for extended periods, and a maximum frequency offset, due to all other factors, of $\pm 1 \times 10^{-9}$. One can then determine the worst-case time errors for various scenarios. For example, if the RbXO syntonizes the OCXO once a week, then, for any period of a month after synchronization, the RbXO will be able to maintain a time accuracy of better than ten milliseconds (i.e., under this scenario the worst-case offset would be 2.7×10^{-9}).

For comparison, the same OCXO without the RbXO would accumulate an offset, due to aging alone, of about 3×10^{-8} one year after its calibration. At that time, it would be able to maintain an accuracy of only 100 msec for a one month resynchronization interval. If the user needed 100 msec per month or better accuracy, then the OCXO would have to be returned to depot for recalibration at intervals of one year or less.

POTENTIAL RbXO APPLICATIONS

One can envision several potential military applications for the RbXO. Examples are:

1. Manpacks and teampacks
2. Vehicles - where, although sufficient power is available for a RFS while the vehicle generator is ON, precise time must be maintained even when the generator is OFF.
3. Troop transport vehicles - after the vehicle transports the troops into the field, the RFS stays with the vehicle, the OCXO's in the manpack(s) are disconnected from the RFS at the start of a mission, and are reconnected at the conclusion of the mission,
4. Missiles and remotely piloted vehicles (RPV) - the RFS stays with the launcher, the OCXO goes with the missile or RPV.

THE OCXO

A miniature, low-power OCXO is a key part of the RbXO. The main candidate for this is the Tactical Miniature Crystal Oscillator (TMXO),[1] which is currently the subject of a Manufacturing Methods and Technology contract with Bendix, Inc. Since the TMXO is not yet available in production quantities, and in order to minimize the risk associated with this task, the RbXO technical requirements specify that "The RbXO interface shall be capable of interfacing with either a 10 MHz TMXO, or any 10 MHz Hewlett-Packard 10811 equivalent OCXO, or any comparable stability OCXO." If, for whatever reason, the TMXO is not available, the power consumption of the RbXO would be higher because other OCXO candidates consume several times more power.

RbXO ENERGY CONSUMPTION AND TIME AND FREQUENCY UNIT

Significantly lower energy consumption is one of the major advantages of the RbXO over continuously operated RFS's. A comparison of the expected RbXO performance with: the performance of a RFS; the expected performance of production TMXO's; and an HP 10811 type OCXO (e.g. the Piezo Crystal model no. 007) is shown in Table 1. The comparison is based upon the Efratom M1000 specifications for the RFS, the use of the TMXO for the OCXO of the RbXO, and assumes that a pair of lithium batteries[2] (BA-5590/U) are available for powering the oscillators. The RbXO increases the battery life from less than a day with a continuously operated RFS, to 52 days.

Each BA-5590 has a capacity of about 6.5 Ah, and a volume of 883 cm^3. Therefore, a "time and frequency unit" consisting of an RbXO, two BA 5590's, a time code generator and a frequency distribution system could operate continuously without battery replacement for over a month while occupying a volume on the order of 3200 cm^3 (195 in^3), e.g., a box of size 14 cm X 15 cm X 15 cm (5½" X 6" X 6").

PHASE I RbXO DEVELOPMENT

During Phase I of the RbXO Development effort (under an FY-83 contract with Efratom, Inc.), a breadboard RbXO was designed and constructed. The breadboard consists of an Efratom M1000 RFS, and an interface box that contains the interface circuits, a government furnished miniature OCXO (the "TMXO"), a time-of-day clock, and a timer with which the ON-OFF intervals of the RFS can be set. The dimensions of the interface box are about 17" X 16.5" X 6". A copy of the Phase I final report is available to qualified requesters from the Defense Technical Information Center.[3]

RbXO PROTOTYPE TEST RESULTS

As the reliability under intermittent operation is a major uncertainty about the RbXO approach, as soon as the RbXO prototype was received in April 1984, it was placed on test at laboratory ambient temperature. The interface box was set to turn on the RFS once an hour for 5 minutes each time. The time error was measured by comparing the RbXO's 1 pps output with that of a Hewlett-Packard 5601 cesium standard.

During the first 700 hours (i.e., 700 on-off cycles), the average time error was about 8 microseconds per day. Changing the ON time changed the slope of the accumulated time error curve; e.g., increasing the ON time to 6 minutes resulted in a slope of about 10 microseconds per day (which corresponds to an average frequency offset of 1.2 X 10^{-10}). The variation of time error with ON time was the result of the variation of the RFS's frequency offset with warmup time.

	RFS alone	RbXO with TMXO	TMXO alone	HP 10811-type OCXO's alone
Power consumption at -55°C	20W	0.35W	0.25W	4W
Power consumption at 0°C	17W	0.25W	0.15W	2.5W
Battery life, at 0°C, with two BA-5590/U's	18 hours	52 days	86 days	5 days
Size	790 cm^3	<1300 cm^3	17 cm^3	230 cm^3
Aging per year (1st year)	2×10^{-10}	6×10^{-10}	3×10^{-8}	3×10^{-8}
Short term stability $\sigma_y(\tau)$ 1 sec $\leq \tau \leq$ 10 sec	3×10^{-11} (τ ½)	5×10^{-12}	5×10^{-12}	5×10^{-12}
Temperature stability	3×10^{-10} -55°C to +68°C	1×10^{-9} -55°C to +68°C (RFS) -55°C to +90°C (TMXO)	1×10^{-9} -55°C to +90°C	1×10^{-8} -55°C to +71°C

Table 1. Oscillator comparisons

After about 1500 on-off cycles, the RFS was cooled to -45°C, while the interface box remained at laboratory ambient. The slope of the time error vs. elapsed time changed to -25 microseconds per day. After about 90 on-off cycles at -45°C, the RFS's internal crystal oscillator failed to hold lock; i.e., it would lock for a few seconds, then unlock, then lock, etc. When the temperature was increased gradually, reliable locking started to occur at about +10°C. After cooling again, the failure to lock was reproduced.

The RFS was returned to Efratom for failure analysis. Efratom confirmed the failure at low temperatures and determined that the cause of failure was insufficient gain in the crystal oscillator circuit. Replacement of the crystal oscillator and resetting the crystal oscillator gain corrected the problem. Since the RFS in the Phase II and production RbXO's will not contain an internal crystal oscillator, this failure is not significant.

After receipt of the repaired RFS, the on-off cycling was continued at room ambient for 1176 cycles. The RFS was then temperature-cycled daily for 38 days between -55°C and +70°C, and on-off cycled about hourly during this 38 day period, for a total of 840 on-off cycles. The time error was measured each day after stabilizing the temperature at 60°C. The accumulated time error vs. elapsed time had a slope of -51 μsec per day, as shown in Figure 1, indicating a constant frequency offset of -5.9×10^{-10}.

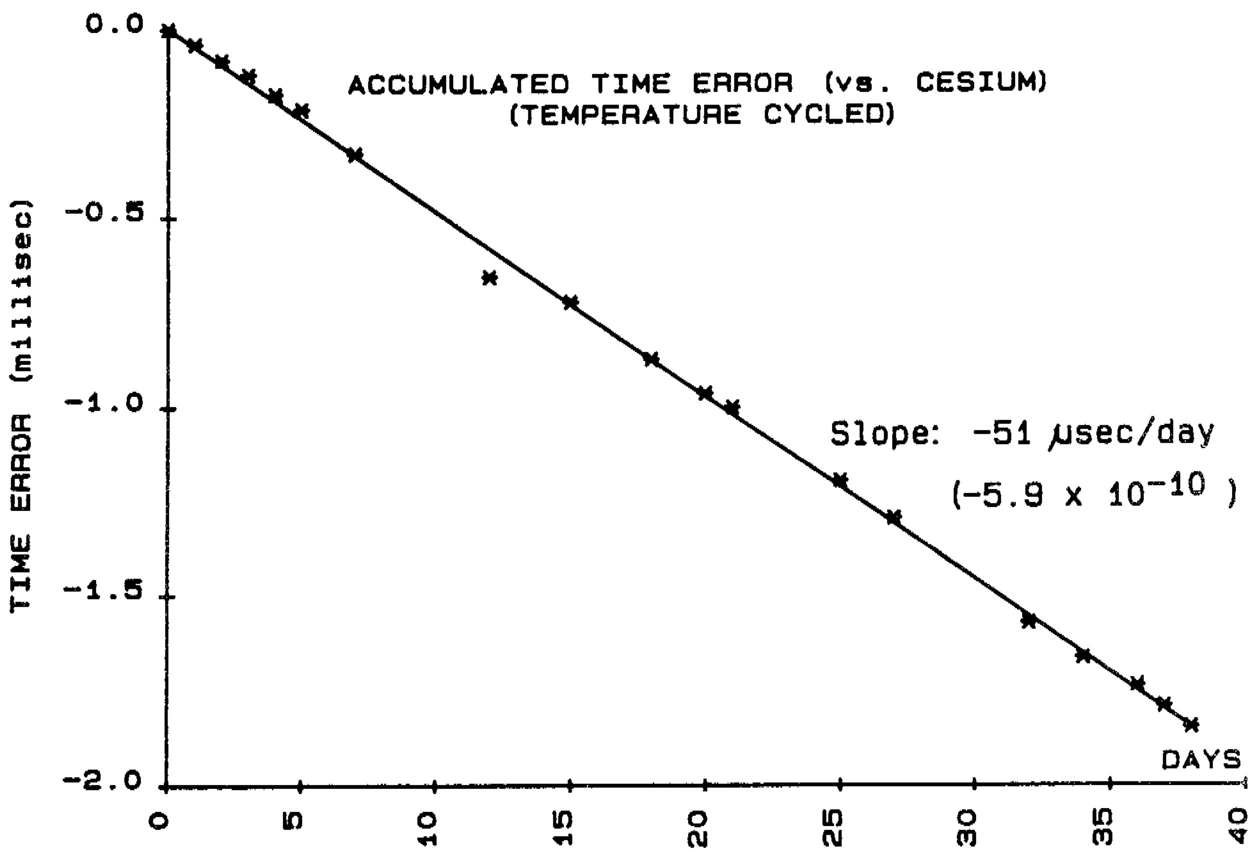

Figure 1. Time error vs. elapsed time

During the temperature cycling, frequency vs. temperature data was collected once a week during a cycle from -55°C to +70°C to -55°C. The RFS was ON continuously during the frequency vs. temperature run. The result of one such run is shown in Figure 2. The frequency excursion was within the M-1000's 3 X 10^{-10} specification.

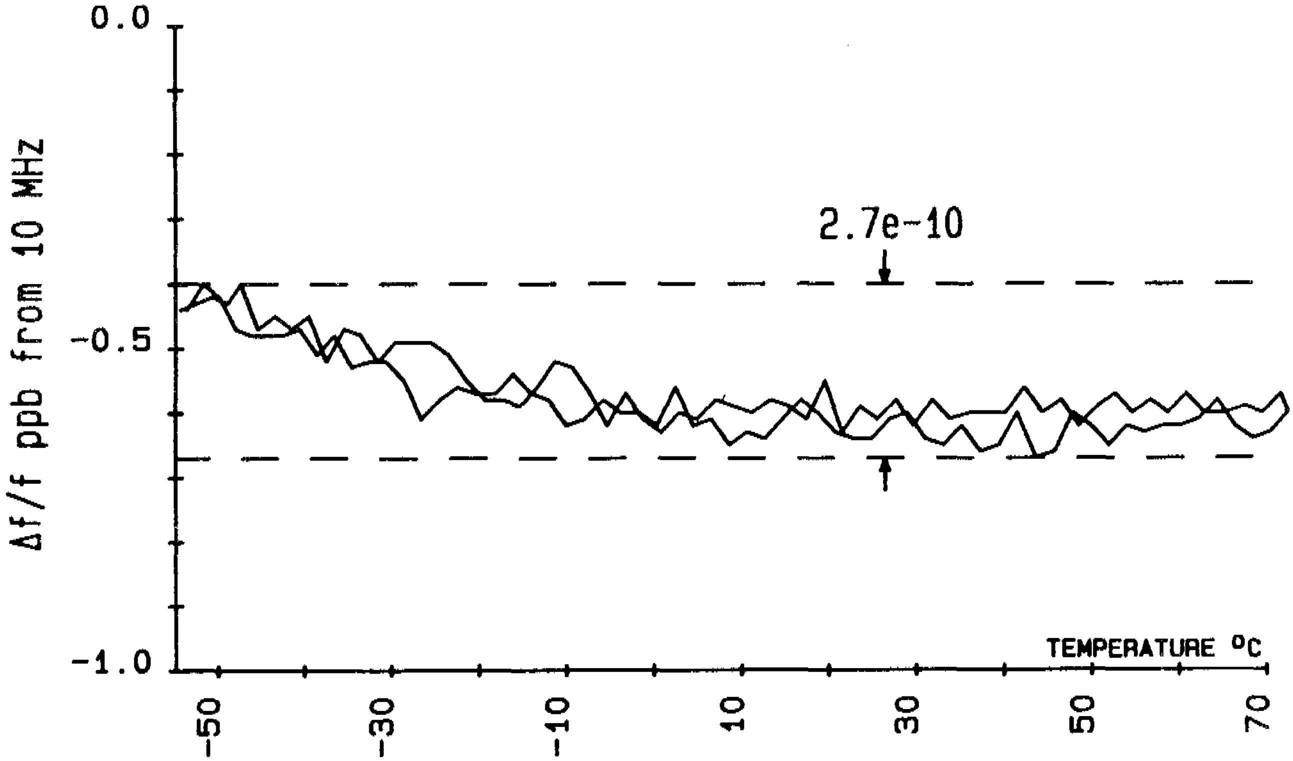

Figure 2. RFS frequency vs. temperature characteristic.

The on-off cycling history of the RbXO prototype RFS is summarized in Table II. The summary includes 600 cycles the RFS experienced at Efratom prior to shipment. That the RFS stayed within specifications for over 4200 on-off cycles (aside from the failure of the RFS's internal crystal oscillator) is very encouraging because it indicates that inherent failure mechanisms due to on-off cycling do not exist. Of course, additional units need to be tested. Sixteen additional units are scheduled to be tested during the Phase II RbXO development, as is described below.

Upon completion of the 4206 on-off cycles, the RbXO prototype RFS was placed on long-term aging while continuously ON, initially at 23°C. The results for the first 44 days at 23°C are shown in Figure 3. (Straight lines in the curve indicate that no data was collected during the period.) On day 12, a momentary power interruption resulted in a frequency offset of -4 X 10^{-11} and an increased aging rate. On day 25, an intentional 10-second power interruption returned the frequency to its previous value. The cause of this "glitch" has not yet been determined. However, if we ignore the offsets, the total aging is 7 X 10^{-12} in 44 days, and the aging rate at day 44 is about 1 X 10^{-13} per day.

RbXO BREADBOARD RFS HISTORY

(APRIL 1984 TO NOVEMBER 1984)

# ON/OFF CYCLES	TEMP	TIME ERROR/DAY	REMARKS
600	23	– – –	AT EFRATOM
1500	23	8 μSEC AVG	
90	−45	ERRATIC	INTERNAL XO FAILED
1176	23	– – –	NO DATA TAKEN
840	T CYCLED	51 μSEC AVG	−55 TO 70 DEG. C
4206	VARIOUS	– – –	TOTAL NUMBER OF CYCLES.

TABLE II

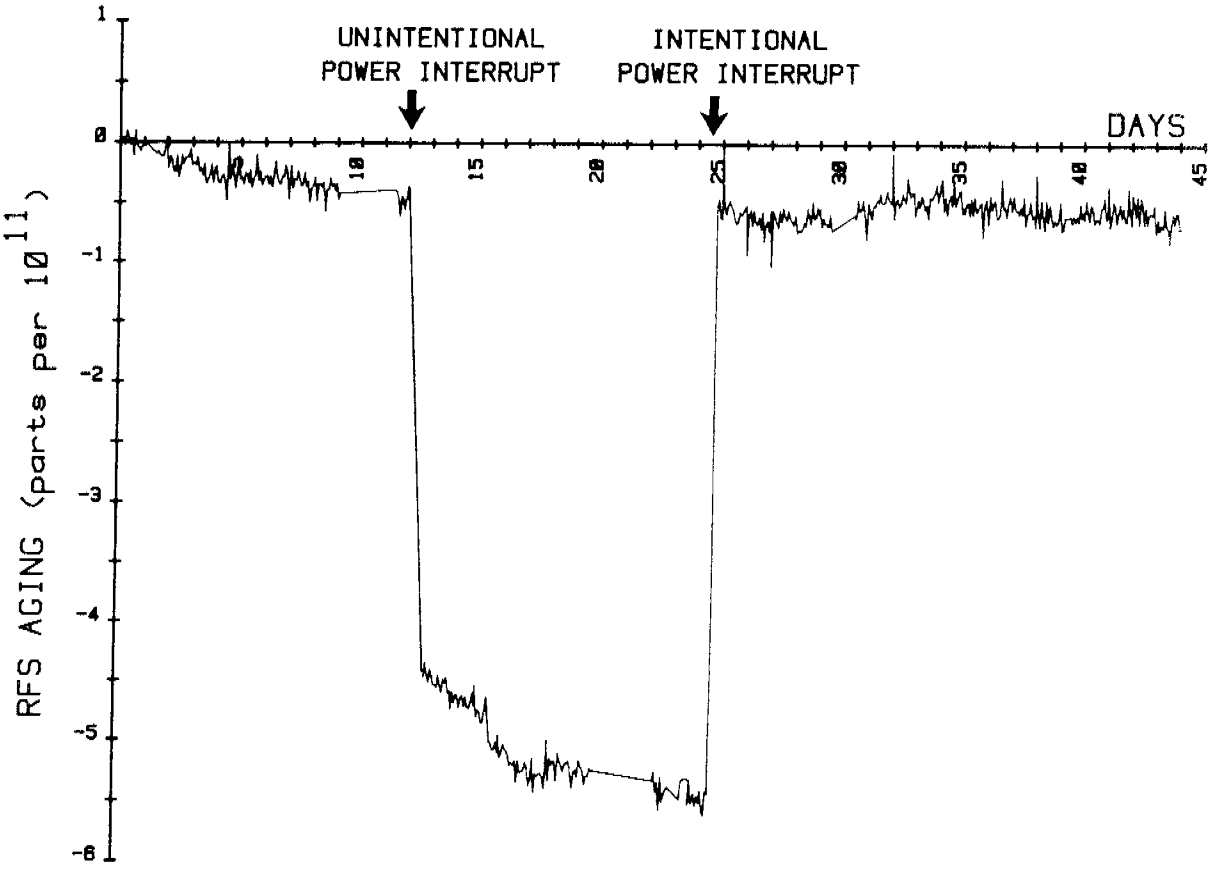

Figure 3. RFS aging after 4200 on-off cycles

PHASE II RbXO DEVELOPMENT

On 26 June 1984, two firm fixed price contracts were signed for Phase II of the RbXO program, one with the Efratom Division of Ball Corp., the other with E.G.& G., Inc. The total cost of the two contracts is $668,000. Both companies are to meet the same requirements and both programs are of 18 months duration. Salient features of the requirements are:

1) Size: 80 cu. in. (517 cm^3) plus the size of the OCXO
2) Operating temperature range: -55°C to +68°C
3) RFS thermal retrace/hysteresis: 5×10^{-11} at all operating temperatures
4) RFS frequency vs. temperature: $\pm 4 \times 10^{-10}$
5) RFS aging after 30 days at 60°C ambient: 1×10^{-12} per day
6) Power consumption at -55° (after warmup): 23W for the RFS, 80mW for the interface circuits
7) Hardened to tactical radiation levels,
8) Usable with 5MHz and 10MHz OCXO's
9) Deliverable hardware from each contractor: 8 RbXO's, four of which have passed the design verification test, plus four which are to be tested by the government, and 3 RbXO demonstrators that include a digital clock and timer for turning the RFS ON periodically.

THE DESIGN VERIFICATION TEST

This requirement of the Phase II RbXO development calls for the RbXO to be temperature-cycled from -55°C to +68°C to -55°C once a day, and for the RFS be turned ON and OFF twenty times a day for a total of 3600 on-off cycles, according to a specified schedule. This test is intended to uncover failure mechanisms and stability changes due to the duty cycling mode of operation.

Prior to this program, there had been only hearsay type of information on the stability and reliability of RFS's operating intermittently. A major goal of the Phase II RbXO program is to determine the degree of risk due to the intermittent operation and to minimize the risk through proper RbXO design. A second goal is to determine the stability of RFS's under intermittent operation.

RbXO SCHEDULE

The RbXO program schedule of major milestones is as follows:

1. Breadboard phase: complete
2. Design and build: August 1984 to March 1985
3. Design verification test by contractors: March 1985 to September 1985
4. Delivery of the 16 RbXO's to government: Oct - Nov 1985
5. Design verification tests by government: December 1985 to June 1986
6. Government long-term tests start: July 1986.

Milestones 3 to 6 assume that the contractors' design verification tests are successful on the initial attempts. If failures occur, contractors will have to correct the problem and repeat the tests. The schedules will then slip.

CONCLUSIONS

The RbXO will make precise time available in systems that lack the power required by atomic frequency standards. The feasibility of the RbXO has been demonstrated. That the prototype RFS has operated properly for 4200 on-off cycles is encouraging. (If the RFS is on-off cycled once a week, the 4200 cycles correspond to an 80 year life!)

Parallel efforts on the Phase II RbXO development are in progress. Two sources for the RbXO are scheduled to be available during 1986.

ACKNOWLEDGEMENTS

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REFERENCES

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