PERFORMANCE OF THE NEW EFRATOM OPTICALLY PUMPED RUBIDIUM FREQUENCY STANDARDS AND THEIR POSSIBLE APPLICATION IN SPACE RELATIVITY EXPERIMENTS

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ABSTRACT

Comparison of the new Efratom units with cesium beam and hydrogen maser standards at the U.S. Naval Observatory showed stability of $\sim 5 \times 10^{-12}$ over two-week periods in a normal laboratory environment. Dependence of frequency upon the environmental parameters of pressure, magnetic field, temperature, supply voltage, and acceleration was measured. A package of three units with automatic phase comparison and recording was designed and constructed to allow a measurement of relativistic effects on time with high accuracy on the Apollo-17 lunar mission. Although NASA management declined to fly the experiment, some aspects of the design and the relativistic effects to have been expected are presented. The technique has applications for ground-based PTTI activities as well as for future space flights.

INTRODUCTION

It has been very gratifying to the first author and others who worked on the original concept of rubidium optically pumped frequency standards in the 1950s after they were invented by Professor Robert H. Dicke of Princeton to see the excellent engineering exhibited in the new Efratom units. When we looked at the room full of equipment used in the first experiments, we jokingly said that eventually it could be reduced to the size of a matchbox. Ernst Jechart and Gerhard Hubner at Efratom have almost succeeded in producing a package approaching a kitchen-size matchbox!

Dimensions:	10 cm-by-10 cm-by-10 cm
Weight:	1.3 kilograms
Power:	13 watts

This small size allowed us to think realistically of assembling a package of three atomic clocks which could be flown to the moon and returned in the command module of the Apollo-17 mission, to measure the gravitational potential effect of general relativity with increased accuracy and to provide a highly convincing demonstration of the reality of the relativistic effects on time.

The large time difference (about 300 microseconds) to be expected from relativistic effects had been recognized during the first manned circumnavigation of the moon by the Apollo-8 astronauts in December, 1968.[1] For the longer Apollo-17 flight, the expected time difference was about 700 microseconds, of which 5 percent was due to the velocity and 95 percent was caused by the gravitational potential difference.

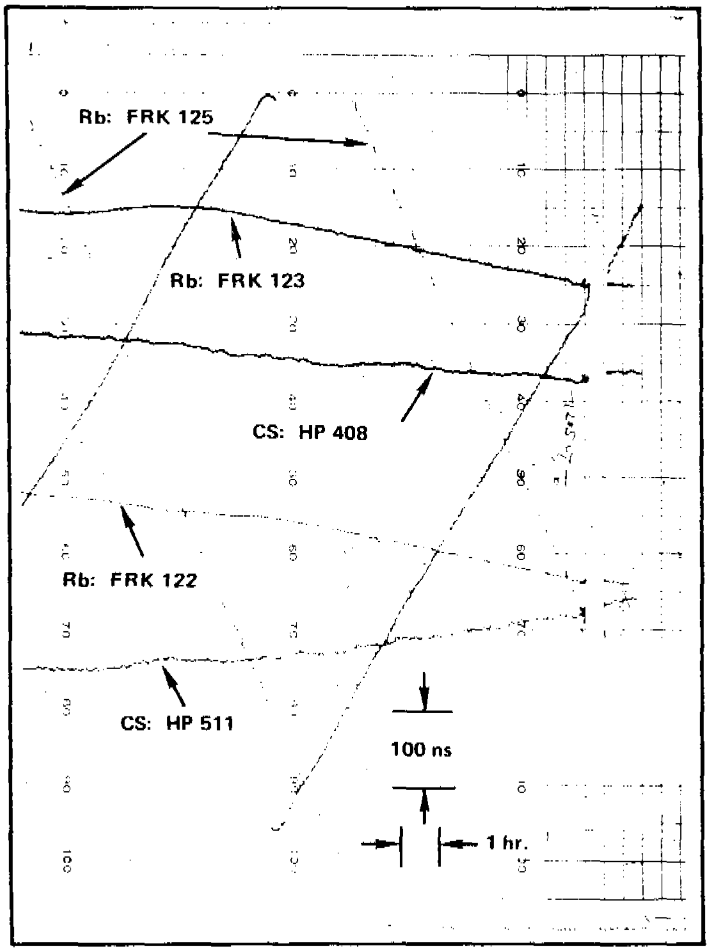
By measuring and recording the three relative phase differences among the three frequency standards it seemed possible to measure the elapsed time with an uncertainty of about 200 nanoseconds over the 296-hour flight. It is to be emphasized that the changes of individual clock rates can be recorded in this way, since such changes do not occur at the same time for each frequency standard. This technique is very old and is regularly used at the U.S. Naval Observatory to improve substantially the accuracy obtainable from straight statistical averaging. It formed the basis for the round-the-world clock experiment of Hafele and Keating,[2] which seems to demonstrate the existence of the relativistic effects with the Hewlett-Packard cesium-beam recording clocks which they carried. (The accuracy of this demonstration was not high since the effects were small and there was difficulty in knowing accurately the velocity and position of the commercial aircraft used.) For the well-tracked Apollo-17 flight an accuracy of 0.03 percent seemed achievable with a package of three Efratom units and intercomparison electronics. The best existing measurement of the gravitational potential effect, the Mössbauer Effect measurements of gamma-ray frequency changes by Pound, Rebka, and Snider,[3] has an accuracy of 1 percent. The possible opportunity to improve this accuracy by a factor of 30, by a completely different method using returned recording clocks (about which there is still continuing controversy), in a very credible experiment using available commercial equipment, suggested an all-out effort to produce the experiment hardware and to attempt to persuade the National Aeronautics and Space Administration to include the experiment on Apollo-17. Although the Apollo-17 measurement would have an accuracy less by a factor of ten than that claimed for the future rocket-probe hydrogen-maser experiment being developed by Vessot,[4] it had the virtues of redundancy, recovery of operating clocks, and immediacy, as well as the dramatic element involving the astronauts, which would be of great value for establishing the reality of the relativistic effects on time in the public consciousness. There was initial encouragement from NASA and a formal proposal was submitted from the University of Maryland. The Office of Naval Research provided financial support to begin the construction of a flight-qualified package in early August 1972. The scientific community gave very strong endorsement to the experiment. In interaction with Apollo spacecraft engineers at the Houston Manned Spacecraft Center and at North American Rockwell it was determined that space, weight, and power were all available, and a copper/water-vapor heat-pipe solution to the heat-transfer problem was identified. Clock intercomparison electronics was designed and constructed using integrated circuits, and a hermetically sealed box to house the clocks and electronics was built to fit the space available in the command module. Nevertheless, it was finally decided in early October by the NASA Administrator, upon the recommendation of the Apollo Program managers, that the short time before the launch (scheduled for December 6) and limited financial resources would result in risks to the mission if the atomic clock relativity experiment were carried, and the proposal was declined.

It is the purpose of this paper to record the performance characteristics of the Efratom frequency standards which we measured in preparing the experiment and to give some further details about the phase intercomparison electronics and packaging. It is expected that a self-contained ensemble of intercompared clocks will be of value for time synchronization trips and other PTTI applications, as well as in future space relativity experiments.

MEASURED PERFORMANCE OF EFRATOM FREQUENCY STANDARDS

The desirable properties of small weight, small volume, and low power consumption of these new units, which became available to us for tests only in July 1972, are further enhanced when associated with a frequency stability superior to that of most optically pumped standards and comparable over periods of hours with those of the typical cesium atomic beam standards. Data in support of this performance are displayed in Figures 1 and 2. The performance is much better than the manufacturer's specification of an upper bound for the frequency stability, $<10^{-10}$ per month, which was deliberately made conservative. The figures are portions of strip charts on which the phase of the output signal frequency (divided by two to yield five MHz) is compared with the phase of the USNO hydrogen maser. For ready comparison the phase of the signal from Hewlett-Packard Model 5061 cesium-beam clocks is displayed simultaneously. In Figure 2 the hydrogen maser reference frequency for the rubidium unit is progressively shifted in phase by an electronic "phase microstepper" so that rate changes of 10^{-13} can be identified. The fine performance of the rubidium unit is apparent. Similar performances have been seen in the other units tested, although two of the seven examined have exhibited a somewhat more noisy short-term performance.

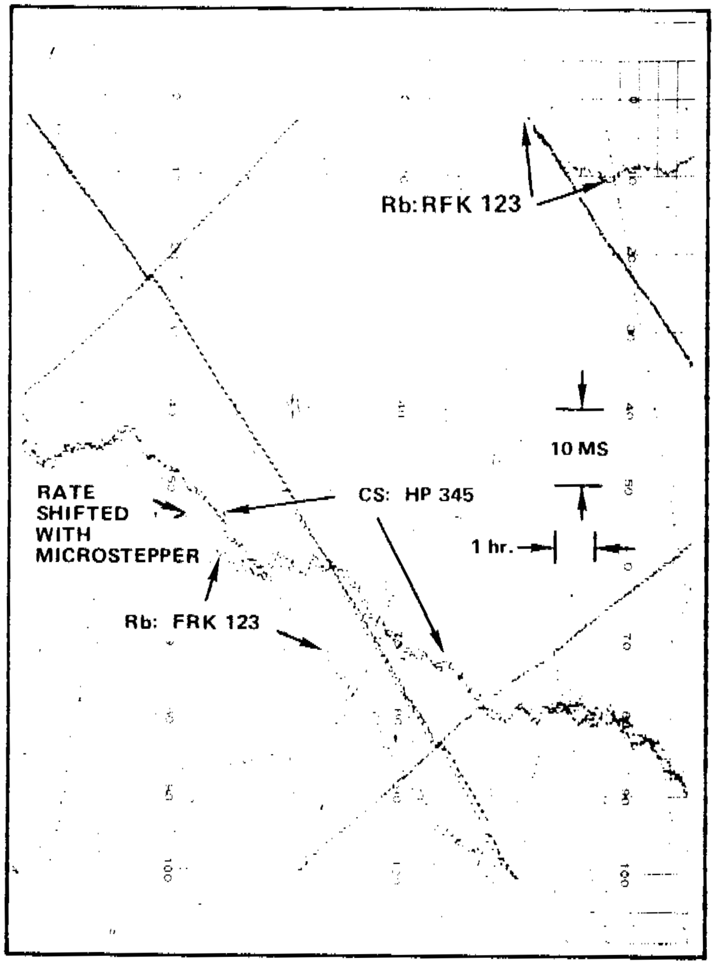
The data which originally convinced us of the quality of the Efratom rubidium units are summarized in Figures 3 and 4. The changes of phase of Efratom unit No. 111 with respect to one of the cesium-beam master atomic clocks of the USNO for the period July 14 to August 1, 1972 are displayed in Figure 2. There was no environmental control other than air conditioning. It became clear that changes of barometric pressure were influencing the frequency when the rates were calculated and plotted as a function of time along with the barometric pressure for the same period, as shown in Figure 4. Subsequent measurements of the pressure dependence of frequency were made by placing the unit in an aluminum pressure chamber yielding a pressure coefficient of 1.4×10^{-13} per millibar change from standard atmospheric pressure. Apart from the slow changes produced by barometric pressure changes, rate changes of a few parts in 10^{12} do sometimes occur, separated by many hours of operation in which the rate is constant to within a few parts in 10^{13}.



COMPARISON OF EFRATOM
FLIGHT UNITS WITH STANDARD
HP 16" CESIUM UNITS

Figure 1. Plot of results of comparison of Efratom and cesium-beam frequency standards.

Other environmental effects on frequency have also been measured for Efratom unit No. 111. These include the dependence on external magnetic fields, temperature, and supply voltage. The magnetic field dependence was measured with 40-inch-diameter Helmholtz coils arranged to give a field in the direction of the local earth field, with a uniformity of 1 percent over the volume of the frequency standard. With the direction of the field in the plane of the cooling fins and 30° from the vertical, the coefficient for small changes about the earth field value was found to be about $+8 \times 10^{-12}$ per gauss. This relatively large coefficient even in the presence of the two mu-metal shields included in the commercial unit suggested the packaging of the unit in two additional mo-permalloy nested boxes having a wall thickness of 50 mils and separated from each



COMPARISON OF EFRATOM
UNIT WITH STANDARD
16" HP CESIUM UNIT

0.1 MICROSECOND FULL SCALE

Figure 2. Plot of results of comparison of Efratom and cesium-beam frequency standards (continued).

other and from the mu-metal case of the frequency standard by about 1/8 inch. Tests with such shielding showed no discernible change in frequency (with resolution of 2×10^{-13}) for changes in the magnetic field equal to the value of the earth's field (~ 0.3 gauss) which would be experienced on a flight to the moon. The initial rough measurements on temperature dependence for unit No. 111 yielded a coefficient of $\sim +7 \times 10^{-13}$ per degree centigrade for the range 20°C to 40°C. Tests on the supply voltage dependence showed a coefficient of $+9 \times 10^{13}$ per volt for variations of a few volts about 28 volts.

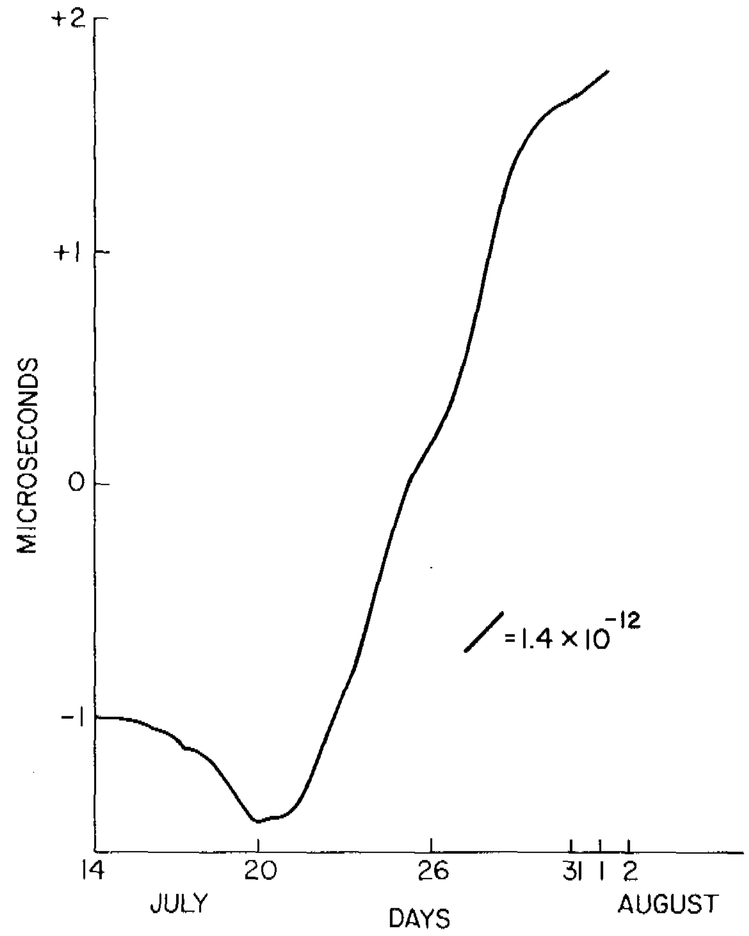


Figure 3. Phase of Efratom unit No. 111 versus USNO master clock, from July 14 to August 1, 1972.

The dependence of rate on the magnitude of acceleration was studied using the centrifuge at the Naval Research Laboratory. It showed a linear change of 8 X 10^{-11} in going by steps from zero to ten g along the optical pumping axis of the clock. No loss of phase lock was observed and recovery to the original rate was observed within the resolution available at that time for the field test (~ 10^{-12}). Other tests have been carried out on the changes of rate produced by turning the unit upside down in the earth's gravity field. For unit No. 111, a change of 2 g along the pumping axis produced a change of ~ 2 X 10^{-11}, consistent with the centrifuge results, with recovery to the original rate within a resolution of ~ 2 X 10^{-13}. Smaller changes were observed for rotations about axes perpendicular to the pumping axis. It is clear that the accuracy of measurement of the relativistic effects in space flight will depend on our ability to predict from tests of this sort the effect of the transition from one g to zero g in free fall.

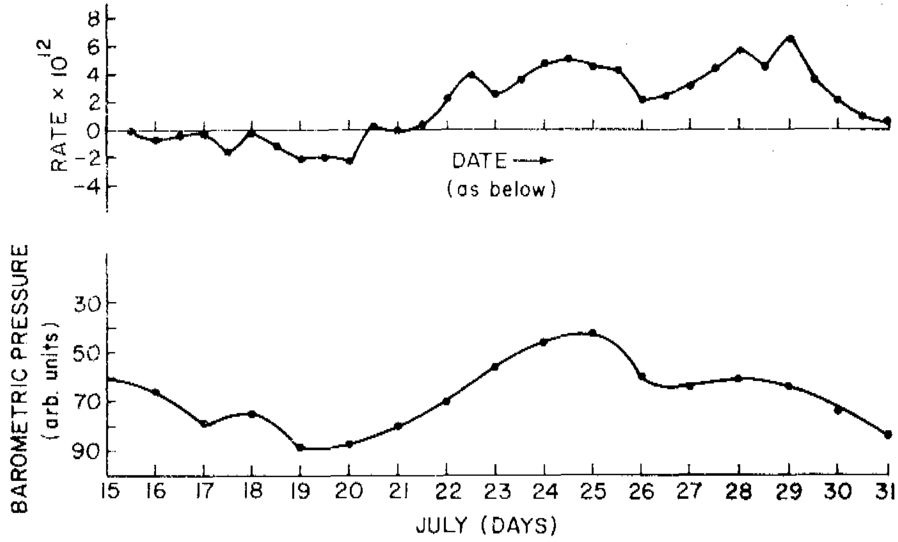


Figure 4. Effect of barometric pressure on Efratom unit No. 111 frequency rate: (top) rate obtained by plotting slope of phase graph (Figure 3); (bottom) barometric pressure over the same period – the points are daily means.

Vibration tests have not yet been conducted. Three units ruggedized for vibration were received from Germany on October 6. The ruggedization was accomplished by bonding certain electronic components to the circuit boards. The plans to conduct the vibration tests of these units before the Apollo flight-readiness test on October 15 had to be curtailed after the negative decision by NASA, since financial resources did not permit the round-the-clock work by large numbers of personnel which was required.

Three additional units have been examined for their frequency stability. They were found to perform as well on long term as Unit No. 111 and the three ruggedized units, although two units showed slightly more short-term noise.

To simulate the condition of no convective cooling which occurs in a free-fall environment, unit No. 111 was operated in its magnetic shields in a chamber evacuated to a pressure of 300 microns for a period of seven hours. Heat conduction was provided by fastening the inner mo-permalloy shield to the heat-transfer plate of the unit and providing a 1/8-inch copper plate between the inner and outer shields on the heat-transfer side of the nested boxes. This side of the package rested on the 1/2-inch aluminum bottom plate of the vacuum chamber. The temperature of the mu-metal case of the commercial unit was monitored using a thermistor. The temperature changed only from 44°C to 45.7°C, showing that a major part of the heat transfer is by conduction. The frequency was measured and showed no change within 2×10^{-12} during the vacuum operation except that change expected from the reduction of the pressure (a higher precision measurement was not attempted).

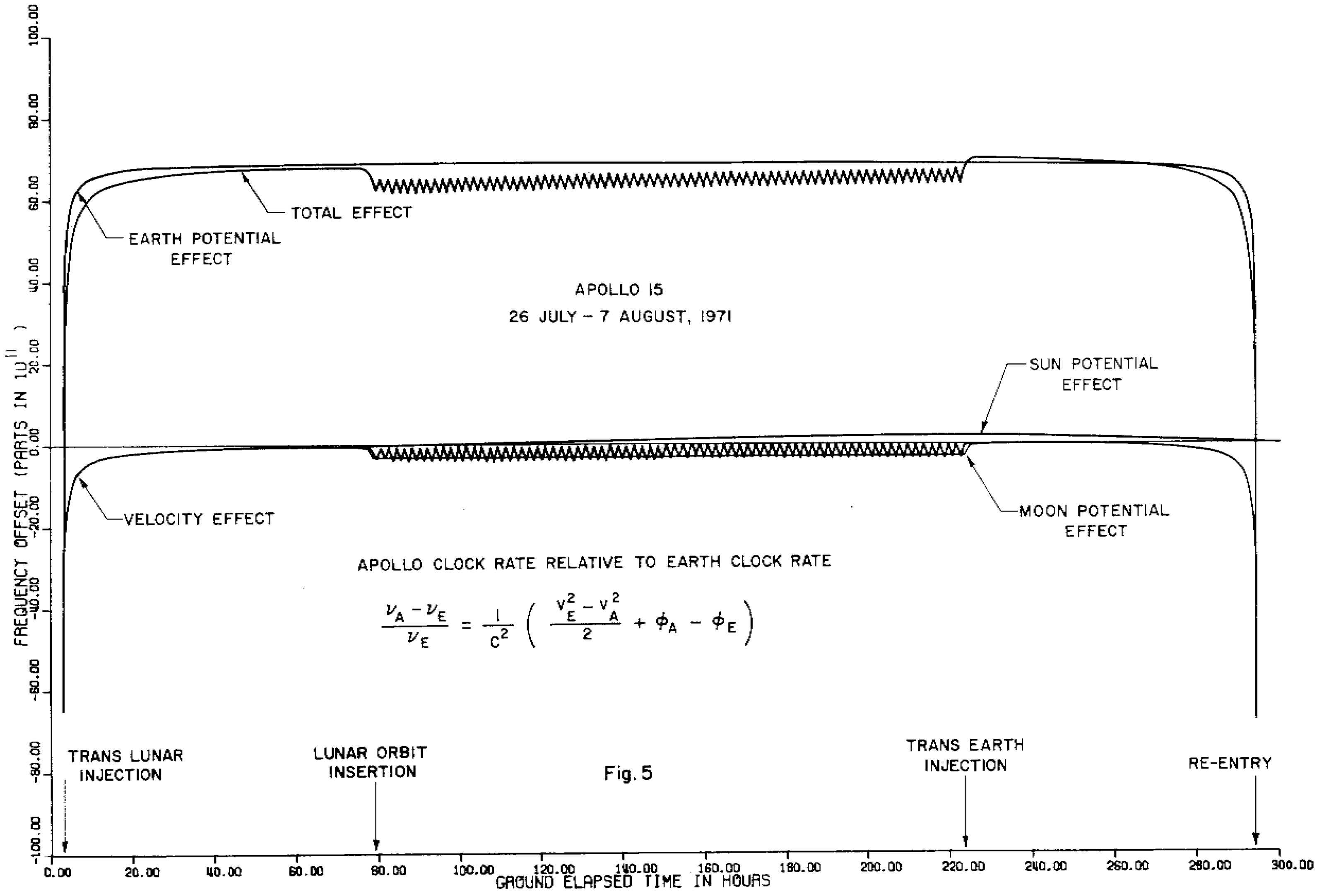


Fig. 5

Figure 5. Results of analysis of Apollo-15 trajectory data.

ELECTRONIC CIRCUITS

The measurement of the relative rates between pairs of clocks in the flight package is made possible by modern integrated circuit techniques requiring relatively little power and volume. It is also possible to measure critical environmental parameters at selected times and record their values in storage registers. Circuits to perform these functions have been designed and constructed by John Giganti and the Electronics Shop at the University of Maryland. They will be only briefly described here, but detailed circuit drawings are available upon request. Four 7-by-10-inch printed circuit boards were built to perform the functions of counting, phase, comparison, housekeeping, and programming.

To convert a *frequency standard* into a *clock*, count-down circuits are needed. The ten MHz frequency from each of the three Efratom units is counted by dividing down to the level of a pulse per second. This pulse is synchronous with the input frequency and is obtained by opening a gate after a series of ripple counting circuits to let through a shaped pulse of 5-ns rise obtained from the original ten-MHz sine wave. In order to provide additional certainty that no counts have been lost, the total number of 0.1 second intervals is stored in each channel for later readout. Outputs through buffer amplifiers are provided at 5 MHz, at 1 MHz, and at 1 MHz with phase reversal each second, as well as the 1-Hz pulses. A composite output is also provided with seconds pulses from clocks A, B, and C. Each counter can be stopped by applying a +10-volt signal through a light-emitting diode connection so that the seconds tick can be adjusted in epoch. To distinguish the three clocks, the seconds pulses from clocks A, B, and C have widths of 1, 2, and 3 microseconds, respectively, on this composite line.

Direct phase comparison at ten MHz is accomplished using hot carrier diode balanced mixers to compare A with B, B with C, and C with A, both directly and in quadrature. The sine and cosine outputs for each pair are quantized with an analog-to-digital converter in nine bits each (equivalent to 0.2 ns) and stored in a magnetic core memory having 4096 words of 18-bit length. This core memory was a back-up unit for the most recent Orbiting Astronomical Observatory and was loaned by the OAO Project Manager at Goddard Space Flight Center. For the Apollo flight of 300 hours, it was planned to sample once every 1500 seconds.

A separate board has been devoted to the programming of the phase measurements and to the routing of the information to the core memory. The sampling rate can be readily varied. For example, the package can be used to transfer time with high accuracy by carrying it to other points on the earth. During these trips, a sampling interval of 100 seconds might be convenient.

Another separate board has been devoted to "housekeeping" functions, which are defined as the monitoring of various environmental parameters. These include the pressure within the sealed box, and the temperature, supply voltage, and crystal-oscillator feedback voltage for each frequency standard. A total of twelve input voltages can be sampled and these voltages quantized and stored in a shift register memory having capacity, for the Apollo-17, of sampling once every three hours.

Power conditioning is accomplished by use of a switching regulator to provide a constant 22.5 volt source for the frequency standards as the buss voltage varies away from 28 volts. It is also designed to accept power from two 28-volt silver-zinc batteries which were designed and space-qualified for the Apollo Lunar Communications Receiving Unit (LCRU) in the event of loss of power from the buss. Two power-converter units are fed from the switching regulator and these provide the voltages needed for the electronic circuits and core memory. The total power requirement is 56 watts.

MECHANICAL PACKAGE

Much attention was given to the problem of heat transfer from the frequency standards to the aluminum box in which they are housed. The temperature of the standards can not rise above 65°C because the optical pumping cell and cavity are thermostated at 72°C and some temperature differential is needed. Therefore vibration and shock isolators which provide some thermal conductivity were chosen. These are made by the Aeroflex Company and consist of spirals of stainless steel rope. Three isolators are used per unit, attaching the outer mo-permalloy magnetic shield to the floor and one wall of the box. It was necessary to add flexible straps of copper braid between each unit and the box for additional heat conduction to maintain a temperature differential of about 20°C when conducting 12 watts.

MAGNITUDE OF RELATIVISTIC EFFECTS FOR AN APOLLO MISSION

To first order, the fractional frequency offset of the Apollo clocks relative to the earth clocks as a function of velocity and gravitational potential is given by

$$\frac{\nu_A - \nu_E}{\nu_E} = \frac{1}{C^2}\left(\frac{v_E{}^2 - v_A{}^2}{2}\right) + \phi_A - \phi_E$$

A numerical evaluation using a computer was carried out by A. Buennagel of the University of Maryland for the actual Apollo-15 trajectory data and the result is plotted in Figure 5.[5] The oscillation due to the vector composition of velocity during the lunar orbits is interesting. It was planned to observe these changes by monitoring the transmitted 1-MHz frequency over the television data link while simultaneously measuring the range rate and range of the spacecraft using the unified S-band tracking system.

CONCLUSIONS

The advantages of using an ensemble of clocks which are regularly intercompared have been recognized at least since the time of Captain Cook's exploratory voyages to the South Seas. He carried a set of four chronometers to use in establishing longitude. It is now possible to build a compact self-contained set of small atomic clocks and intercomparison electronics as a result of the dramatic size reduction achieved by Efratom's design of optically pumped rubidium standards and the use of modern integrated circuit electronics. Such packages, which can readily incorporate a controlled environment for example, constant pressure can be used in many situations to increase accuracy and reliability. In particular such packages are well suited for future space flights and it is anticipated that not only will the relativistic effects on elapsed time be measured with high accuracy, but also the correction for such effects will become routine in space-navigation and time-transfer operations.

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