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Preliminary Investigation of the Satellite Gravitational

Red Shift Experiment

Contract No. NASw-143

SN-88122

Final Report

February, 1961

for the period from April 1, 1959 to September 30, 1960

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1. Gravitational Red Shift Measurement

The work performed under this contract involved study, design, and construction of experimental equipment to perform a short-term measurement of the gravitational red shift^{1,2}. In the system designed, phase comparison techniques are employed so that the time interval required to obtain a single measurement for one altitude is of the order of one minute. An elliptical orbit was chosen to permit measurement of frequency shift as a function of altitude. One particularly attractive orbit is that having a 12-hour orbiting period (perigee, 270 miles, apogee 24,800 miles). This orbit, shown in Fig. 1, allows continuous measurements to be made over an 11-hour interval during which time the altitude is varying greatly. Measurements can not be made for the succeeding 14 hours. Since the variation of frequency difference with altitude is of greatest interest, a fixed offset or a slow drift between the oscillator on the ground and the oscillator in the satellite will not invalidate the measurements.

The short-term measurement technique can be described briefly as follows:

- 1) A transmitter on the earth radiates a signal of frequency F .
- 2) This signal is received at the satellite and mixed with a signal of frequency $2F$ (measured on the satellite) obtained from the satellite frequency standard.

¹Contract proposal, "Short-term Measurement of Gravitational Red Shift," submitted to NASA, June 15, 1959, and Technical Memorandum No. 2 (same title) June 15, 1959, Research Laboratory of Electronics, M.I.T.

²S. F. Singer, "Application of an Artificial Satellite to the Measurement of General Relativistic Red Shift," Phys. Rev. 104 (October 1, 1956).

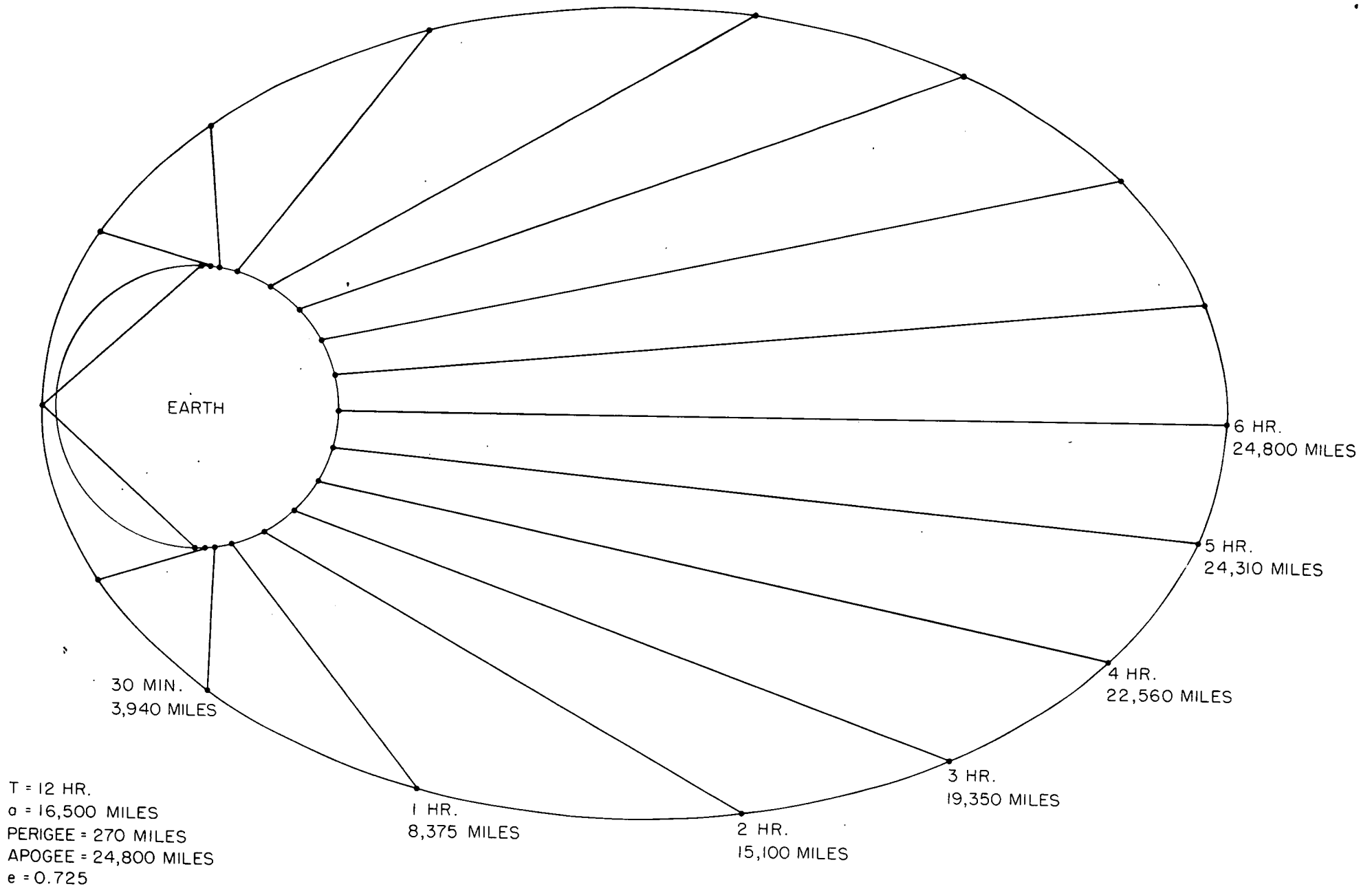


FIG. 1 TWELVE-HOUR SATELLITE ORBIT (OVERHEAD AT APOGEE)

3) The difference frequency output of the mixer is amplified and retransmitted back to the earth where the received signal frequency is compared with the standard frequency F .

The effect of the mixing operation in the satellite is to "pre-distort" the satellite transmitter frequency in such a way as to cancel the first order doppler shift acquired by the signal in propagation from the satellite to the earth.

Four possible system designs for performing the above manipulations, a pulse system, a CW frequency offset system, a dual-frequency (symmetrical) CW system, and a dual-frequency (offset) CW system were outlined and discussed in block diagram form in the Interim Progress Report dated March 1, 1960. Because of the power limitations inherent in the satellite transistor transmitter, it was felt that (at the present time at least) a CW system and in particular the dual-frequency offset system was probably the best for use in this experiment. Of course it should be emphasized that if the "boundary conditions" are changed in any significant way, one of the other systems or some completely different system might very well be the best under these new conditions.

To determine the extent to which the proposed CW system would suffer from saturation and self-oscillation difficulties, a portion of the satellite receiver was constructed and tested. The four RF-signal frequencies which would be present at the satellite were applied to the satellite receiver input, along with a signal representing the signal from the ground transmitter. Upon removal of the true signal, the receiver output reduced to noise, indicating satisfactory performance in the presence of the interfering signals.

It was originally proposed to use highly stable crystal oscillators as the source of frequencies in both the satellite and on the ground. With the best presently available crystal oscillators, a measurement accuracy of approximately 10 per cent was predicted. If more accuracy is desired, then crystal oscillators will not suffice. However, if atomic frequency standards are substituted for the crystal oscillators, and the base frequency used in the transmission between ground and satellite is raised into the microwave region, say, 3000 megacycles, then accuracies of better than 1 per cent, possibly one-tenth of a per cent could be obtained.

2. Related Studies

A. Variable Capacitance Frequency Multipliers

All of the systems described in Section 1 require some means of multiplying frequency from that of a low frequency crystal up to the UHF or microwave region. A study was initiated of the feasibility of using variable capacitance diodes as frequency multiplying elements in both low order and high order multipliers. The studies done under this contract plus a large amount of work done under the Basic Research Contract in RLE have culminated in three master's theses^{3,4} and a doctor's thesis⁵,

³D. B. Leeson and S. Weinreb, "Frequency Multiplication with Nonlinear Capacitors - a Circuit Analysis," Proc. IRE, vol. 47, pp. 2076-2094; December, 1959.

⁴B. L. Diamond, "Idler Circuits in Varactor Frequency Multiplier," S.M. EE Thesis, M.I.T., February 1961.

⁵R. P. Rafuse, "Parametric Applications of Semiconductor Capacitor Diodes," Ph.D. Thesis, EE Dept., M.I.T., September, 1960.

the latter by Dr. R. P. Rafuse (supported by the Basic Research Contract, RLE). References 4 and 5 are presently the definitive works in the field of parametric frequency multiplication.

B. Crystal Oscillator Frequency Stability Investigations

Considerable experimentation was done to determine the short-term stability of crystal oscillators, first, for use as the frequency standards in the 10 per cent measurement of the gravitational red shift; and second, for use as the stabilizing elements in atomic frequency standards. In order to permit short-term frequency comparison of two highly stable quartz oscillators, the system of frequency multipliers and mixers shown in Fig. 2 was assembled. An effective multiplication of frequency difference of approximately 10,000 is provided. The output phase difference is displayed unambiguously on an oscilloscope and can be determined to within 15° at any instant. Thus a frequency difference between oscillators averaged over a 100-second interval can be measured with an accuracy of 4×10^{-14} .

In order to improve the signal-to-noise ratio of commercially available stable crystal oscillators, a second crystal oscillator is injection-locked to the highly stable oscillator and in effect acts as a very narrow band filter on the stable oscillator output.

Using commercial oscillators modified in the above manner, we made a series of measurements and found that instabilities 1×10^{-10} , averaged over a two-minute interval are common, with occasional drifts of 3×10^{-10} , occurring over the same interval. Power spectrum measurements have also been conducted with the use of a modified wave analyzer.

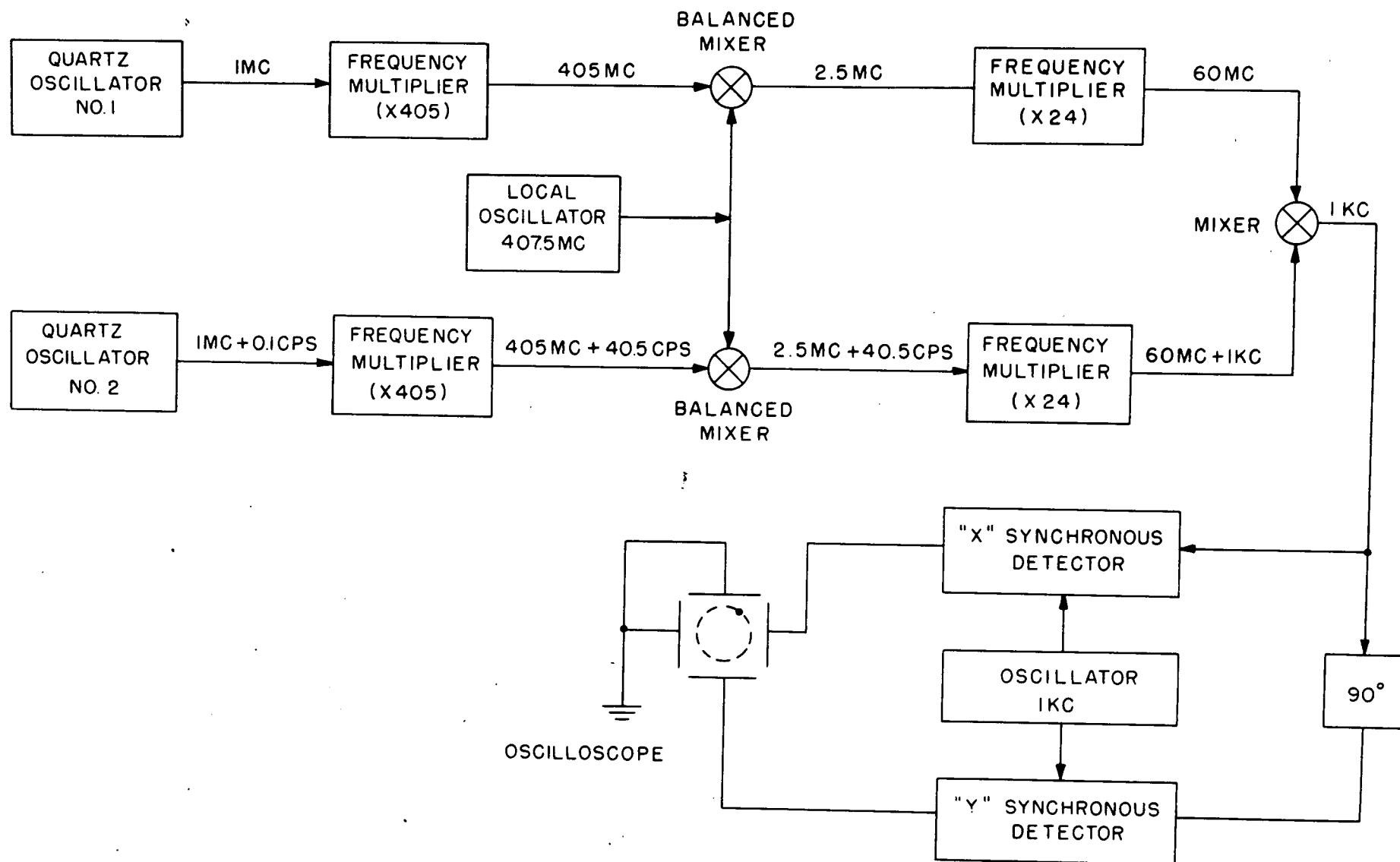


FIG. 2. OSCILLATOR STABILITY MEASUREMENT SYSTEM

In these experiments, a 10-second interval of the 1 kilocycle beat note from the oscillator stability measurement system is recorded on a tape at 15 inches per second. The resulting fractional resolution bandwidth referred to the original oscillators is now 1×10^{-10} . The power spectrums obtained have essentially the same shape as that of a clean audio signal fed directly to the analyzer. This shows that there are no instabilities greater than 1×10^{-10} which occur at rates faster than 0.4 cycles per second. This rate being determined by the length of tape used.

C. Propagation Effects

Propagation errors introduced by dual signal transmission through the atmosphere and ionosphere introduce frequency errors in the measurement believed to be in the vicinity of 1% at 500 mc and 0.1% at 3 kmc. Subsequent measurements which are to be (or may have been) performed using satellite transponders, radar reflections from satellites, etc., should yield conclusive data concerning these effects.