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Time Transfer Using the TIMATION II Satellite

[Unclassified Title]

J. A. BUISSON, D. W. LYNCH, AND T. B. MCCASKILL

Space Metrology Branch
Space Systems Division

May 3, 1973

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NAVAL RESEARCH LABORATORY
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CONTENTS

ABSTRACT
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The TIMATION principles, although originally proposed as a method of navigation, can be used to transfer time between any number of sites. Time-transfer experiments were performed between NRL and several other ground stations using passive ranging techniques and the TIMATION II satellite. The results indicate this method is capable of transferring time to an accuracy of approximately one tenth of a microsecond.

PROBLEM STATUS

An interim report on a continuing NRL problem.

AUTHORIZATION

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TIME TRANSFER USING THE TIMATION II SATELLITE
[Unclassified Title]

INTRODUCTION

(U) TIMATION II is the second satellite launched in connection with the development of the TIMATION navigation system. It was launched into a 500-naut.-mi.-high circular orbit on Sept. 30, 1969, and has been used continuously since launch for evaluation of the TIMATION navigational principles.

(U) During the conceptual period of the TIMATION project, it was realized that a clock at a remote site could be synchronized by receiving navigational data from the satellite. Experimental verification of this time-transfer capability was obtained with TIMATION I results and has been further verified through the use of TIMATION II. The accuracy achieved was sufficient to stimulate the interest of those working in the field of world-wide time dissemination. The purpose of this report is to present some time-synchronization results obtained in the continuing evaluation of the TIMATION II experiment.

SYSTEM DESCRIPTION

(U) The TIMATION navigation system employs passive ranging. A navigator determines his distance from the satellite by measuring the propagation time required for a signal to travel from the satellite to his receiver and multiplying by the velocity of propagation.

(U) The satellite carries a "clock" driven by a very stable quartz-crystal oscillator operating at 5 MHz. From this signal, two carriers are coherently derived, one at 149.5 MHz and the other at 399.4 MHz. In addition. other frequencies are derived in the bands of 149.0 to 150.0 MHz and 398.9 to 399.9 MHz to provide the equivalent of nine modulation frequencies from 100 Hz to 1 MHz. The carriers are transmitted continuously to permit doppler tracking at two frequencies for orbit computations; the use of two frequencies provides the necessary data to correct for ionospheric effects. The modulation frequencies are transmitted in a time-sharing sequence for 4.8 s out of each minute. This pattern of transmissions permits a user with a TIMATION II receiver, which also contains a clock, to measure the time difference between the signal received from the satellite and the receiver clock. This time difference is the sum of the time required for the signal to propagate from the satellite to the receiver and the synchronization error between the satellite and receiver clocks.

(U) The resolution of the time-difference measurement is approximately 1 percent of the period of the highest modulation frequency, or 10 ns. The lowest modulation frequency, 100 Hz, provides ambiguity resolution of 10 ms. This resolution insures an unambiguous measurement, since the propagation time can vary from about 3 to 12 ms as the satellite travels from directly overhead to the horizon.

(U) The time difference, measured using the 400-MHz band, can be multiplied by the velocity of propagation to obtain an "observed" range. This range corresponds to the geometric distance from satellite to receiver plus contributions due to clock-synchronization error and to ionospheric and tropospheric effects. For the transfer or comparison of time between two observers, the clock-synchronization term is the one of interest. The accuracy to which it can be determined is a function of how well the other factors can be specified or eliminated.

(U) Figure 1 is a typical curve of range error due to the troposphere vs elevation angle. In practice the error varies with atmospheric conditions but in general remains within ±30 percent of the value given by the curve. Since a 1-ft range error corresponds approximately to a 1-ns time error, the total error introduced by the troposphere is less than 0.1 μs for elevation angles greater than 5°. Further reduction of this error is achieved through cancellation, when observations from two stations are compared. If still greater accuracy is required, the tropospheric range error can be calculated to about 3 ft from the measured values of the atmospheric conditions or the surface index of refraction. *

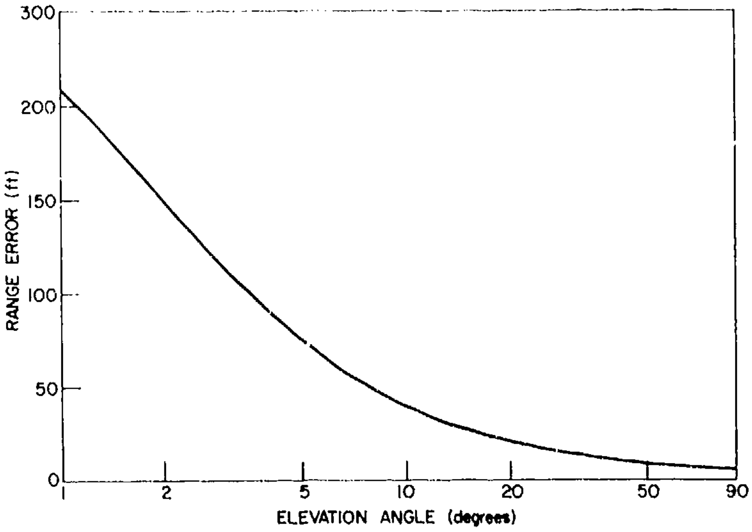

Fig. 1 (U) — Range error resulting from a nominal troposhere

(C) The excess range introduced into the observed range by the ionosphere is a function of elevation angle, solar zenith angle, and ionospheric content. Typical values of this error for an observer at 33°N latitude are shown in Fig. 2, where the error is plotted against elevation angle for 3 or 21, 6 or 18, 9 or 15, and 12 hours local sun time. These curves represent "normal" solar activity; the error can become several times larger during periods of extreme solar activity. Since time comparison for two sites is obtained by

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*L. D. Breetz, "Refractivity Measurements Related to a Minimum Troposphere Range Error," NRL Memorandum Report 2294, July 1971.

differencing measurements made at the two sites, some cancellation of the ionospheric error results, but the remaining error can amount to several tenths of a microsecond. Where increased accuracy is required, a calculated value of the error can be used to obtain some improvement, but the best method of reducing the ionospheric error is to measure the time difference using both the 150-MHz and 400-MHz bands and to apply the standard two-frequency correction. This method should reduce the error to something less than 10 percent of its uncorrected value and keep the error under 0.1 μs.

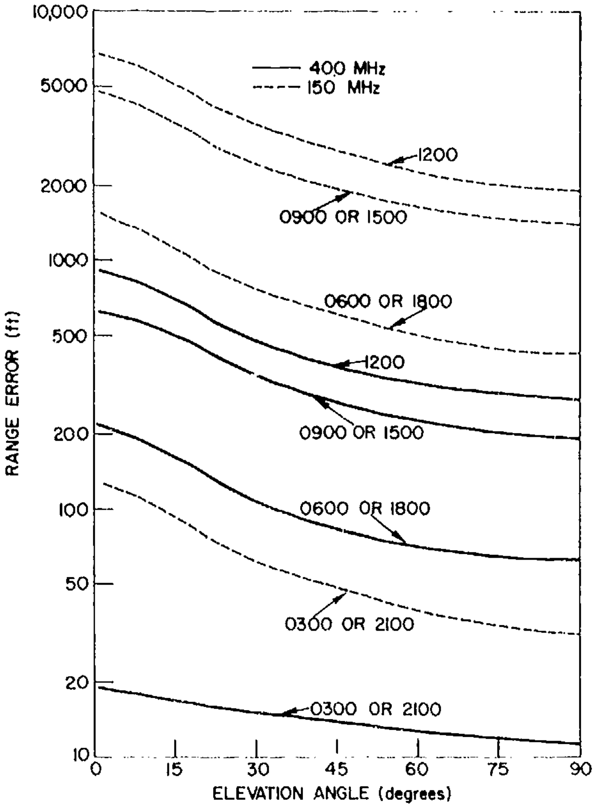

Fig. 2 (U) — Range error resulting from a nominal ionosphere for various local sun times

(U) To obtain the difference in time between a receiver clock and the satellite clock, the propagation time has to be removed from the time-difference measurement. This requirement leads to the consideration of two different cases, first, where the position of the receiver is known, and second, where the position of the receiver is unknown.

(U) Using the known position of the receiver and the position of the satellite as given by the ephemeral data, the geometric distance from satellite to receiver can be calculated; the propagation time then is found by dividing this distance by the velocity of propagation.

This calculated propagation time can be subtracted from the observed time difference, leaving the difference in time synchronization between the satellite and receiver clocks. Since the ephemeral data are not perfect, some error results from the uncertainty in satellite position. The largest component of the uncertainty in satellite position is along the satellite track. The error due to this component can be minimized by taking the time-difference observation when the satellite is near the point of closest approach to the receiver and therefore is moving nearly normal to the line of sight. The point of closest approach is also the point of maximum elevation, so the tropospheric and ionospheric effects are also minimized, and further corrections may not be necessary.

(C) When the horizontal position of the receiver is not known, a minimum of three time-difference measurements must be used, so that latitude, longitude, and clock difference can be calculated. In general, a time difference is measured each minute the satellite is visible to the receiver, and ten to fifteen observations are used to make a redundant-data solution for the three unknowns. The time difference between the satellite and receiver clocks found in this manner is usually within 0.1 μs of the value found when the position of the receiver is known.

EXPERIMENTAL RESULTS

(U) The time difference between the receiver clock at NRL and the satellite clock is shown for a several-day period in Fig. 3. This time difference was obtained using the known coordinates of NRL; each point represents a single time-difference measurement made at the minute nearest the time of closest approach. The slope of this curve represents the normalized frequency difference between the NRL receiver clock and the satellite clock. For example, a frequency difference of 1 part in 10^{10} would cause a slope of 8.64 μs/day. Since the NRL clock is referenced to a hydrogen-maser clock, which in turn is kept within a few nanoseconds of the Naval Observatory standard, the frequency difference can be considered to be the amount the satellite oscillator is off nominal frequency. The satellite oscillator can be tuned by telemetry command, and tuning is done as required to keep it within a few parts in 10^{10} of nominal frequency. By more frequent tuning, the frequency could be maintained much closer to nominal, but to study the aging of the oscillator, it is necessary to remove the discontinuities caused by tuning. This study could be made easier and could provide better results with infrequent tuning.

(U) Figure 4 is a section of the frequency record showing the tuning discontinuities; Fig. 5 is a complete frequency record with the tuning discontinuities removed. The initial positive slope of the frequency curve is due to the normal aging of a quartz crystal. As this effect decreased with time, the radiation effect on the crystal became predominant, and the negative slope resulted.

(U) If time differences between receiver clock and satellite clock are measured for two receivers and the results subtracted, the time difference between the two receiver clocks is obtained. Experimentally the differences between NRL and several other sites have been determined. Figures 6 through 9 are plots of the results obtained over periods of several days for receivers in Virginia, Florida, Colorado, and Alaska. Again the slopes of the curves or lines are a measure of the frequency differences of the receiver clocks. For

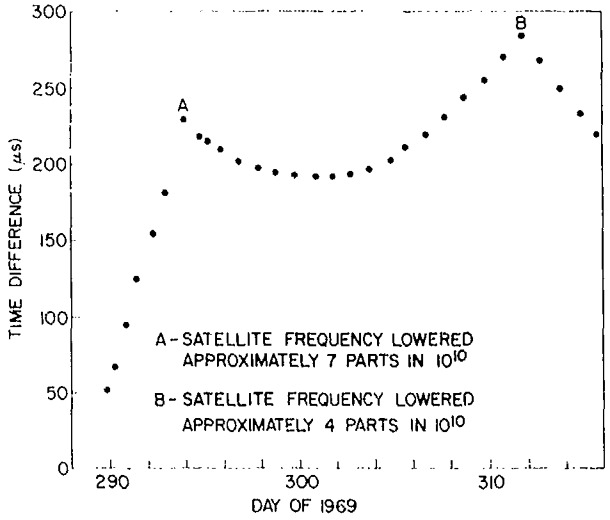

Fig. 3 (U) — Time difference between the satellite clock and the clock at NRL

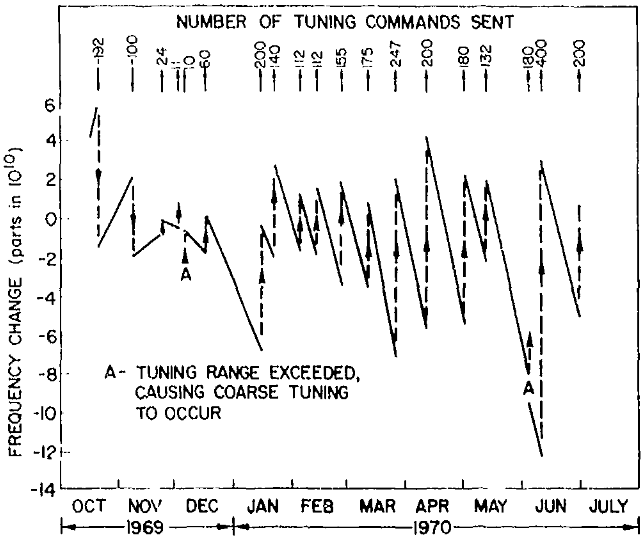

Fig. 4 (U) — Frequency history of the satellite oscillator showing the discontinuities due to tuning commands from the ground

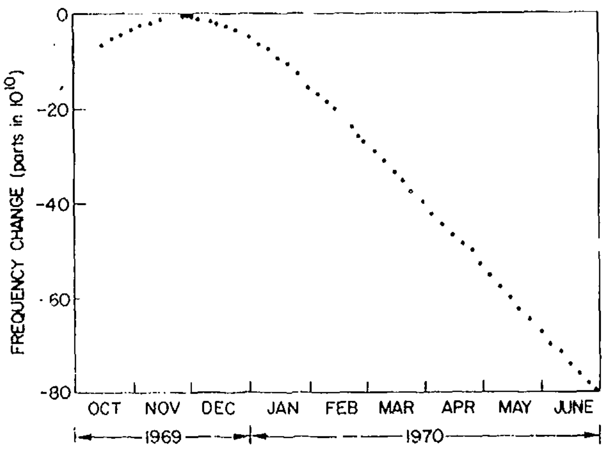

Fig. 5 (U) — Frequency history of the satellite oscillator with the tuning discontinuities removed

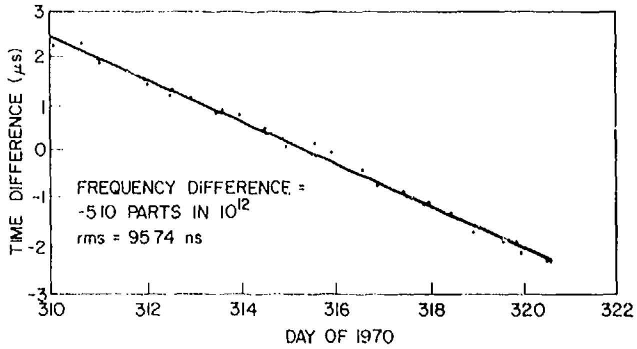

Fig. 6 (C) — Time comparisons between NRL and Virginia obtained from TIMATION data

this experiment, all receivers used cesium-beam clocks, with the exception of the one at NRL, which was referenced to the local hydrogen maser. Assuming the receiver frequencies to be constant, the rms fit of the points to a straight line indicates that the individual time-difference measurement between remote receivers can be made to about 150 ns and that the frequency difference can be determined to approximately one part in 10^{13} using a ten-day span of measurements. The receivers used for these measurements were the regular 400-MHz experimental ranging receivers built for the evaluation and demonstration of navigation using the TIMATION system without ionospheric correction.

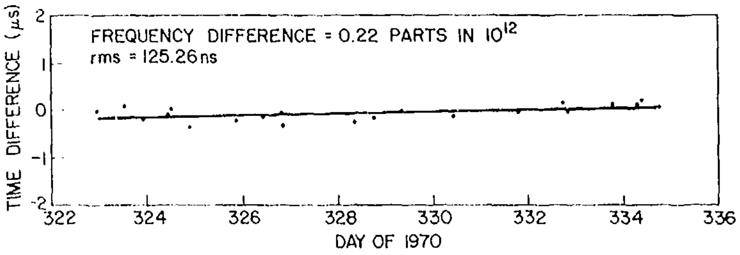

Fig. 7 (C) — Time comparisons between NRL and Florida obtained from TIMATION data

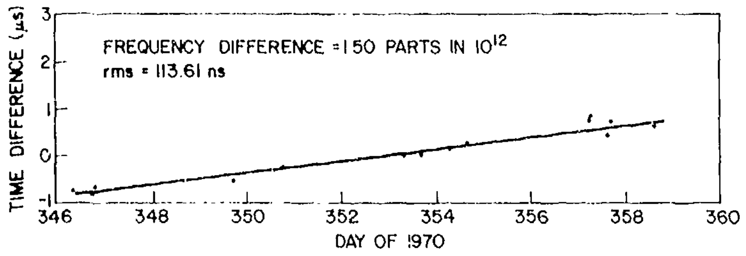

Fig. 8 (C) — Time comparisons between NRL and Colorado obtained from TIMATION data

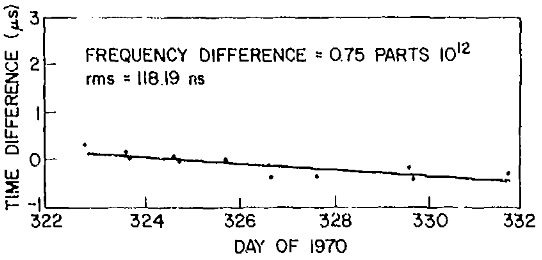

Fig. 9 (C) — Time comparisons between NRL and Alaska obtained from TIMATION data

(C) Some time-transfer experiments were also performed using an experimental "time-dissemination" receiver built for NRL by RCA. This receiver operates on the 400-MHz band, combining the 0.1-, 1-, 10-, and 100-kHz modulation frequencies to obtain a "range" measurement in milliseconds. The digitally displayed measurement is updated once a minute while the satellite signal is being tracked. The receiver was taken to the Naval Observatory, and a number of satellite passes were observed. Using the known position of the receiver at the Observatory and the predicted position of the satellite, epoch transfer was achieved (Fig. 10). The difference for each minute of data obtained during a satellite pass is plotted against time measured from the minute nearest the time of closest approach. The tendency of the differences to exhibit a slope during the pass is due to the error in satellite-position data, which is a result of predictions being five to nine days old during the passes shown. As discussed earlier, the most reliable time transfer should occur at the point of closest approach. Considering only the minutes of closest approach, it appears that the effect of this slope is minimized. This receiver has since been modified by RCA to use the 1-MHz modulation frequency, and a 150-MHz receiver has been built. Using both of these receivers, time transfer should be possible to an accuracy of about 0.1 μs.

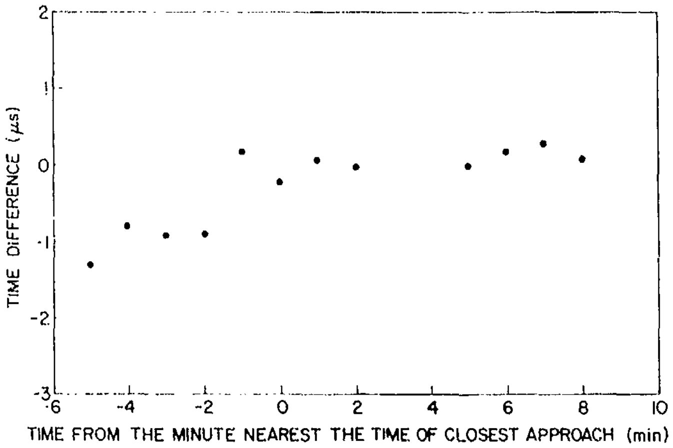

Fig. 10 (C) — Time comparisons between NRL and the Naval Observatory obtained from TIMATION measurements made during one satellite pass

FUTURE WORK

(U) The next major step in the TIMATION program is the launching of TIMATION III some time in 1974. This satellite will have modulation frequencies up to 8 MHz and will transmit on 335 and 1600 MHz. The orbit will be circular, with a period of eight hours and an inclination near 125°. This satellite will "see" more than 1/4 of the surface of the earth at any time and will provide data for time transfer for several hours per day at any place on earth.

ACKNOWLEDGMENTS

(U) All members of the Space Metrology Branch have contributed to the success of the TIMATION II experiment. Particular credit is due Roger L. Easton, Branch Head, who is responsible for most of the conceptual work and the guidance of the project. The authors also thank those members of the Branch who have spent so many hours collecting data at NRL and the Bendix personnel who have operated the field sites. The data processing and compilation of the results for this report were done with the invaluable aid of Mrs. Cecelia Burke, Miss Judith Thompson, and Mr. Robert Turner of the Advanced Techniques and Systems Analysis Section.

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Clock synchronization						
Ionospheric refraction						

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