built for $600 \leq N \leq 1100$ at various frequencies between 40 and 120 MHz showed close agreement with the theoretically predicted performance data [9].

A 1024 bit line of this type operating at a bit rate of 100 MHz has a length of about 1 inch and a width of 0.1 inch. If closely stacked, such lines can store binary information at a density of about 10^5 bits per inch^3. Since the side surfaces need not be finished to high precision, the finishing costs are essentially those of the end faces which amount to 2 inch^2 for 10^5 bits. At high bit rates, the material costs become a small part of the finishing costs, which, in turn, should not exceed those of an equivalent integrated-circuit surface area. One therefore may surmise that at high bit rates, a delay line store should be economically competitive with other forms of storage such as semiconductors.

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Satellite VHF Transponder Time Synchronization

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***Abstract*—This paper describes an experiment designed to transfer accurate time between two widely separated clocks using a VHF satellite transponder. The satellite used was the NASA Applications Technology Satellite, ATS-1. The experiment used atomic oscillators to maintain accurate time at each station, and the synchronization was accomplished by measuring the round-trip delay times between the stations. The goal of the experiment was to evaluate a VHF system, because of the low-cost ground equipment involved, in contrast to microwave systems. The paper discusses the results and the various factors that contributed to the timing errors.**

Introduction

THE NASA Applications Technology Satellite (ATS-1) has been used in a series of experiments to explore one method of synchronizing widely separated precision clocks. The synchronization was achieved by making round-trip time delay measurements, via the satellite transponder, between master and slave clock locations. Similar experiments have been conducted [1], [2] previously using satellites with microwave transponders. The present experiment was conducted with the ATS-1 VHF transponder. Although the microwave frequency region is ideal from the point of view of avoiding atmospheric signal distortion, the VHF system has an advantage in that relatively simple and low-cost ground equipment may be used. Synchronization of the clocks was achieved to within a few microseconds.

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The Satellite VHF Transponder

The NASA satellite ATS-1 was launched December, 1966, in near synchronous orbit. A part of the ATS satellite system is devoted to supporting experiments at VHF. The VHF repeater or transponder operates as a frequency translator. Signals received at 149.220 MHz with frequency modulation are heterodyned to an intermediate frequency, 29.95 MHz, and then heterodyned to 135.600 MHz for retransmission to earth. An eight-element phased-array antenna system operating in duplex is used for both receiving and transmitting, while signal limiting and bandwidth filtering are employed simultaneously in the satellite signal chain. Because of this, amplitude modulation is not possible at

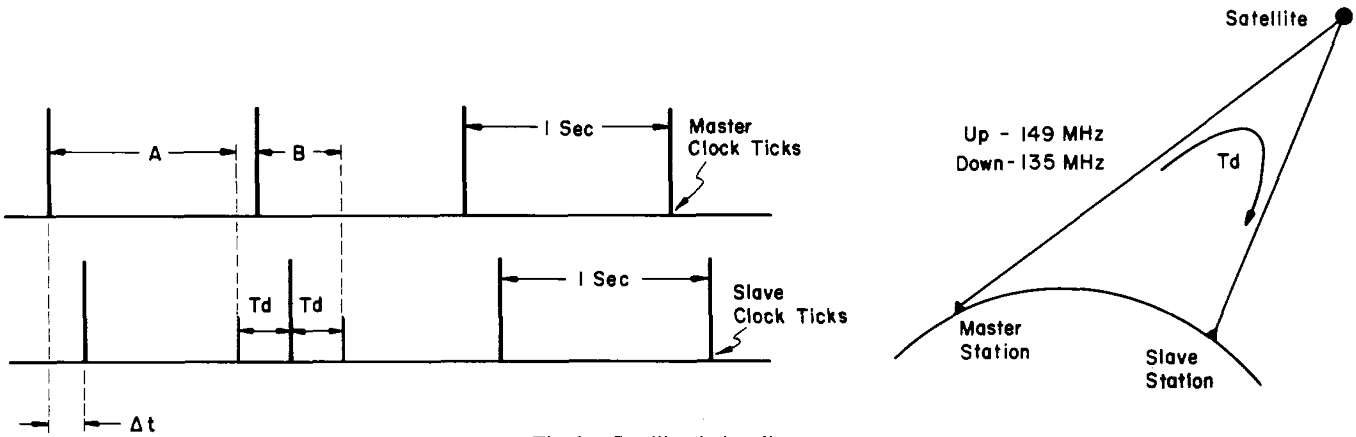

Fig. 1. Satellite timing diagram.

full satellite power levels and the overall system bandwidth is restricted to 100 kHz. For this experiment frequency modulation was employed.

System Description

Fig. 1 shows the geometry of the timing experiment and a timing diagram which is used to derive the equations necessary for the synchronization. The description here is simplified to make clear the general principles of operation. As will be described in more detail in later paragraphs in this section, the synchronization was initiated by transmitting 1-pps pulses from the master station. For this experiment, it was assumed that the master and slave clocks did not differ initially by more than one second. If this condition had not been met, then a slower pulse rate would have been used to unambiguously set the slave clock to the master clock. Since one of the main considerations in the experiment design was simplicity of operation, particularly at the slave site, the signal was adjusted in time and transmitted from the master station to arrive "on time" at the slave station with respect to the slave station clock. This adjustment was achieved by maintaining a communication link between the master and slave stations. The operator at the slave station simply told the master station operator to either advance or retard the transmitted tick until it appeared to arrive in coincidence with the slave clock tick. This was done by the use of a voice channel over the satellite or by telephone communication. The amount of time by which the transmitted pulse leaving the master transmitter must be delayed with respect to the master station clock to arrive "on time" with respect to the slave clock is designated A in Fig. 1.

By inspection, from the figure,

$$A = \Delta t + (1 - T_d). \tag{1}$$

Δt is the time difference between the master and slave clocks and T_d is the one-way path delay from one ground station, via the satellite, to the other ground station.

After A was determined and recorded at the master station, the slave station transmitted pulses directly from the slave station clock without adjustment. These pulses arrived via the satellite at the master station B seconds late with respect to the master clock. Again, by inspection from the figure,

$$B = \Delta t + T_d. \tag{2}$$

Since both A and B were measured at the master station, the master station operator could determine the difference between the master and slave clocks by solving (1) and (2) simultaneously to obtain

$$\Delta t = (A + B - 1)/2. \tag{3}$$

Strictly speaking, (3) holds only if $0 \leq \Delta t \leq T_d$. In most practical cases Δt will be less than T_d (0.25 second) so that (3) will be applicable. However, there are two other possible cases. If

$$T_d \leq \Delta t \leq 1 - T_d,$$

then

$$\Delta t = (A + B)/2,$$

and if

$$1 - T_d \leq \Delta t \leq 1,$$

then

$$\Delta t = (A + B + 1)/2.$$

Since T_d is approximately known in advance, it was possible to inspect the measured values of A and B and then to select the correct one of the three possible cases. The actual choice was easy because both A and B had to fit the inequality. A range of values for A and B was computed using the known range to the satellite.

Details of System Operation

Fig. 2 shows block diagrams of the master and slave stations. As stated in the previous section, synchronization is initiated by the master station. The master station transmits 10-kHz tone bursts that are adjusted in time to arrive at the slave station nearly coincident with the slave clock pulse. A 1-pps rate is used first to avoid ambiguity. When the 1-pps pulses have been adjusted to arrive very nearly on time, the pulse rate is increased to 100 pps. This higher rate aids the detection process and increases the precision of measurement.

After it had been established that the pulses transmitted by the master station were "on time" with respect to the slave clock at the slave station, the direction of transmission

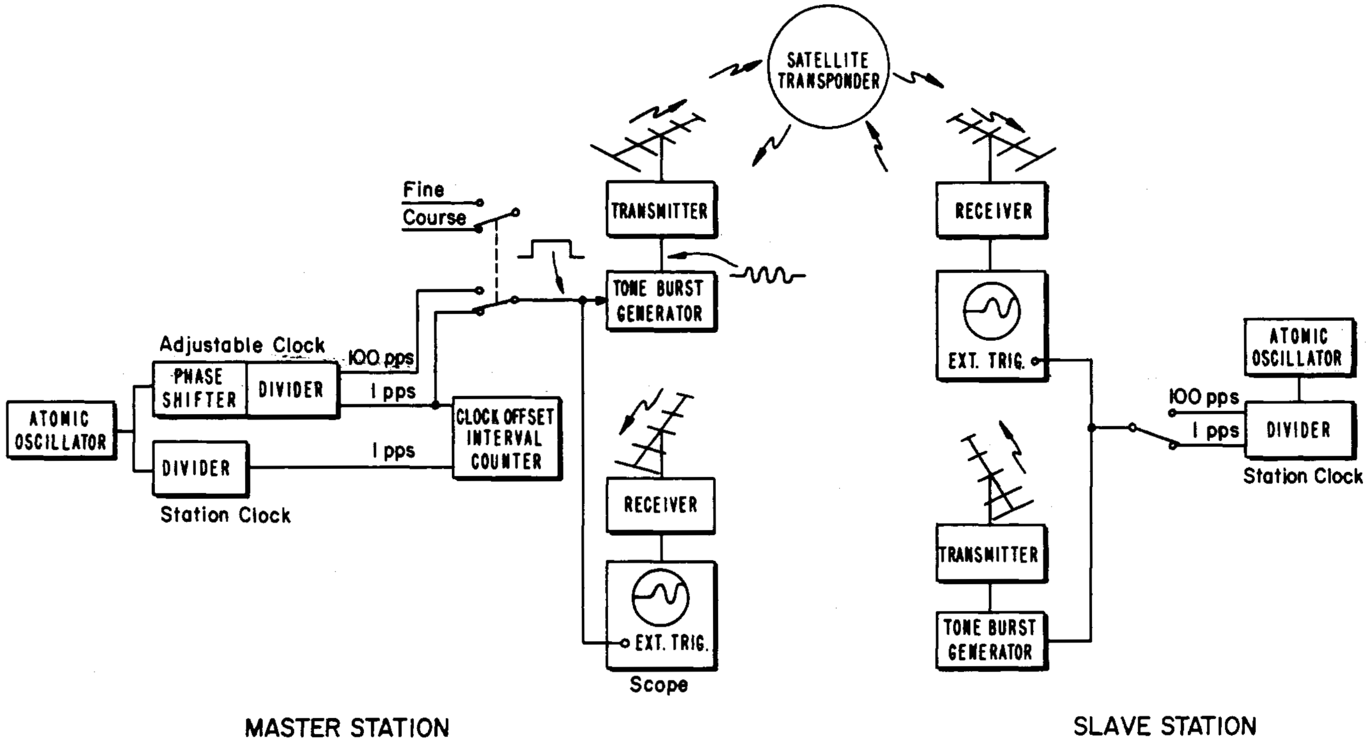

Fig. 2. System block diagram.

was reversed. The slave then transmitted its own clock pulse to the master without any adjustment. First a 1-pps rate was used and then a 100-pps rate. The master then measured the quantity B, which was the difference between the arrival of the slave time tick and the master clock.

At both master and slave stations, the "clocks" consisted of coherent 100-pps and 1-pps dividers driven by an atomic standard. The digital clock output was used to trigger a sine-wave tone burst generator which in turn frequency modulated the transmitter. The tone burst started at zero phase and lasted for one-half second or 5 milliseconds, depending on the pulse rate chosen.

Because the bandwidth of the system would not transmit the necessary spectrum to reproduce the start of the tone burst without distortion, the actual time "mark" used was the start of the third cycle of the burst. The first cycle was easy to see and the operator simply counted zero crossings to find the third cycle.

The equipment delays at each station were measured by converting a sample of the transmitter output to the receiver frequency using a broad-band mixer. In this way, using the modulation format of the timing system, the combined transmitter-receiver delay could be measured. Next the transmitter was driven by the tone burst generator and a sample was again converted with a broad-band mixer to a reasonably low frequency for direct display of the frequency modulation on an oscilloscope. The receiver and transmitter delays could then be separated. Based upon equipment delay measurements made over periods of several days, it was concluded that the variability is ± 2 μs. The actual delay was about 150 μs for each set of equipment used.

The time coincidence detector used in this experiment was a triggered oscilloscope. The station clock was used to trigger the sweep and the receiver video output was displayed. Prior to each run, the time bases of the oscilloscopes were calibrated using the atomic standard divided output.

Sources of Error

1. *Equipment Delay Measurements*

In the derivation of the timing equations in a previous section, no mention was made of equipment delays. If it can be assumed that the equipment delays from master to slave and slave to master are equal, then the equations as derived are valid, since the equipment delays can be assumed to be included in the term T_d. In fact, the delays are not identical, and the measurements must be corrected for these delays before the equations can be applied. As previously mentioned, the variability was found to be ± 2 μs, and the magnitude of the equipment delay for one transmitter-receiver set was about 150 μs.

2. *Signal-to-Noise Considerations*

There will be a certain amount of error due to the fact that the signal is received in a noisy environment. Table I gives a signal-to-noise calculation which typifies the down link operation.

The rms jitter in the arrival time of a zero crossing of the signal is

$$\text{rms jitter} = \frac{t_r}{(2S/N)^{1/2}}$$

where t_r is the period of the modulation and S/N is the signal-to-noise power ratio. Substituting the appropriate values into this equation, we obtain

TABLE I
SIGNAL-TO-NOISE CALCULATION

Down link	135.6 MHz
Satellite transmitter power, dBW	16.0
Satellite antenna gain, dB	9.0
Ground station antenna gain, dB	10.0
Space attenuation, dB	−167.0
Received power	−132.0 dBW
Noise temperature, dB	30.0
Boltzmann's constant, dBW	−228.6
Bandwidth (30 kHz), dB	44.8
Received noise power	−153.8 dBW
Carrier-to-noise ratio, dB	21.8
FM improvement,* dB	4.8
Signal-to-noise ratio, dB	26.6

* For 10-kHz deviation and 10-kHz modulation.

$$\text{rms jitter} \sim \frac{100\ \mu s}{(457)^{1/2}} \cong 5\ \mu s$$

on the zero crossings of the 10-kHz tone bursts. This calculation assumes that the S/N ratio received at the satellite is sufficient for the transponder to retransmit a clean signal at its maximum output of 40 watts. A calibration was run to determine how much effective radiated power from the ground station was required to obtain a clean satellite signal. On the basis of this test it was determined that an effective radiated power of 2500 watts was sufficient to obtain full signal power from the satellite.

3. *Faraday Rotation*

Because of the presence of the earth's magnetic field, the ionosphere is a birefringent medium which causes a linearly polarized wave to split into two elliptically polarized components with opposite senses of rotation. As a result of this splitting, a linearly polarized signal changes its orientation as it passes through the ionosphere so that there is no assurance that maximum signal will be received at either the satellite or ground receiving antennas simply by aligning the transmitting and receiving antennas. In principle, it is possible to calculate the amount of rotation if the electron content and the earth's magnetic field are known along the propagation path. In practice, it is easier to either rotate the ground transmitting and receiving antennas until maximum signal is received or to use circularly polarized ground transmitting and receiving antennas. Both techniques were used in this experiment. The error introduced by the Faraday rotation is indirect in the sense that the effect is as though the satellite transmitter power has been reduced.

4. *Amplitude and Phase Scintillations*

Amplitude and phase scintillations on the timing signals are due to the presence of irregularities in the refractive index of the ionosphere which move between the signal source and the observer. Generally, the period of the scintillations is of the order of minutes. By amplitude scintillations it is meant that the signal appears to fluctuate in brightness, whereas for phase scintillations it is meant that the location (or angle of arrival of the signal) appears to change with time [3]. In general, both of these effects are related to phase distortion of the signal. That is, the phase front of the signal is distorted in the region of the ionosphere containing the irregularities. As the signal propagates away from this region, the distorted wave interferes with itself to produce amplitude modulation of the signal which is a function of the distance from the irregularities and upon the amount of initial phase distortion at the irregularities. Typically, at 100 MHz at medium latitudes, the amplitude fading (when it is present) is about 10 percent of the mean signal strength, which will cause no particular problem for timing experiments [4]. However, on some occasions, particularly at either high or low latitudes, the signal fluctuations could be considerably greater and could possibly, on some rare occasions, render the system inoperable. The phase scintillations introduce path length fluctuations which at most would not amount to more than a few centimeters (1 km ~3 μs), which is negligible from the point of view of this timing system.

5. *Ionospheric Absorption*

In the scintillations discussed above, there is no net loss of energy, just a redistribution. However, the ionosphere could also produce a true absorption, particularly at times of solar disturbances. But observations [5] indicate that, at 100 MHz, under even the most disturbed conditions, the absorption should not exceed 1 dB.

6. *Path Nonreciprocity Effects*

An explicit assumption for the proper operation of the system is that the electromagnetic path between the master and slave stations is reciprocal. Strictly speaking for ATS-1, this assumption is not correct, for the following three reasons.

1) The up and down links to the satellite differ by 13.62 MHz so that there will be some differential delay due to the slight difference in group velocities at these two frequencies. However, we estimate that with reasonably normal ionospheric conditions, this difference should not exceed 0.1 μs.
2) ATS-1 is not in an absolutely synchronous orbit. However, the amount of error introduced by the satellite motion during the few minutes required for clock synchronization does not exceed 1 μs in the worst case [6].
3) The amount of delay in the satellite itself is of no consequence as long as it does not change appreciably during the course of the clock synchronization. Experiments conducted prior to the launch indicate that the satellite delay should be stable in this respect to 0.1 μs or less [7].

OBSERVATIONS

Experiments were conducted for a 10-day period during June and July of 1967. Signal exchanges were made between the NASA STADAN field site near Barstow, Calif., and stations located at the WWVH site at Maui, Hawaii, the NBS Laboratories at Boulder, Colo., and a satellite-tracking station at Gunbarrel Hill, operated by the U. S. Environmental Science Services Administration, about 10 miles north of Boulder. Two independent sets of equipment were located in the same room at Boulder. To check the accuracy of the procedure, portable cesium clocks which were checked prior to and after the experiments were located at the NBS, ESSA, and Maui sites. In addition, a crystal clock was available at the STADAN site. Several different kinds of comparisons were made. For example, by exchanging signals between Maui and STADAN the difference between the STADAN crystal and Maui cesium clocks was determined. At the same time, however, the Boulder sites could monitor this exchange. A few minutes after the STADAN-Maui exchange, a STADAN-Boulder exchange was made to determine the difference between the STADAN and Boulder clocks. In the meantime, these exchanges were being monitored at Maui. By comparing the difference between the STADAN and Boulder clocks and between the STADAN and Maui clocks, it was possible to determine the difference between the Maui and Boulder clocks with the STADAN clock as an intermediary. It might be objected at this point that some error could arise because of the fact that the STADAN station did not have a cesium clock; but since the complete set of signal exchanges occurred in a few minutes of time, the amount of drift in the crystal clock was negligible. Table II gives the results of various intercomparisons. The accuracy shown is the average of the absolute value of the time difference for all observations. The standard deviation is given as the error.

TABLE II

Locations	Accuracy, μs	Number of Observations
Boulder-STADAN-Maui	4.2 ± 2.0	5
Boulder-Gunbarrel Hill	4.1 ± 1.8	8
Boulder-Maui	4.0 ± 2.6	4
Boulder-Boulder	3.0 ± 2.8	4

The values given in Table II were obtained by comparing the measured difference determination via the satellite with the known clock differences. The difference between the cesium clocks was known to within one-half microsecond at all times during the experiment. Earlier, the rms phase jitter of the zero crossing was calculated to be about 5 μs. For almost all of the observations, visual inspection of the oscilloscope trace indicated a peak-to-peak jitter of about 15 μs. From the tabulation of the data we see that the accuracy of all intercomparisons was about 4 ± 2 μs. Thus, the measured and computed results are in good agreement. Even though the signals showed a large peak-to-peak jitter, it was possible, by observing the trace, to estimate the average arrival time to within a few microseconds. In fact, recalling that equipment delay measurements had a variation of ± 2 μs, it is apparent that one can estimate the average arrival time with good precision.

Another interesting fact is that the accuracy of the clock setting, within the precision of the measurements, does not depend upon the geographical clock separation. This is not particularly surprising since the round-trip distance from slave to master station via the satellite does not depend very strongly upon the distance between the master and slave stations.

Finally, the comparisons between Boulder and Maui via STADAN are as accurate as any of the others, although an extra measurement step is involved. We attribute this to the fact that better receivers and higher gain antennas are available at the NASA STADAN site so that the signal jitter is less than that observed at the other stations.

Conclusions

A synchronous satellite (ATS-1) containing a VHF transponder has been used to synchronize widely spaced clocks to a few microseconds. The techniques involved exchanging radio timing signals, via the satellite, between the locations of the clocks to be synchronized. An analysis is made of the various factors which might affect the accuracy of the system and it is concluded that the predominant errors were probably related to variations in equipment delays and to fundamental limitations based upon signal-to-noise calculations. Although the signals were in the VHF region, the ionospheric perturbations of the signals produced errors which were negligible compared with other error sources in the system; and it appears that these ionospheric errors did not exceed one microsecond. However, with more sophisticated equipment and stronger signals from the satellite, it is probable that ionospheric limited synchronization could be achieved.

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