THE SIRIO-1 TIMING EXPERIMENT

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ABSTRACT

During the 1979 a time synchronization experiment was performed via the SIRIO-1 satellite. The experiment is sponsored by the Italian National Council of Research (CNR) and was proposed and studied by the Istituto Elettrotecnico Nazionale, Turin, Italy.

The RF communication channels are in the SHF region, with the uplink carrier at 18 GHz and downlink at 12 GHz. The synchronization has been performed between two ground stations located in the northern and in the central part of the country.

One-way and two-way techniques have been evaluated.

Two modes of operation are tested in the two-way technique:

- sequential, time multiplexed, signal transmission on the same communication channel;
- simultaneous transmission using separate communication channel.

In the sequential mode of operation an advanced technique, using range and doppler measurements provided by the timing signals, is used, to take in account for the satellite motion.

A low cost, versatile, time transfer unit (TTU) was designed, to generate the timing signals and the functions (RF carrier and receiver switching, time tagging of the data, etc.) required to perform automatic time synchronization and data acquisition with a minimum of external components.

(1) The work was performed when the author was at IEN.

INTRODUCTION

During the 1979 a time synchronization experiment was performed in Italy via the SIRIO-1 satellite. The experiment was sponsored by the Servizio Attività Spaziali (Space Aotivities Service - SAS) of the Italian National Research Council and was proposed, studied and performed by the Istituto Elettrotecnico Nazionale (IEN), Torino (Italy).

One-way and two-way techniques have been evaluated. Two modes of operation are tested in the two-way technique:
- sequential, time multiplexed, signal transmission on the same communication channel;
- simultaneous transmissions using separate communication channels.

In the sequential mode of operation an advanced technique, using range and doppler measurements provided by the timing signals, is used, to take in account for the satellite motion.

The synchronization has been performed between two ground stations located in the northern and in the central part of the country. The results of the time comparisons have been checked using the TV method and portable clock trips.

The SIRIO-1 satellite

The SIRIO-1 satellite is a synchronous, spin-stabilized, experimental communication satellite, designed to conduct telecommunication experiments and study propagation phenomena at frequencies of 12 and 18 GHz, and was launched by NASA from the Kennedy Space Center on August 25, 1977.

The experimental SHF telecommunication payload consist of a transponder with three separate channels - one for propagation experiments and two for broad and narrow band communication experiments.

The broadband communication channel (34 MHz RF bandwidth at -1 dB) has been used for the time synchronization. The 17.10 GHz uplink carrier is frequency modulated; the available video (baseband) bandwidth used is 6 MHz. The downlink carrier frequency is 11.52 GHz.

Earth stations

The two ground stations, operated by Telespazio S.p.A. (the company is responsible in Italy for the operation of commercial telecommunication space links, mainly through the Intelsat satellites), are located in the northern part of the country, at the top of the Como Lake, near the Swiss border (Lario station) and near Rome (Fucino station).

The two stations, to operate with the SIRIO-1 satellite, are equipped with 17 m diameter azimuth-elevation mount autotrack antennas. The Fucino station serves also as the main control center of the operation of the satellite (tracking and command operations).

THE TWO-WAY TECHNIQUE

In the two-way time synchronization technique (ref. 1) two clocks, located in A and B (fig. 1a), exchange the time information through a satellite communication link.

The basic equation giving the time difference between the clocks is:

$$\varepsilon = \frac{[T_1 - T_0] - [T_3 - T_2]}{2} + \Delta\varepsilon \text{ (corrections)} \tag{1}$$

where ε is the time difference between the clocks in A and B [actually $\varepsilon = T(B) - T(A)$], T_1 and T_3 are the times of reception of the time signals transmitted at the times T_0 and T_2 by A and B (fig. 1b).

The corrections take in account several effects affecting the time synchronization process: the difference in the forward and return paths (from A to B and from B to A) due to the satellite motion and to the Earth rotation, the atmospheric propagation delays and the equipment delays.

Corrections due to the satellite motion

If the signals transmitted by A and B are relayed by the satellite at two different times t_1 and t_2 (fig. 1b) and the satellite changes its position in the time interval (t_2-t_1), the two paths (r_{AB} from A to B and r_{BA} from B to A) are no longer equals; this results in a correction to be applied to eq. (1), that can be written as:

$$\Delta\varepsilon_s = \frac{r_{BA} - r_{AB}}{2\,V_p} \simeq \frac{r_{BA} - r_{AB}}{2c} \tag{2}$$

where V_p (speed of propagation) is assumed to be nearly equal to c (light velocity)

Corrections due to the propagation effects in the atmosphere

Two types of effects have to be considered:

a) tropospheric effects
b) ionospheric effects

The tropospheric effects are frequency independent, so they nearly cancel out when performing the two-way time synchronization (in fact, they contribute nearly equal delays in the forward and return path).

The ionospheric effects (that are frequency dependent) are to be taken in account, again by adding to eq. (1) a second correction $\Delta\varepsilon_p$ in the form:

$$\Delta\varepsilon_p = \frac{\Delta\tau_B(f_u) - \Delta\tau_B(f_d)}{2} - \frac{\Delta\tau_A(f_u) - \Delta\tau_A(f_d)}{2} \tag{3}$$

where $\Delta\tau_N$ (N = A, B) is the additional delay (with respect to the free-space propagation) introduced in the path between the station N and the satellite; f_u is the uplink carrier frequency and f_d is the downlink carrier frequency for the station N (separate carriers may be employed in A and B).

At the frequencies employed in the SIRIO-1 experiment, the effects due to the eq. (3) are negligible.

Instrumentation delays - ground segment

The delays in the transmitting and receiving equipments must be taken in account; they contribute a correction $\Delta\varepsilon_{eq}$ given by

$$\Delta\varepsilon_{eq} = \frac{[\Delta\tau_{tr}(B) - \Delta\tau_{rec}(B)] - [\Delta\tau_{tr}(A) - \Delta\tau_{rec}(B)]}{2} \tag{4}$$

where: $\Delta\tau_{tr}(N)$ is the delay in the transmitting equipment and $\Delta\tau_{rec}(N)$ is the delay in the receiving equipment, at the station N $(N = A, B)$.

Instrumentation delays - space segment

The correction $\Delta\varepsilon'_{eq}$ takes in account for the differential delay in the satellite transponder; if f_N is the frequency used by the station N, this correction can be written as:

$$(5) \qquad \Delta\varepsilon'_{eq} = \frac{\Delta\tau_{transp}(f_B) - \Delta\tau_{transp}(f_A)}{2}$$

where $\Delta\tau_{transp}(f)$ are the group delays of the satellite transponder at the frequency f.

Modes of operation

Let we set (fig. 1b)

$$(6) \qquad \Delta t = T_2 - T_1$$

Δt can be regarded as an arbitrary time interval (and we will make use of its arbitrariness in the following analysis) defining three possible modes of operation:

a) $\Delta t > 0$: the two stations transmit sequentially in time;
b) $\Delta t \simeq 0$: the signal transmitted by A is simply transponded back by B;
c) $\Delta t < 0$: the two stations transmit simultaneously to the satellite.

If the two stations transmit sequentially in time (case a), only one communication channel can be used, but in this case the satellite motion must be taken in account, to compensate the differences between the forward and return paths. In addition, if one channel is used, the correction due to eq. (5) vanishes.

If two channels are used, the two stations can transmit simultaneously, in order to have the signals relayed nearly at the same time by the satellite (case c), so that the change in paths due to the satellite motion can be neglected.

THE SIRIO-1 EXPERIMENT - SEQUENTIAL MODE OF OPERATION

The time synchronization SIRIO-1 experiment was designed to test and precisely measure the effects of the satellite motion.

Each ground station (fig. 2a), in addition to receive the signals transmitted by the other station, receives its own signal, relayed back to Earth by the satellite. This can be implemented easily, as shown in fig. 2b. We use a fixed synchronization sequence, that will be covered in detail later, so that the time of transmission for each station is at fixed times, according its own time scale.

With reference to the geometry depicted in fig. 2a, the basic synchronization equation, in which the corrections for the satellite motion are taken in account, becomes:

$$\varepsilon = \frac{(T_1 - T_0) - (T_3 - T_2)}{2} + \frac{(r_2 + r_2') - (r_1 + r_1')}{2c} \tag{7}$$

Now, we can write with good approximation [if $(t_2 - t_1)$ is small]:

$$r_2' = r_1 + \dot{r}_A (t_2 - t_1) + \ldots$$

$$r_1' = r_2 + \dot{r}_B (t_1 - t_2) + \ldots$$

where $\dot{r}_N$ is the range rate of the satellite with respect to the station $N (N = A, B)$ and the higher order terms in the series expansion are negligible.

Let we define the pseudo-ranges $\bar{r}_1(t_1)$ and $\bar{r}_2(t_2)$ as:

$$\bar{r}_1(t_1) = \frac{T_4 - T_0}{c} \quad ; \quad \bar{r}_2(t_2) = \frac{T_5 - T_2}{c} \tag{9}$$

so that, by having a sequence of n synchronization measurements, an estimate of the range rate can be obtained in the following form:

$$\dot{r}_A = \frac{\bar{r}_1(t_1)_{n+1} - \bar{r}_1(t_1)_n}{(t_1)_{n+1} - (t_1)_n} \tag{10}$$

(10) $$\dot{r}_B = \frac{\bar{r}_2(t_2)_{n+1} - \bar{r}_2(t_2)_n}{(t_2)_{n+1} - (t_2)_n}$$

so that we finally obtain:

(11) $$\varepsilon = \frac{(T_1 - T_0) - (T_3 - T_2)}{2} + \frac{\dot{r}_A + \dot{r}_B}{2c} (t_2 - t_1)$$

where: $$t_1 \simeq \frac{T_4 + T_0}{2} \; ; \quad t_2 \simeq \frac{T_5 + T_2}{2}$$

Obviously the determination of t_1 and t_2 is biased by the relativistic effect due to the Earth rotation (Sagnac effect) and by the non-reciprocity of the forward and return paths; however, these effects produce only a very small error on ε, so that they can be neglected.

But the time interval $(t_2 - t_1)$ is biased by a larger error: this is the same difference ε between the clocks, since t_2 and t_1 are measured in different time reference frames.

In principle, the two-way time synchronization technique sets no limits to the initial value of ε, that can be very large; the only limitation comes from the technical implementation of the synchronization procedure. It may be shown that for the fixed synchronization sequence implemented in the SIRIO-1 experiment, ε can be initially as large as 100 ms, without affecting the automatic operation of the equipment (mainly the data acquisition system).

Iterative solution

A simple iterative technique overcomes this problem. Let we neglect the offset ε, biasing the time interval $(t_2 - t_1)$; neglecting for now the other sources of error, it's easy to see that the error $\delta\varepsilon$, on the determination of ε, produced by the bias on $(t_2 - t_1)$, is given by:

(12) $$\delta\varepsilon = \frac{\dot{r}_A + \dot{r}_B}{2c} \varepsilon$$

This suggests that an iterative procedure can be stated, the error $\delta\varepsilon_{k+1}$ at the k+1 iteration step being expressed by:

$$(13) \qquad \delta\varepsilon_{k+1} = \frac{\dot{r}_A + \dot{r}_B}{2c} \varepsilon_k$$

The iteration converges very quickly to the resolution of the measurement system, since the term $(\dot{r}_A + \dot{r}_B)/2c$ is very small; usually one step is all that it is required to minimize the error due to ε.

Close form solution

A close form solution can be obtained by introducing ε in the right side of eq. (11), that now becomes:

$$(14) \qquad \varepsilon = \frac{(T_1 - T_o) - (T_3 - T_2)}{2} + \frac{\dot{r}_A + \dot{r}_B}{2c}(t_2 - t_1 - \varepsilon) + \text{+ corrections}$$

from which it is easy to obtain:

$$(15) \quad \varepsilon = \frac{[(T_1 - T_o) - (T_3 - T_2)] + \frac{\dot{r}_A + \dot{r}_B}{c}(t_2 - t_1) + \text{corrections}}{2\left(1 + \frac{\dot{r}_A + \dot{r}_B}{2c}\right)}$$

Corrections due to the propagation in the atmosphere and satellite transponder differential delay.

Only a very small bias is expected due to the propagation effects in the atmosphere; since it is quite small as compared with the resolution of the measurement system (based on the HP5345 counter, whose resolution is 2 ns), this bias can be considered negligible.

Since only one communication channel is used, the satellite transponder does not affect the synchronization accuracy. The satellite motion is precisely measured, so that, except for the Sagnac effect, that can be easily computed, no other effects, related to the space communication link (from one ground antenna to the other), affect the synchronization accuracy in the SIRIO-1 experiment, the main source of error still being represented by the uncertainties in the measurement of the ground communication equipments delays.

Corrections due to the Earth rotation (Sagnac effect)

This correction was computed and, due to the relative geometry of the satellite with respect to the ground stations, the total effect was evaluated to be about 15 ns.

A complete derivation of the equation giving this correction is reported in app. A, for reference.

THE TIME SIGNALS

The time signals used in the SIRIO-1 experiment consists in a burst of ten pulses (fig. 3); the duration of each pulse is 1 ms and the repetition period of the pulses within the burst can be manually set by the operator to be 5 or 10 ms (the time signal must be the same for both stations).

The received pulse repetition rate shows no relative doppler against the transmitted pulses, because of the small satellite motion in about 100 ms (that is the maximum duration of the burst), so that the repetition period between the received pulses can be considered constant and equal to the transmitted repetition period.

This allows ten measurements of the time T_n, since the relative time of occurrence of each pulse with respect to the first one is constant and well known. The time T_n is then computed as the mean over ten separate values; moreover, the standard deviation over this set of ten independent time measurements is related to the precision obtained in the determination of the time T_n. This allows to monitor the uncertainty in the determination of the time of reception of the signals in each station.

GROUND EQUIPMENT CONFIGURATION

The instrumentation installed in each station is shown in fig. 5. One cesium beam frequency standard (HP 5061 and Oscilloquartz 3200) generates the local time scale. The 1 MHz and 1 Hz output signals are fed into the time transfer unit (TTU), that actually controls the synchronization procedure.

The 1 Hz distribution amplifier provides several outputs that are used in the TTU calibration procedures and for the TV synchronization subsystem.

The time interval counter used is a HP 5345A, that receives the start and stop signals from the TTU; it is fully controlled (functions, trigger levels, output mode, etc.) by a HP 9815 programmable desk calculator, that acts also as a data acquisition system (via HP-IB bus), receiving the results of the measurements from the counter and storing the data on the built-in magnetic tape unit.

The TTU generates and receives the time signals from the communication equipment; the existing FM modulators-demodulators are used: the available video bandwidth is 6 MHz. The output of the modulator is the first 70 MHz IF, switched, under the TTU control, to provide the RF carrier suppression in the sequential mode of operation (while the gating of the received signal Rx is performed internally by the TTU itself).

The two cesium standards are also compared by using the passive TV synchronization system via the TV synchronization subsystem.

The time transfer unit (TTU)

The time transfer unit (TTU) controls the synchronization procedure by performing several functions:

1) generation, according the selected mode of operation, of the time signal Tx to be transmitted;
2) generation, in the correct sequence, of the start and stop signals to the counter;
3) time tagging of the data;
4) switching of the RF carrier in the sequential mode of operation, and gating of the receiving functions (to avoid noise related problems when the carrier is off).

Moreover, the TTU has a self-test capability (by simulating the signals received from the satellite in both the operation modes) and provides the internal switching to measure the internal delays (the results of these measures are also stored on tape with the data, in a separate file).

A block diagram of the TTU is shown in fig. 6.

The TTU receives the 1 MHz and 1 Hz signals from the frequency standard. All the other signals are generated from the 1 MHz signal; however, since the synchronization results are usually referred to the 1 Hz output signal from the clock, this is internally used to synchronize all the TTU functions.

The main purpose of the TTU is the generation of the time signals; this functions is performed by the Signal Generation Subsystem (SGS); the repetition period of the ten pulses in the transmitted signal (fig. 3) can be set manually by a front panel switch to 5 or 10 ms.

The transmission time T_n (fig. 3) can be shifted over a 1 s time interval (that is the synchronization frame, see sect. 6) in 1 ms steps via a 3 digit thumbwheel switches; this is important when performing the time synchronization in the simultaneous mode of operation.

The generated signals are fed into the Logic Control Subsystem (LCS), that provides the signals to be transmitted (Tx) with the proper transmission rate; this rate can be set by another thumbwheel switch to generate a synchronization measurement:

- every second;
- every odd or even second (to avoid ambiguities in the switch setting at the two stations);
- every fifth second;
- every tenth second.

The LCS controls also the operation mode (sequential or simultaneous synchronization) and the status of the TTU (self-test or operation).

The LCS generates the start and stop signals to the counter and the control signals for the RF carrier switching and the gating of the received signals Rx (sequential mode of operation only).

In the self-test mode the LCS receives the simulated return signal from the satellite simulator subsystem (SSS), that is in turn controlled, according the operation mode, by the LCS.

The LCS receives also the time-of-the-measurement information from the internal clock, via a special subsystem called Time

Tag Interval Generator (TTIG). The TTIG receives a truncated time information (minutes and seconds of the measurement, the hours are omitted, the code is BCD parallel) from the clock and generates a variable length time interval (VLTI); the duration of the VLTI, in µs, corresponds to the digital readout of the internal clock (i.e.: if the clock time is XX hours, 26 minutes and 56 seconds the duration of the VLTI is 2656.OYY µs, where X and Y are undefined digits).

The internal clock is driven directly by the 1 Hz signal generated by the SGS; this is obtained by dividing the 1 MHz signal from the frequency standard; 6 thumbwheel switches allow the time setting of the clock (hours to seconds); the residual setting (up to 1 µs) is performed automatically by the internal 1 Hz synchronization circuit.

The TV measurement subsystem

TV signals received in both stations are used to compare the two frequency standards after an initial and routine clock trips to measure the propagation delays have been performed.

A differential, passive method of comparing the two clocks against a common reference (a selected field synchronization pulse in the TV transmission) has been used; the measurements are performed when test patterns are radiated, once a day, from a central location (the television channel monitored is the state broadcasting television network), in order to minimize uncertainties and possible errors due to microwave links switching over different routes when local programs are transmitted. Moreover the test pattern provides a more stable and high quality signal.

The TV receiver (fig. 7) is a special, in-house built, receiver, designed to improve the separation of the signal of interest, that is performed digitally.

A programmer subsystem with an internal clock is provided; this controls the power switching of external equipment (HP 9815 calculator and HP 5345 counter), with the proper timing [to load and start the program (the 981.5 is in the autorun mode), to program the counter, to generate the proper signals to the counter, to record the data on the tape, to update the file name and other variables] to execute automatically, once a day at the selected time, the TV synchronization procedure without any operator intervention in both the stations.

SEQUENTIAL MODE TIME TRANSFER

The time transfer in the sequential mode of operation is depicted in fig. 8.

The basic synchronization frame is 1 second; that means that it is possible to obtain one value of ε from the measured data over a 1 s interval.

The approach chosen is a fixed synchronization scheme, in which the two stations transmit at fixed times according their own time scale. The main advantages of this approach are:

1) the basic synchronization frame can be lenghtened by simply rearranging the data, as we will show later;

2) the initial synchronization error (time difference ε between the clocks) can be as large as 100 ms without affecting the timing of the time transfer.

Since all the times shown are within a 1 s time interval, starting at the time T_o, all the time measurements are unambiguously referenced to T_o; the time tag measurement resolves the second ambiguity.

The time transfer (fig. 8) is started by the transmission of the time signal at 0 seconds (T_o) by the station A. This signal is not expected, obviously, to be received in both stations within the next 0.2 s.

The first 100 ms are then devoted in both stations to time tag the measurement.

A start pulse is generated at 0.5 μs (this 500 ns delay allows the setting of the internal clock counters after the count transition) and a stop pulse is generated after a time tag interval (TT), whose duration in μs is equal to the clock reading at T_o (minutes and seconds).

In this way, the first measurement obtained by the counter is the time tag of the measurement.

At 100 ms (from T_o) another start pulse is generated and now the counter in both stations will be stopped by the leading edge of the first received pulse.

This gives the coarse measurement of the time of arrival of the pulses relayed back by the satellite (T_4 and T_1). For example, at the station A the measured time interval will be ($T_4 - T_o - 0.1$ s).

After the first pulse is received, nine start pulses are generated synchronously with the local clock and with the same repetition rate of the transmitted pulses. The corresponding nine stop pulses are provided by the remaining pulses of the received signal (fig. 4).

Since the doppler shift over these pulses can be neglected (see sect. 4) these nine measured intervals provide nine additional values to determine the time of arrival T_4 (or T_1) [modulo the repetition rate of the pulses, but any ambiguity is removed by the first measurement].

This allows $T_4(T_1)$ to be computed as the mean of the measured values and to obtain an extimate (based on the standard deviation of the measurements) of the precision related to the determination of the time $T_4(T_1)$ in each station separately and for each measured value.

At 0.5 s (according its local clock) the same time signal is transmitted by the station B; a start signal is generated in both sites at the time 0.6 s and the same procedure outlined before is repeated to recover the times T_3 and T_5.

A total of 21 measured values is recorded at each station for every synchronization measurement in the sequential mode of operation.

RF carrier switching

A timing diagram of the RF carrier switching and the gating of the received signals Rx is shown in fig. 9.

The basic requirements that are satisfied by such an arrangement are:

a) the carriers from A and B do not enter the satellite at the same time and a suitable time window is provided to avoid any interference (since the propagation delay is not the same for the two sites and the timing is, in principle, based on clocks that are to be synchronized;

b) a suitable time interval is allowed to stabilize the RF carrier before transmitting the time signals;

c) the gating of the received signal is implemented in such a way that the Rx signal (that provides some stop signals to the counter, as shown in fig. 8) is enabled only after the RF carrier is received and stabilized.

The RF carrier switching is implemented at the first IF level (70 MHz); this simply shifts 70 MHz apart the RF carrier at 17 GHz, outside the bandwidth of the RF power amplifier.

Some considerations on the sequential time transfer

The fixed synchronization scheme as implemented is very useful to provide a variable lenght synchronization frame.

Suppose to implement the time synchronization over the basic frame (fig. 8) repeated every second (the TTU provides a selection of different repetition rates for the basic synchronization frame).

This provides a synchronization result $\varepsilon(\tau = 1\ s)$ every second, showing the relative behaviour of the two clocks. At this level the correction due to the satellite motion is negligible $((t_2-t_1) \simeq 0.5\ s)$ and we are perfectly aware of this (this is not an assumption) because we are able to evaluate the correction with the range-rate estimates (eq. 11); the correction, in this typical case, is in the order of 1 ns.

Now, let we consider the same basic sequence, but expanded over a 10 s interval; this can be obtained easily by simply taking the measured times of arrival T_4 and T_1 from the synchronization frame at T_o and the times T_3 and T_5 from the synchronization frame at $T_o + 10$ s.

Now the time interval $(t_2 - t_1)$ is about 10.5 s and the correction is about 10 times greater (eq. 11). In this way we have another set of values $\varepsilon(\tau = 10\ s)$. We can compute these values without applying any correction. The difference between each $\varepsilon(\tau = 10\ s)$ and $\varepsilon(\tau = 1\ s)$ shows exactly the effect due to the satellite motion and, moreover, we are able to compute this correction and compare our estimate (based on a first order approximation of the satellite motion) with the measured values.

This procedure can be repeated for every τ of interest by using the same data. A reference set of values is always provided by the $\varepsilon(\tau = 1\ \mathrm{s})$ set.

SIMULTANEOUS MODE OF OPERATION

In addition to the sequential time transfer, a simultaneous mode of operation time synchronization has been planned. Using this well-known technique, the time signals emitted by the two ground stations are relayed by the satellite at the same time, thus avoiding any error on ε due to the satellite motion (see fig. 10).

The basic synchronization equation becomes now:

$$\varepsilon = \frac{(T_1 - T_0) - (T_3 - T_2)}{2} + \text{corrections} \qquad (16)$$

where the corrections are due only to equipment delays, propagation delays and to the relativistic correction (app. A): as was shown, the corrections due to the propagation effects in the atmosphere can be considered negligible.

Two separate RF communication channels are obtained by splitting the available 40 MHz RF bandwidth in two 15 MHz bandwidth channels, at the expense of a reduced signal to noise ratio, while maintaining the same video bandwidth (6 MHz) as in the sequential mode of operation.

The two RF carriers are obtained with a change of the local oscillator frequency at the 2nd IF (transmission) and 1st IF (reception), so that the available 70 MHz modulators-demodulators are still used.

Since now two separate channels are used, the differential delay in the satellite transponder must be taken in account as a corrective term, given by eq. 5.

This delay has been measured by Telespazio (ref. 2) and resulted to be about 0.5 ns/MHz. At a carrier separation of about 20 MHz, the value of the correction to the synchronization result ε is about 5 ns.

Procedure to obtain the simultaneous transmission from the satellite

A simple mean to adjust the transmission time in order to obtain the desired simultaneity of transmission of the time signals from the satellite is provided by adding an additional receiver (demodulator + IF) at one site (see fig. 5). This additional equipment receives back the signal transmitted by the same station, to allow a comparison to be made with the signal transmitted by the other site.

In this way the simultaneity is checked by observing the local pulses as received back from the satellite along an oscilloscope, the pulses coming from the other station. The transmitted signal is then shifted until nearly coincident (within a few ms) times of reception are achieved (fig. 11).

Even if the simultaneity error α (fig. 11) can be reduced in this way to less than 1 ms, usually a much larger error can be tolerated.

In fact, it can be easily shown by using the same equations as in sect. due to sequential mode of operation (where now $t_2-t_1 = \alpha$) that the error $\delta\varepsilon$ on ε due to α is approximately given by:

(17) $$\delta\varepsilon \simeq \frac{\dot{r}_A + \dot{r}_B}{2c}\alpha$$

so that α can be as large as 100 ms without introducing a noticeable error on ε.

Simultaneous mode time transfer

The simultaneous time transfer is again obtained by using the same equipment described, and again a fixed synchronization sequence is easily generated by the TTU (refer to fig. 12) over a basic synchronization frame of 1 second.

The first 100 ms are devoted to time tag the measurement, so that any ambiguity is removed for later data processing; this is the only constraint. The first 100 ms are not used in this case for time transfer; however this can be implemented freely in the following 900 ms.

In fact, in this case, the transmission times in both sites are not fixed and, moreover, can be changed during the operations to compensate for the satellite motion: so, the time of transmission $T_o(T_2)$ must be recorded and this is accomplished by generating a start pulse at 0.1 s and a stop pulse when the time signal is transmitted (T_o or T_2); in this way the second time interval measurement recorded for each frame gives the transmission time.

After 10 ms (at the time $T_o(T_2) + 10$ ms) a new pulse is generated; since T_o is recorded, also the time of this pulse is known.

The leading edge of the first received pulse stops the counter at the time $T_3(T_1)$; this gives the coarse measurement of the time of reception of the pulses. Following the same procedure described above, nine start pulses are generated to provide additional nine values for the time of reception (modulo the repetition period of the pulses in the time signal).

A total of 12 measured values is recorded at each station for every synchronization measurement (1 s frame) in this mode of operation. The TTU provides as usual different repetition rates for the basic synchronization sequence.

CONCLUSIONS

The SIRIO-1 experiment was designed and implemented to measure and analyze the effect of the satellite motion on the accuracy of the two-way time synchronization and to demonstrate the feasibility of accurate time transfer using only one communication channel, time-multiplexed between the two stations.

The main features of the experiment are briefly summarized here:

1) the experiment tests and compares different techniques to implement the two-way time synchronization, and

2) precisely monitors the satellite motion;

3) a new technique has been proposed to correct for the satellite motion effect, while performing the time synchronization;

4) the experiment features a fixed synchronization scheme, allowing the flexibility of a variable length synchronization frame;

5) the synchronization in the sequential mode of operation is obtained by a time multiplexing technique, with automatic, fast RF carrier switching;

6) no effects affecting the accuracy at the 1 ns level are due to the space segment (from one ground antenna to the other) in the sequential mode;

7) the technique can be easily extended to a multiple site synchronization; inherent advantages of the methods tested are:

8) the low cost and almost automatic operation; moreover the time signals used

9) allow the independent determination of the uncertainties of the time-of-arrival measurements at the two stations, to separate the contribution of each station to the total precision.

This last feature can be important to understand the contribution of local phenomena (ground equipment, atmospheric condition affecting the signal attenuation, especially rain at SHF, etc.) to the synchronization precision.

Especially the sequential time transfer technique can be proposed as a useful tool to synchronize ground telecommunications stations; in addition to the time synchronization, it can provide also measurements related to the satellite orbital status (range and range-rate) with interferometric capabilities (since two stations are involved at the same time and the clocks offset is measured with high precision), that can be used to track the satellite or update the orbit elements with different techniques (i.e., differential correction of the existing parameters).

A complete analysis of the initial measurements is under way and the results will be available at a later time. The first results show a precision between 5 and 10 ns (1σ) for rough (non filtered) data.

The accuracy is expected to be only dependent from the accuracy in the measurement of the ground equipment delays (see app. B).

ACKNOWLEDGEMENTS

The authors would like to thank the Telespazio personnel at the two ground stations, and particularly Mr. Marello, Mr. Guerra and Mr. Saggese, for their generous assistance.

We wish also to acknowledge the work of the IEN personnel in performing the experiment; we are especially grateful to V. Pettiti, P.G. Galliano, E. Angelotti, F. Cordara, G. Moro, L. Canarelli, L. Pietrelli and V. Marchisio that actually carried on the measurements at the two sites, to G. Rietto for the software support, to E. Bava, A. De Marchi and A. Godone for the RF work, to Mr. G. Galloppa for the drawings and to Mrs. M. Castello for the typewriting.

This work was made possible by a grant from the Italian National Research Council.

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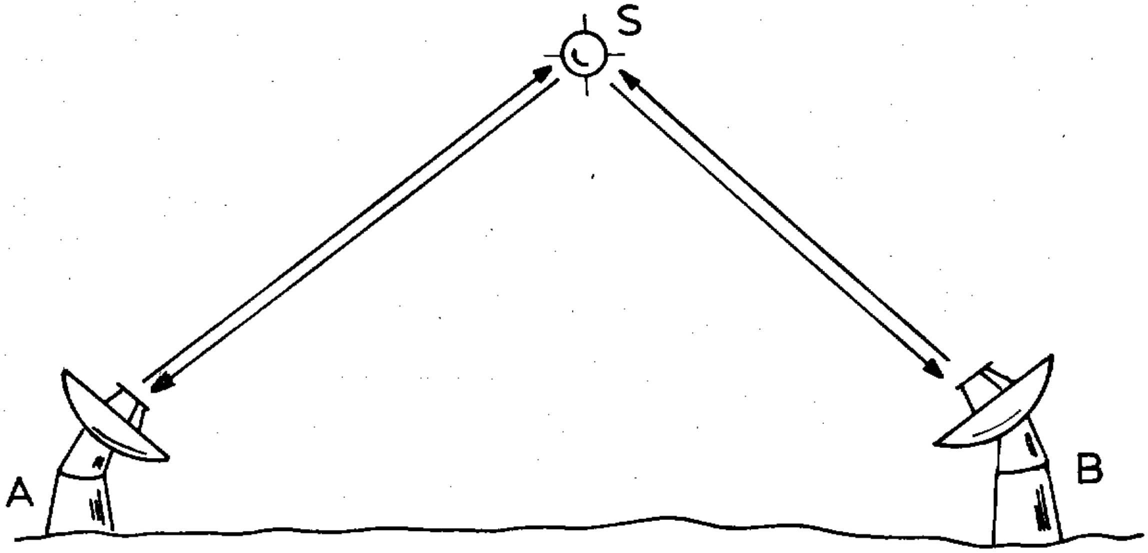


Figure 1a. Two-Way Time Synchronization Via Satellite

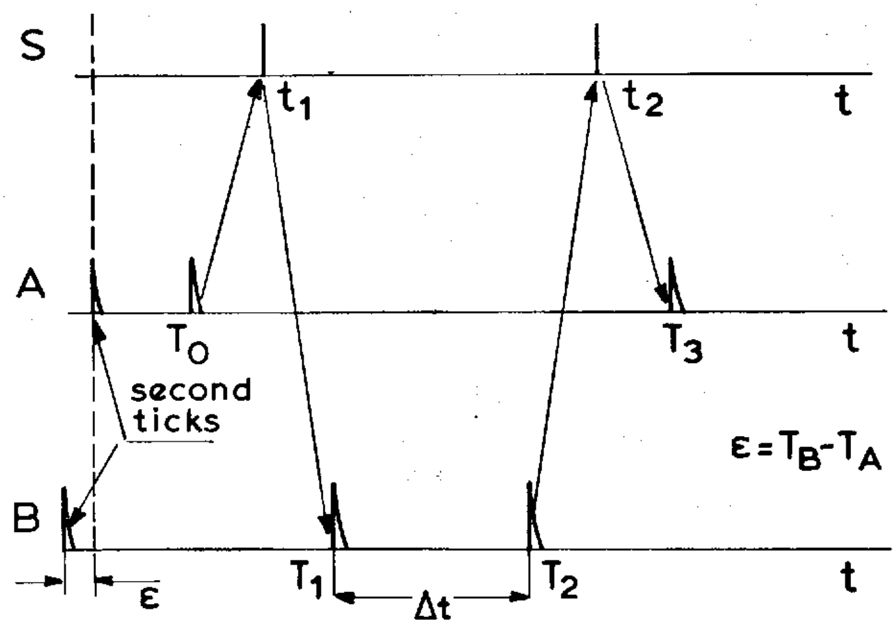


Figure 1b. Timing Diagram

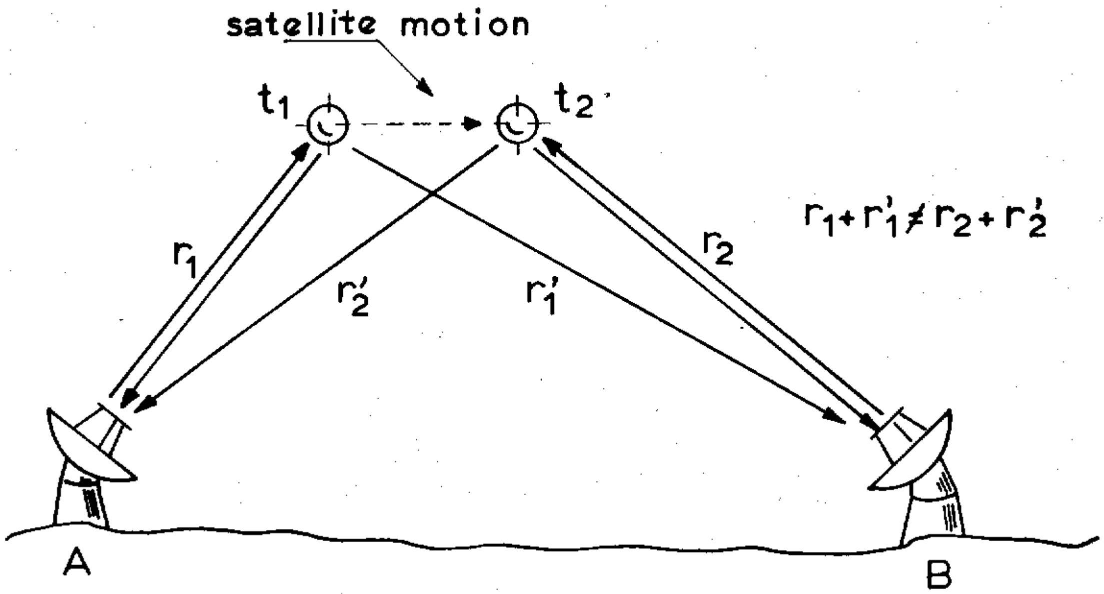


Figure 2a. Two-Way Time Synchronization – Sequential Mode

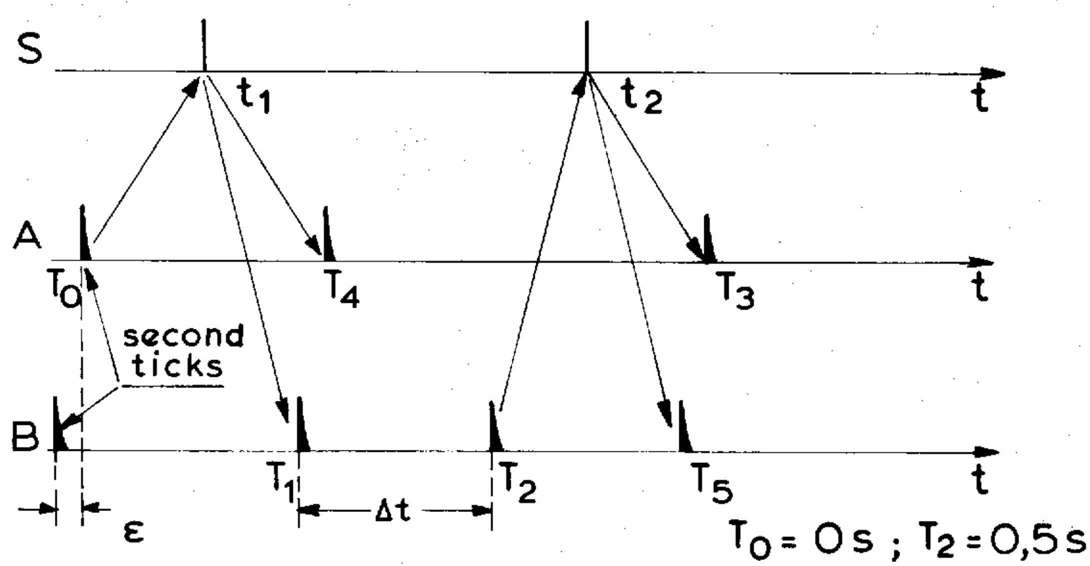


Figure 2b. Sequential Mode – Timing Diagram

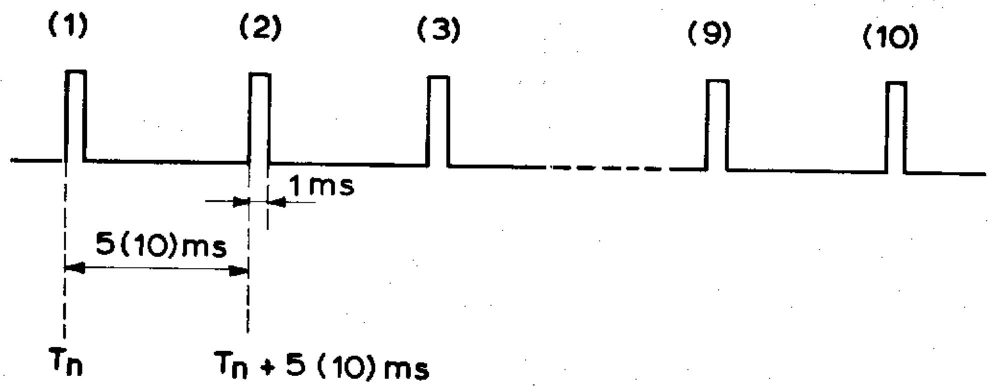


Figure 3. Timing Signal

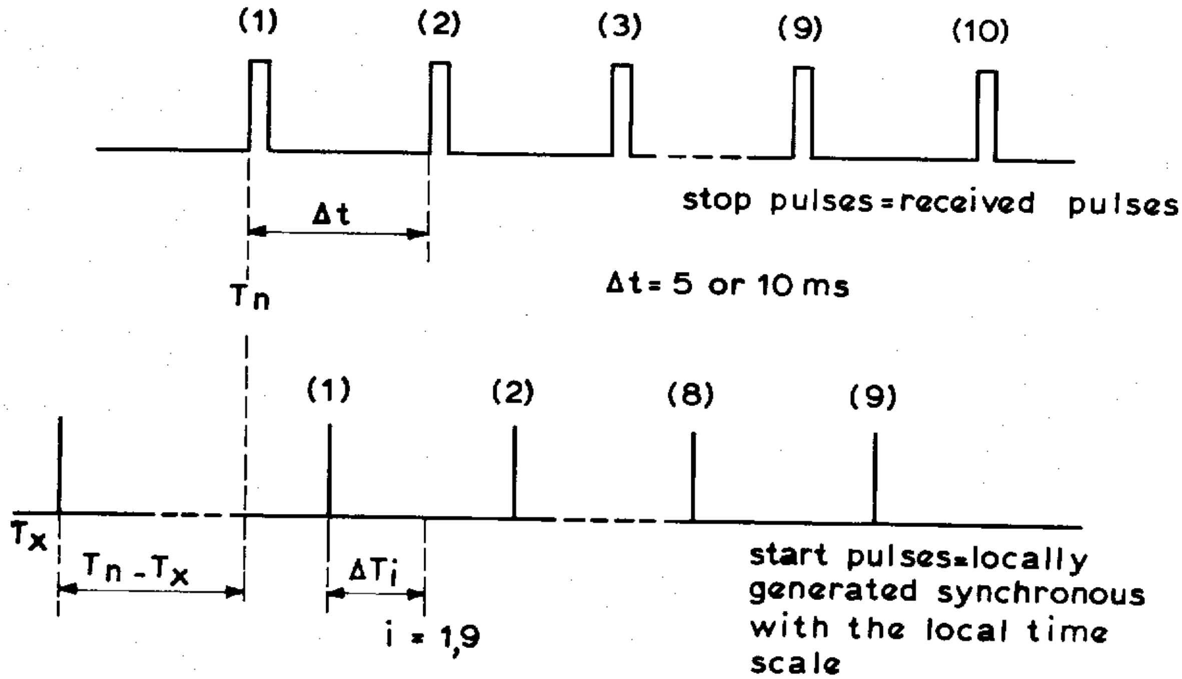


Figure 4. Time of Reception Measurements

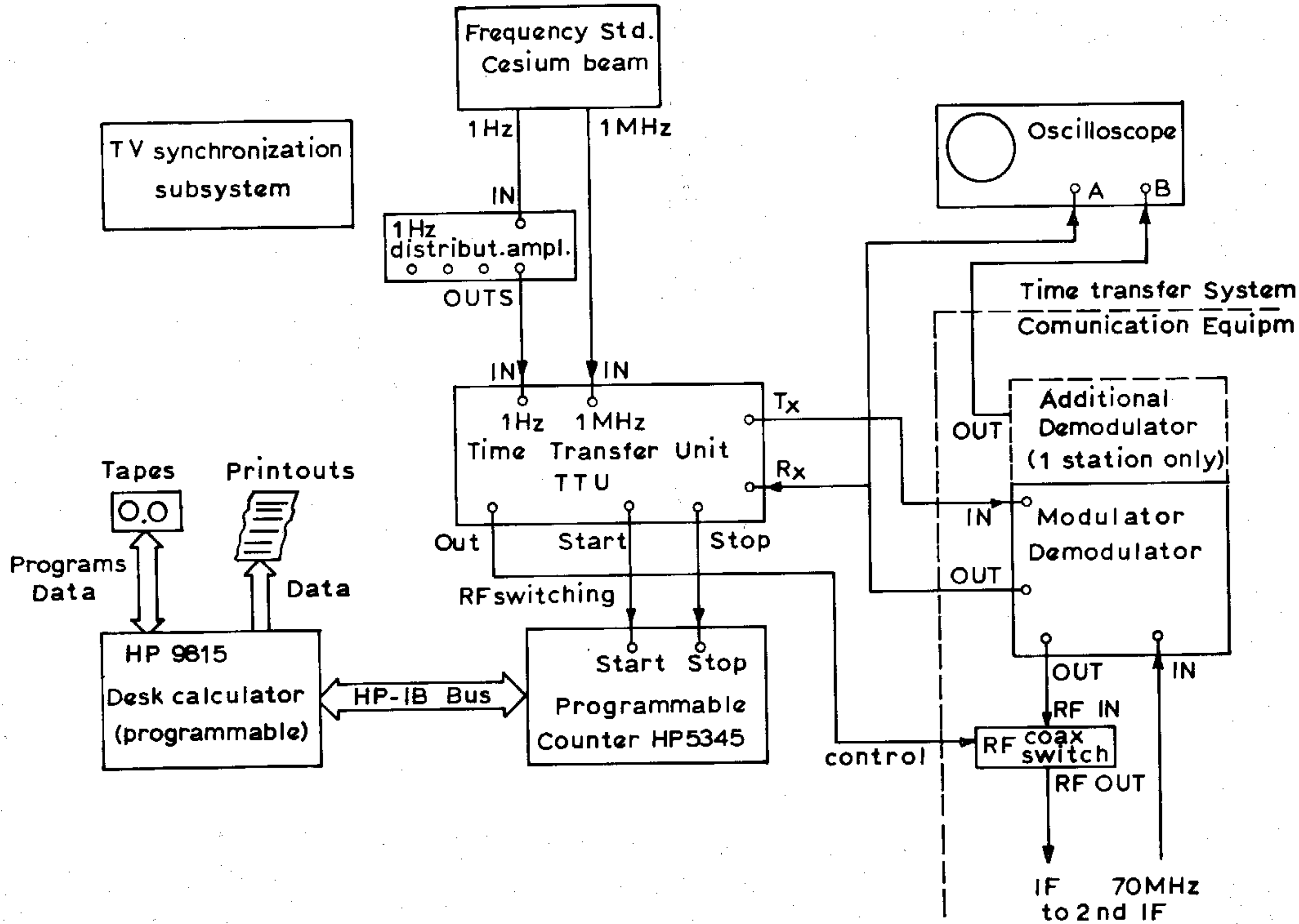


Figure 5. Experimental Set-Up

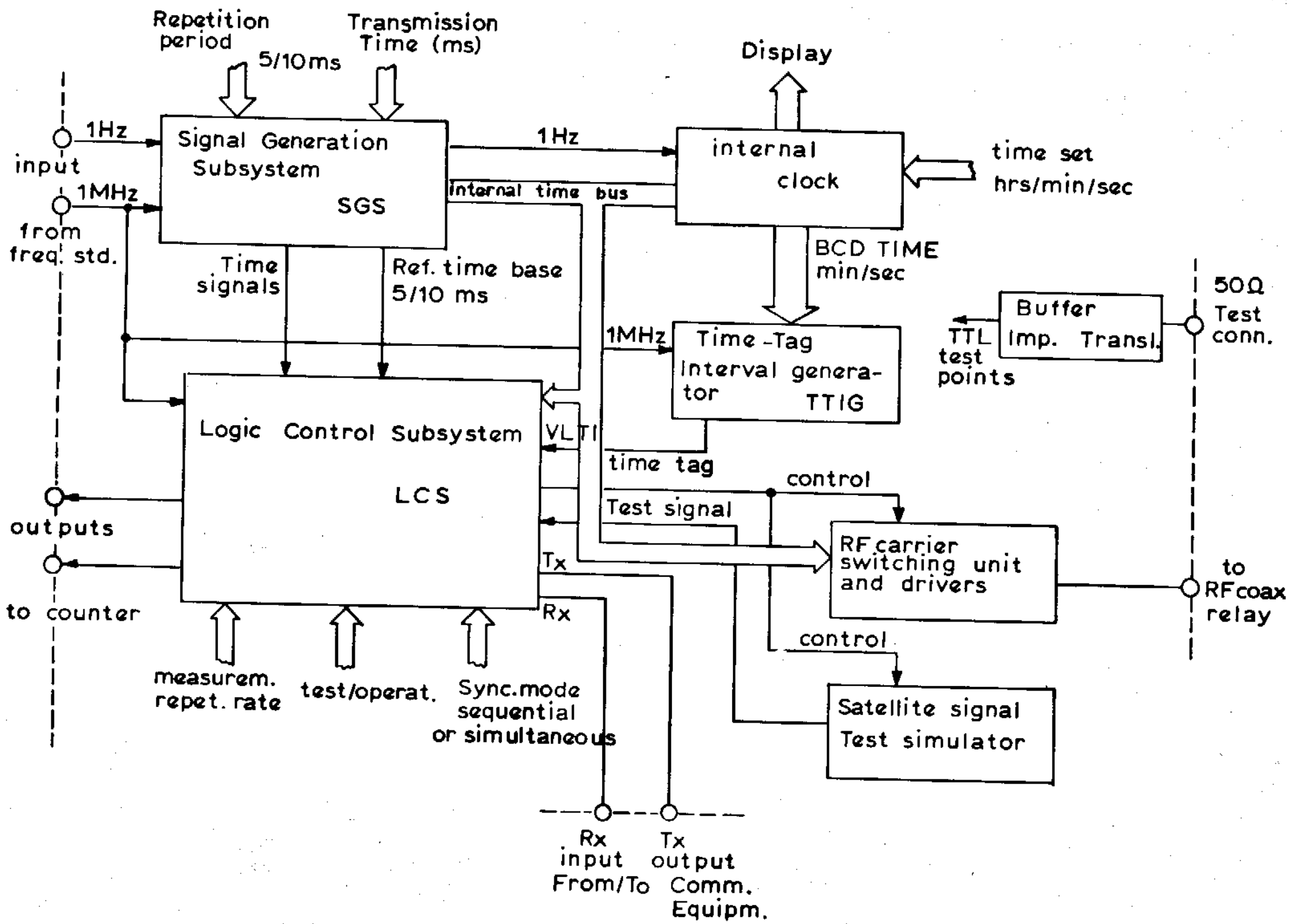


Figure 6. Time Transfer Unit-Block Diagram

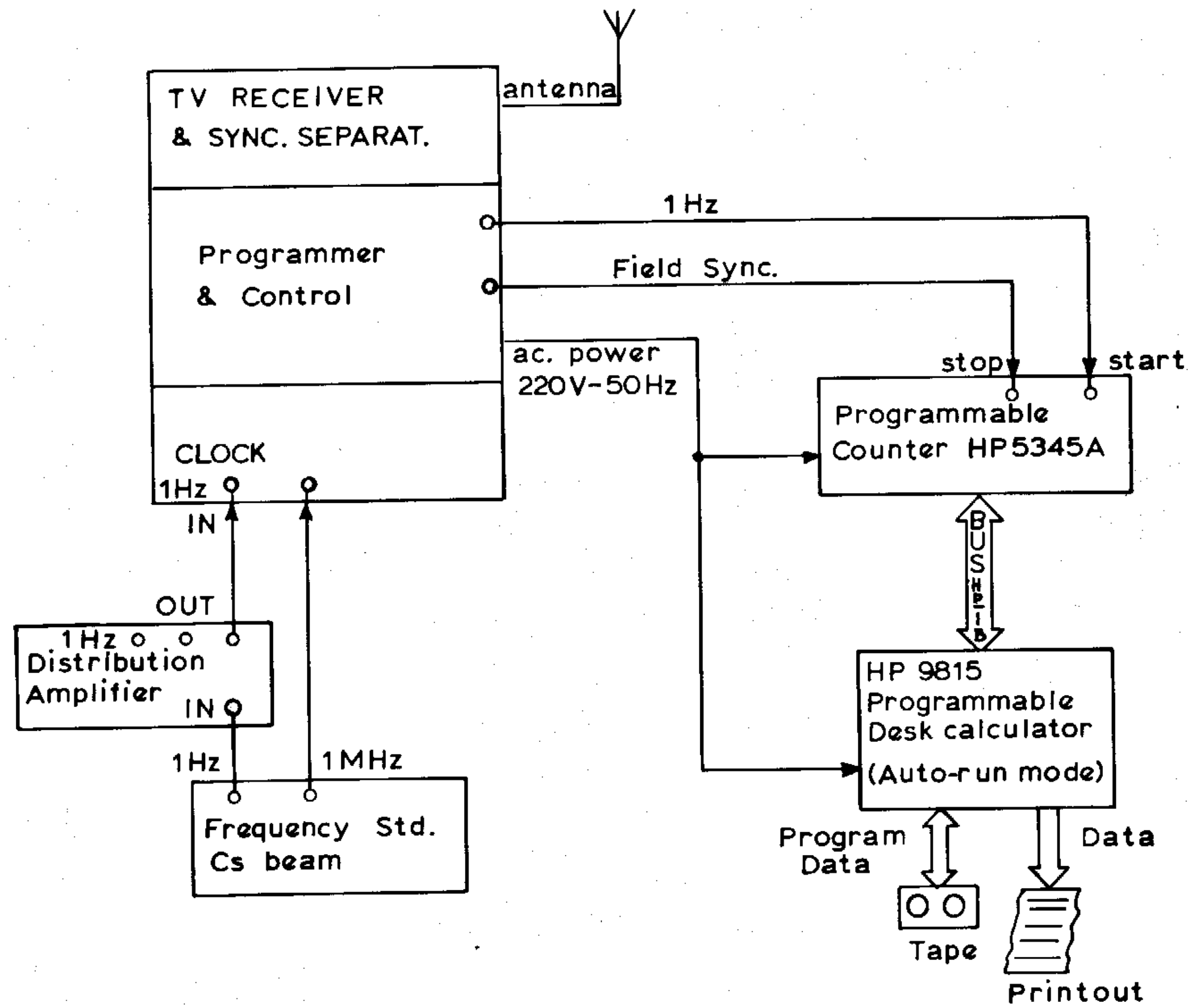
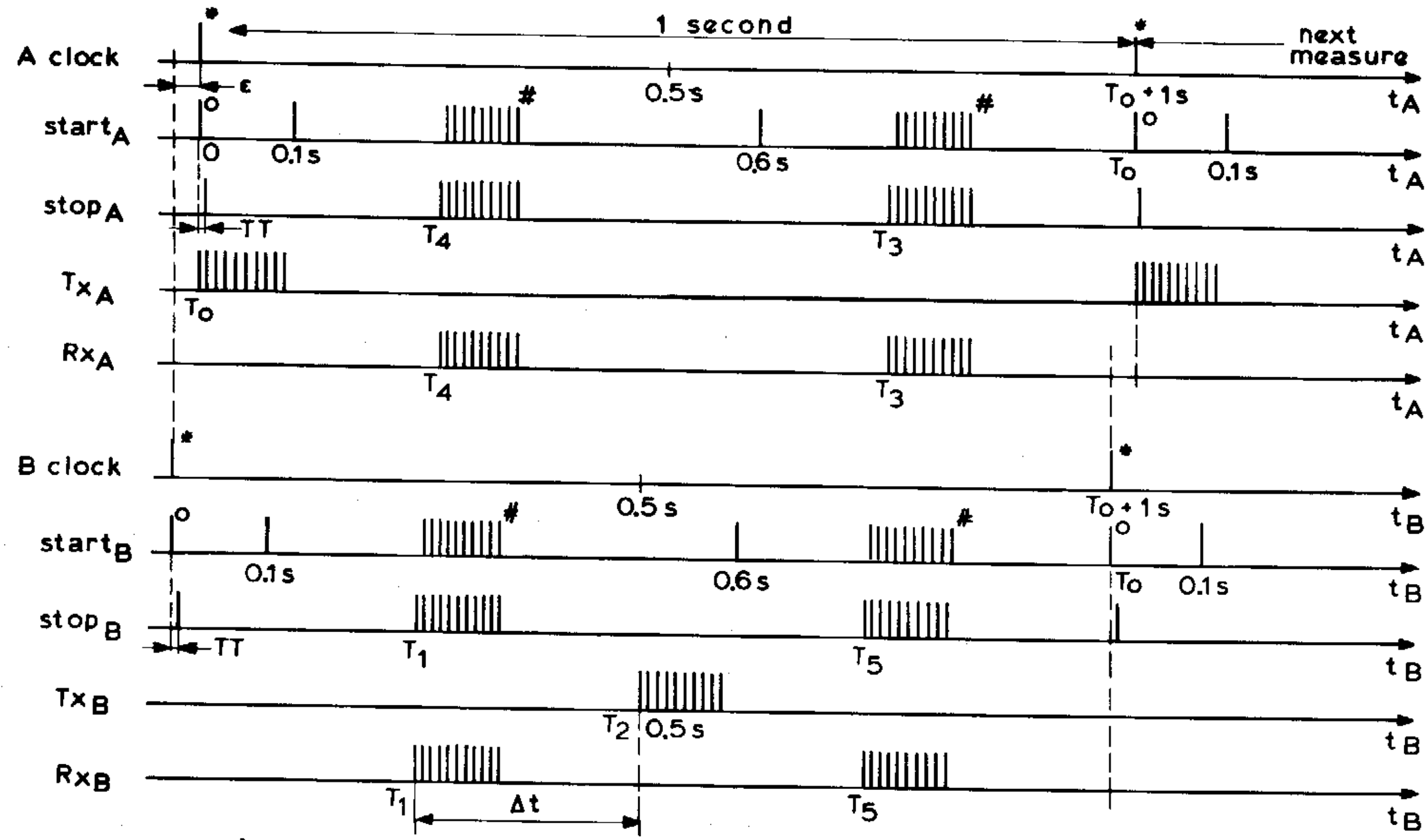


Figure 7. TV Synchronization Automatic Subsystem



ref. to fig.2b for the times

T_o = 0 s (according local clock)

* = second ticks

o = actually $T_o + 0.5\,\mu s$

TT = Time Tag Interval (variable-max 5959 μs)

\# = see fig.4

Reference frame = 1s

Pulse repetition period: 0.01s

Figure 8. Sequential Mode Synchronization Frame

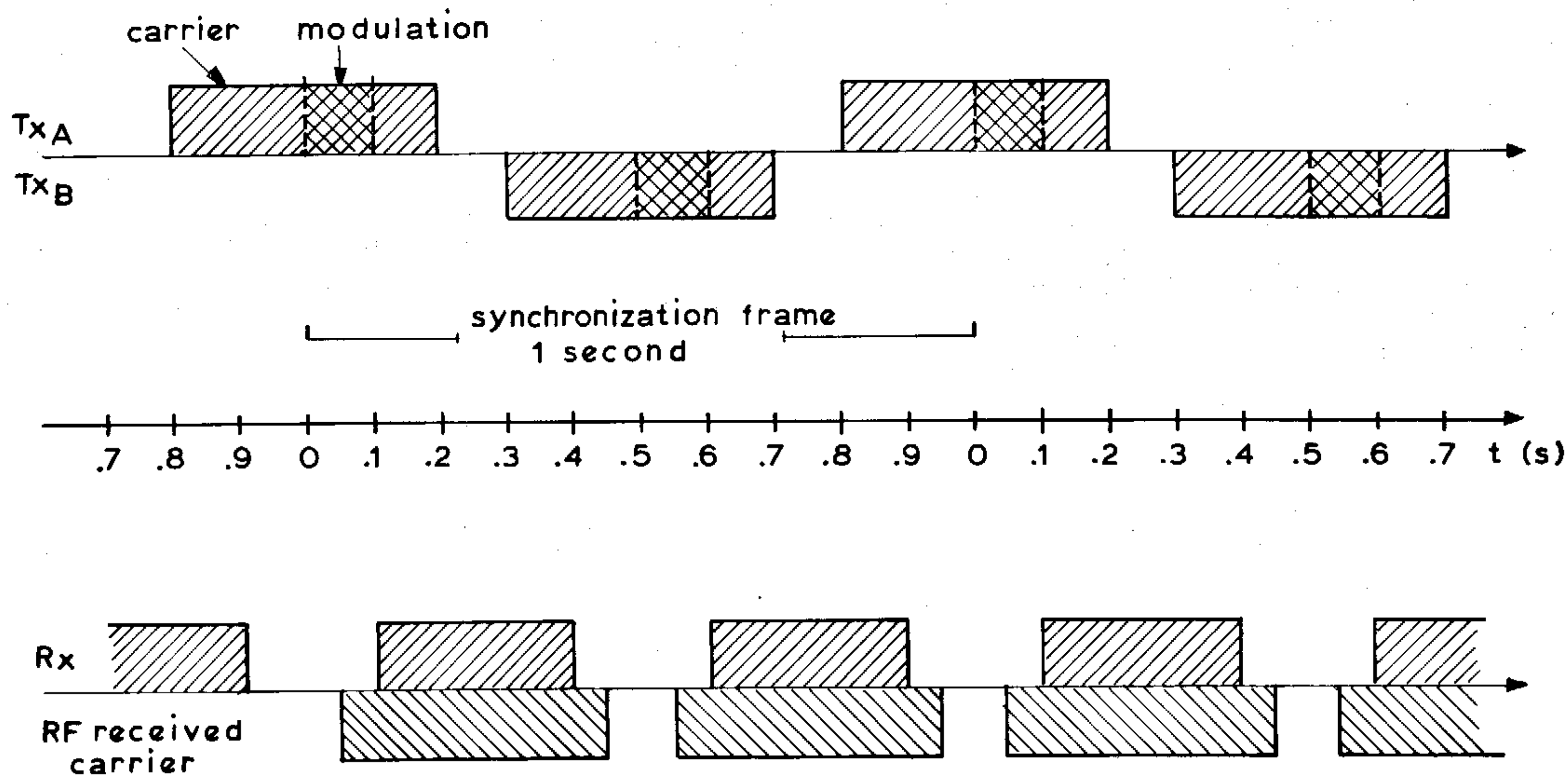


Figure 9. RF Carrier Switching

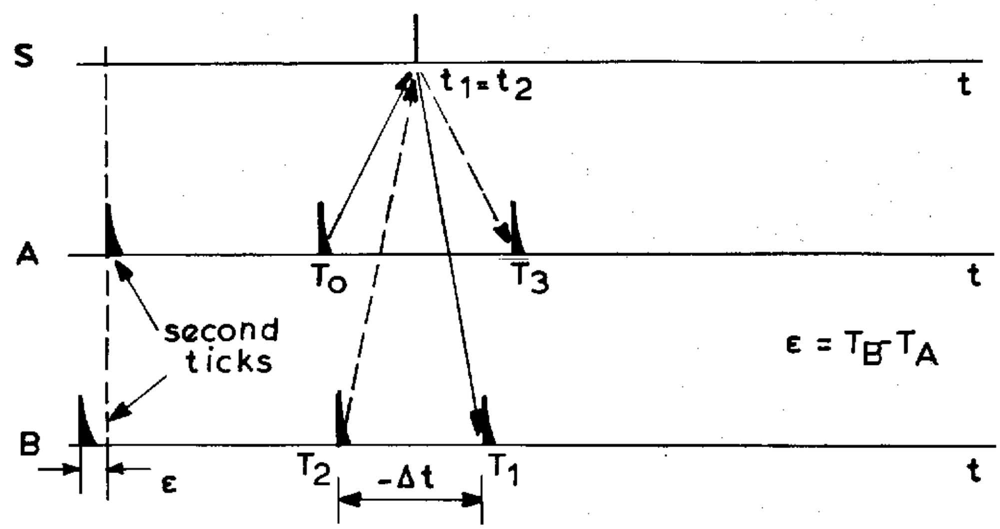
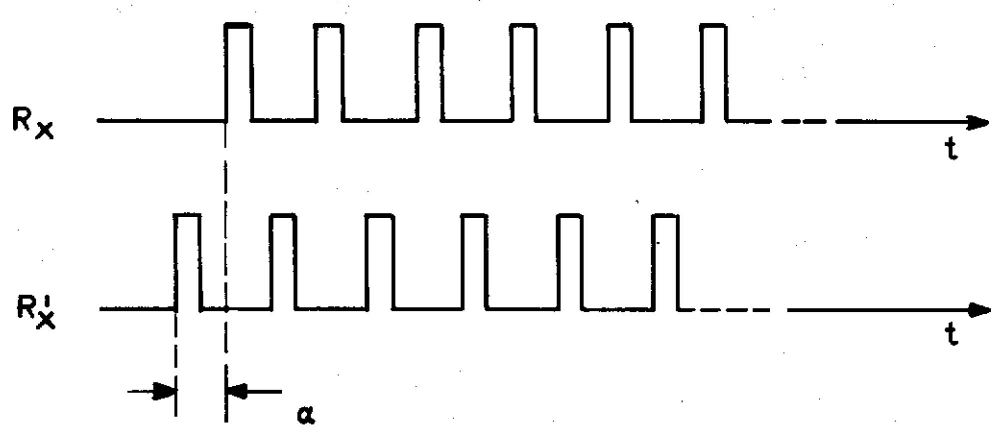


Figure 10. Simultaneous Time Transfer – Timing Diagram



R_X = signal received from the other station

R'_X = signal transmitted and received back (own signal)

α = simultaneity error = $|(t_2 - t_1)|$

Figure 11. Simultaneity Check

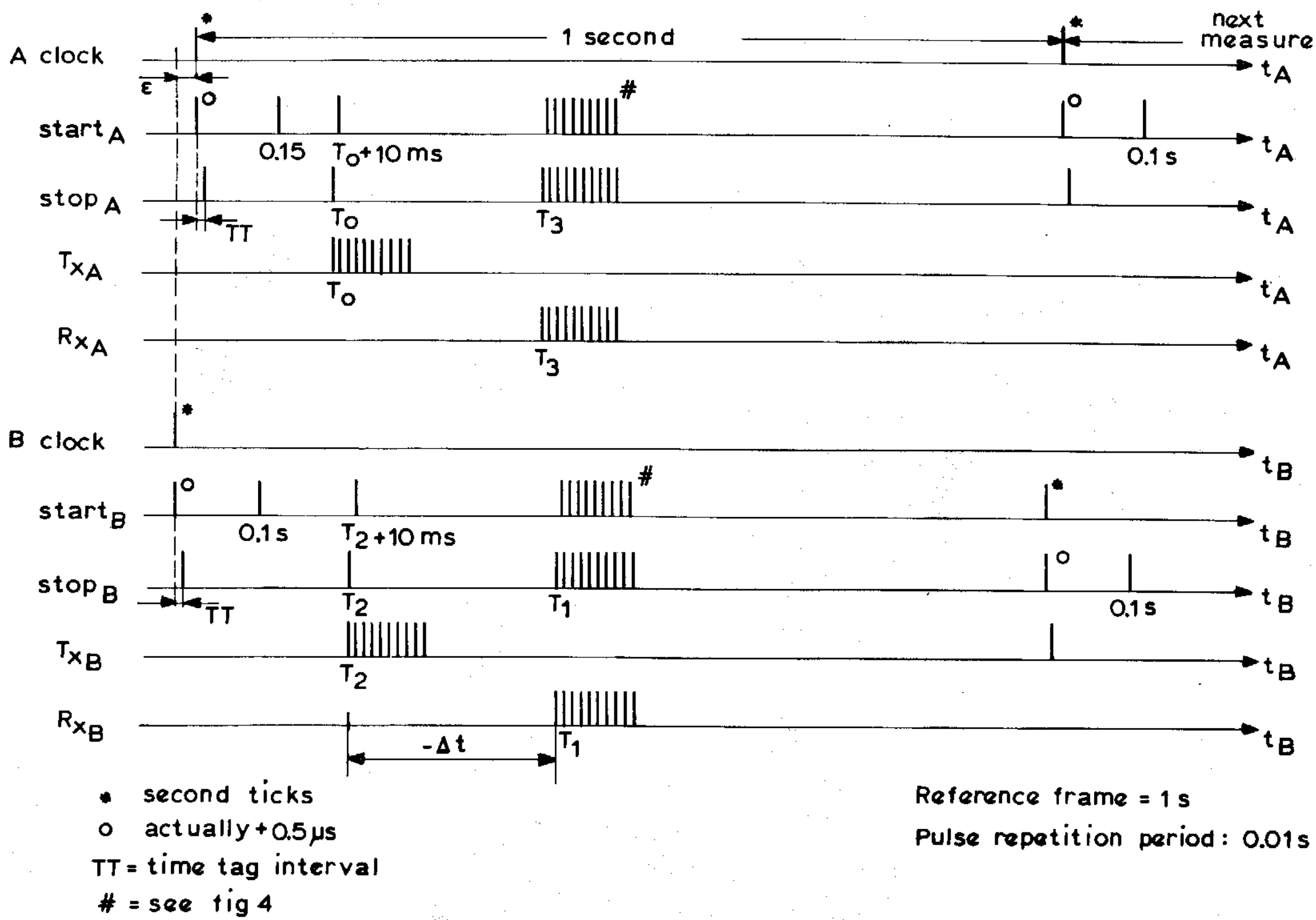


Figure 12. Simultaneous Mode Synchronization Frame

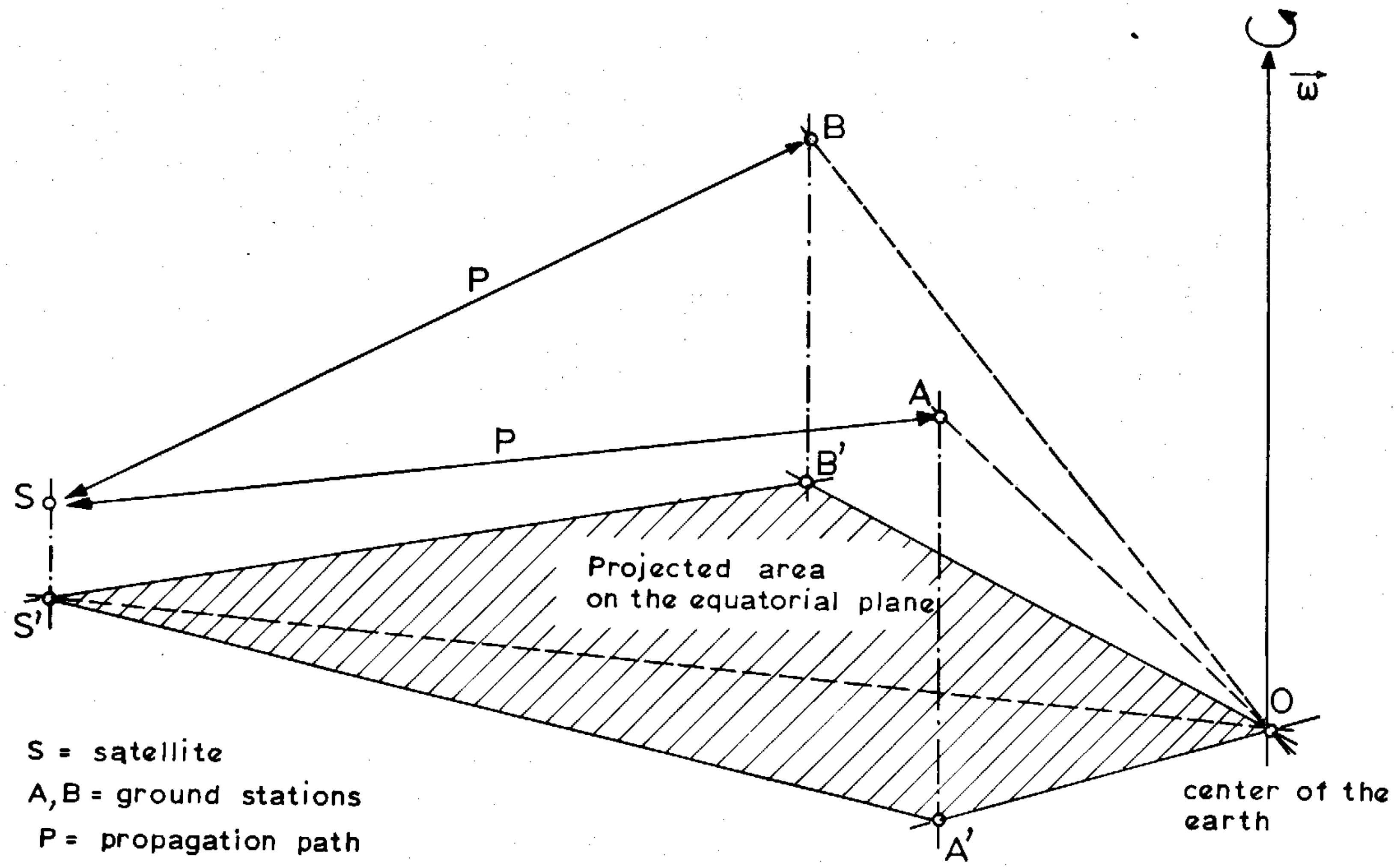


Figure 13. Sagnac Effect Geometry

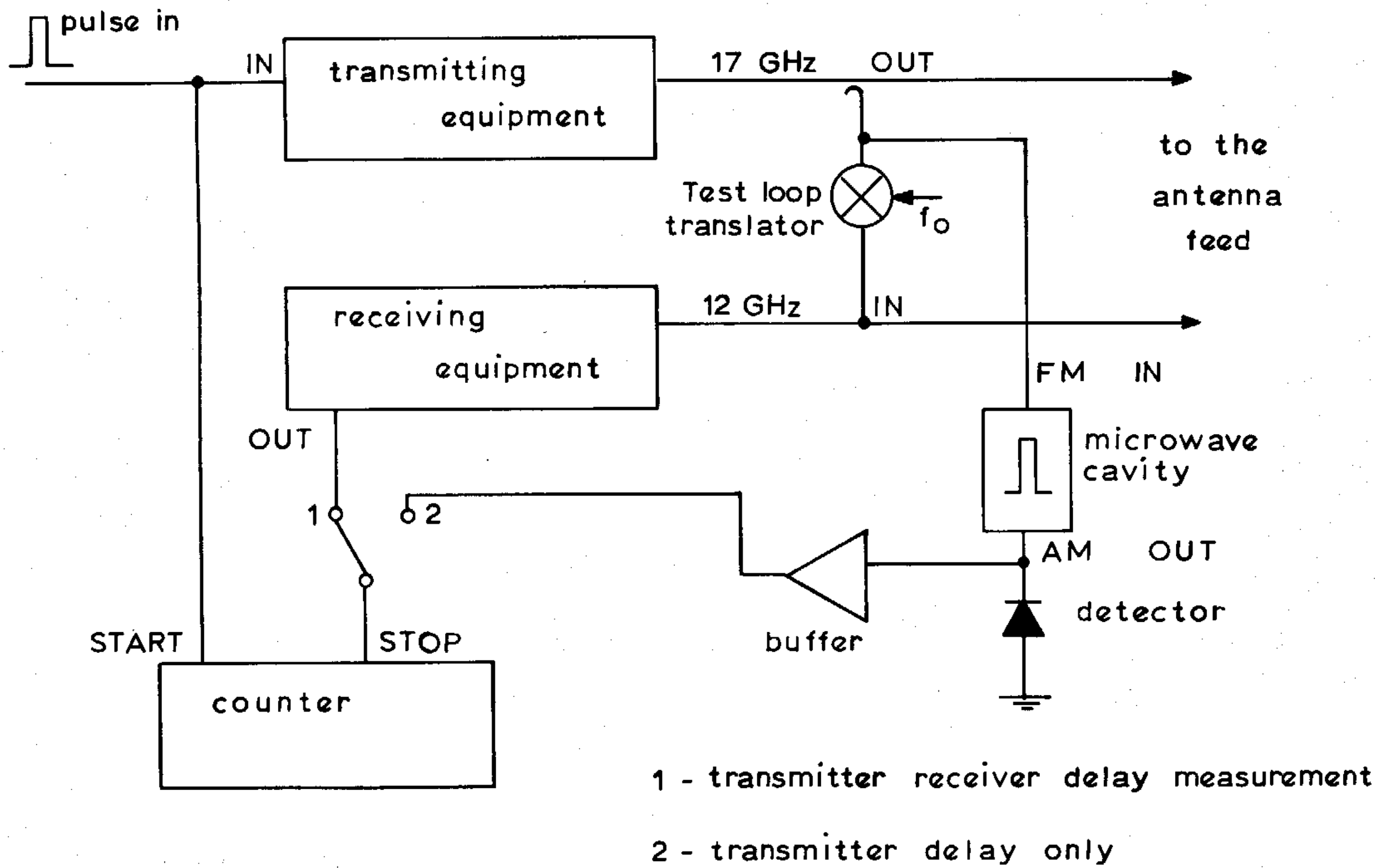


Figure 14. Ground Equipment Delay Measurement

APPENDIX A

RELATIVISTIC CORRECTION DUE TO THE EARTH ROTATION (SAGNAC EFFECT)

This effect, due to the Earth rotation, introduces, if not properly taken in account, an error in the determination of the offset between the clocks using the two-way technique. The sign of the correction to be applied to compensate for this effect depends obviously by the relative longitude of the two stations. The magnitude of the correction can be easily derived (see ref. A1 and A2).

The metric in a flat Minkowsky space is given by:

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2 \tag{A.1}$$

In a polar coordinate reference system we have:

$$\begin{cases} x = r\cos\lambda\cos\varphi \\ y = r\sin\lambda\cos\varphi \\ z = r\sin\varphi \end{cases} \tag{A.2}$$

Applying a uniform rotation with angular velocity ω (in the direction of the z-axis) we have:

$$\begin{cases} x' = x\cos\omega t - y\sin\omega t \\ y' = x\sin\omega t + y\cos\omega t \\ z' = z \end{cases} \tag{A.3}$$

By combining eq. (A.2) and (A.3), taking the differentials and squaring, after a few manipulations it's easy to obtain:

$$ds^2 = (\omega^2r^2\cos^2\varphi - c^2)dt^2 + (2r^2\cos^2\varphi\,\omega d\lambda)dt + (dr^2 + r^2d\varphi^2 + r^2\cos^2\varphi\, d\lambda^2) \tag{A.4}$$

The propagation of the electromagnetic signals at the speed of light c is obviously characterized by $ds^2 = 0$; so the eq. (A.4) is actually a simple second-order linear equation in dt, and again it's easy to obtain immediately:

$$\text{(A.5)} \qquad dt = \frac{-(r^2\cos^2\varphi\,\omega\,d\lambda) \pm \sqrt{(r^2\cos^2\varphi\,\omega\,d\lambda)^2 - (\omega^2 r^2\cos^2\varphi - c^2)(dr^2 + r^2 d\varphi^2 + r^2\cos^2\varphi\,d\lambda^2)}}{(\omega^2 r^2\cos^2\varphi - c^2)}$$

By integration over the propagation path P (that is actually a round-trip path) we obtain:

$$\text{(A.6)} \qquad \Delta t = \int_p dt = -2\omega \int_p \frac{r^2\cos^2\varphi}{{}^2r^2\cos^2\varphi - c^2}\, d\lambda$$

that is the time difference in the propagation delays from one station to the other (via the satellite) and back, assuming a uniform speed ω of the Earth rotation.

The error $\Delta\varepsilon_r$ in the determination of ε is actually half the magnitude of Δt, so we have a correction:

$$\text{(A.7)} \qquad \Delta\varepsilon_r = -\omega \int_p \frac{r^2\cos^2}{{}^2r^2\cos^2\varphi - c^2}\, d\lambda \simeq \frac{\omega}{c^2} \int_p r^2\cos^2\varphi\, d\lambda$$

where the term $\omega^2 r^2\cos^2\varphi$ can be neglected, since it is quite small as compared to c^2.

A simple geometric representation (fig. 13) can be given for eq. (A.7) (according ref. A1). By assuming the term $r^2\cos^2\varphi = r'^2$ as the projection of the vector radius r on the equatorial plane, we have:

$$\text{(A.8)} \qquad \Delta\varepsilon_r = \frac{\omega}{c^2} \int_p r'\,d\lambda$$

The integral in eq. (A.8) is actually twice the area A generated by the vector radius r'(lying on the equatorial plane), so we can write:

$$\text{(A.9)} \qquad \Delta\varepsilon_r = \frac{2\omega A}{c^2}$$

According the geometry relative to the SIRIO experiment the $\Delta\varepsilon_r$ correction was evaluated to be about 15 ns. This is not to be considered a constant, but a slowly varying term (period 24 hr) around 15 ns because of the satellite motion relative to an Earth fixed reference frame.

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APPENDIX B

GROUND EQUIPMENT DIFFERENTIAL DELAY MEASUREMENT

The measurement of the delays of the ground communication equipment is performed at each station as shown in Fig. 14. A test loop translator is available at each ground station; this allows the measurement of the sum of the delays in the transmitting and in the receiving equipment at the same site.

However, in the time transfer the difference of these delays must be considered (eq. 4): a simple method to measure the transmitting equipment delay alone has been devised.

Since the RF carrier is frequency modulated, a microwave cavity is used as a frequency discriminator coupled to the feed of the antenna. The AM resulting signal (if a pulse is applied at the input of the modulator, the output signal is actually an on-off RF signal) is detected by a fast rectifier, which provides via an amplifier the stop pulse to the counter.

Two basic requirements must be satisfied by the microwave cavity: it must be able to detect the shift of the RF carrier as a result of the input pulse (this means that a high Q is required), while it must introduce the smallest delay as possible (low Q); a suitable Q value for our purpose is between 1000 and 2000.

In this way, measuring the delay in the transmitter alone and the sum of the transmitter and receiver delays, the eq. 4 can be easily solved.