INTER – SATELLITE TIME TRANSFER: TECHNIQUES AND APPLICATIONS

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Abstract

The role of the NASA Tracking and Data Relay Satellite System (TDRSS) is to increase the volume and frequency of communication between an orbiting spacecraft and the Earth, while at the same time providing command and tracking functions with extended coverage via a network of orbiting satellites and one or more ground stations. The same concept is currently being studied and is planned by the European Space Agency (ESA) under the name of Data Relay Satellite System (DRSS).

TDRSS is an answer to the increasing complexity of new satellites and space missions that, especially in the field of scientific and application satellites, are placing increasing requirements in terms of mission support.

New satellites, designed for scientific missions, such as astronomical observatories, or earth applications, for remote sensing, geodesy and precise navigation, are relying on precise onboard clocks to accomplish their missions.

All these spaceborne clocks require precise synchronization to some external ground reference, synchronization that must be provided as a part of the standard mission support. Since mission support is the primary role for the TDRS systems, synchronization must be provided through the same links used for telemetry, command and data acquisition.

There have been many time transfer experiments, and the techniques are well known and established throughout the years. A number of experiments have evolved into operational services now available worldwide and, in the case of the GPS, even to satellites in low earth orbit.

However, the requirement to provide timing support as a part of the standard support to the space missions, has resulted in NASA providing timing services to user spacecraft directly via the TDRSS. The same service is being considered for the new Advanced TDRSS (ATDRSS) and the ESA Data Relay Satellites (DRS).

We will start with a brief review of the well known time transfer techniques that have been studied and tested throughout the years. We will then discuss the applicability of time transfer techniques to a timing service as provided through a TDRS/DRS System, the problems related to the choice of the timing signal within the constraints imposed by the existing systems, and the possible practical implementations, including a description of the time synchronization support via TDRSS to the Gamma Ray Observatory (GRO).

TIME TRANSFER: DISSEMINATION AND SYNCHRONIZATION

In general, the knowledge of the relative time offsets between two or more clocks is desired. This requires the comparison of the readings of the clocks. If the clocks are remotely located this may be difficult, depending on the degree of synchronization required by the measurement.

We will refer to the exchange of timing information between two or more clocks, an exchange leading to the determination of the clocks respective offsets in time, as the *synchronization* procedure.

When the time information is transmitted or broadcasted to two or more users it is called *"time dissemination"*, and it is generally performed by transmitting time coded information (time codes).

Dissemination by itself does not imply the presence of a clock at the user site: the user can simply get its time from the decoded message. Synchronization, being the measure of the offset between two clocks, always requires a clock at the user site.

Since, in many occasions, the two procedures are used together (sometimes just to reduce the initial ambiguity of the synchronization procedure) they are both, in general, referred to as *"time transfer"* procedures.

Radio or optical signals have been used to transfer time over long distances. In both cases, a timing signal or marker must be modulated on the electromagnetic wave acting as the carrier.

Usually an event marker is used to synchronize clocks. This can be a pulse, or the zero crossing of a sine wave, or a particular status of a Pseudo Random Noise (PRN) Code. The time mark, sometimes referred to as a "tick", must be identifiable and precisely resolved in time. If a pulse is used as a timing marker, usually its leading edge is taken as the on–time reference, and the sharpest rise time is desirable. If the zero crossing of a sine wave is used, the higher the frequency the better the timing resolution for a given Signal to Noise (S/N) ratio. But this requires a better "a priori" knowledge of the relative position of the two clocks being synchronized, since the number of zero crossing per unit of time increases with the frequency; this presents another problem: *ambiguity resolution.*

Time dissemination usually relies on the transmission of full numeric coded information. The process of transmitting such information generates an RF spectrum that is far from optimum for synchronization. Moreover, the unavoidable delays and jitters of the coding/decoding equipment adds uncertainty to the measurements and finally degrades the precision and accuracy of the time transfer.

However, being able to read the time from the received message, without reasonable ambiguity, the user does not need its own clock to keep time: usually a time code reader and display unit is all that is required.

USE OF SATELLITES FOR TIME SYNCHRONIZATION

Satellites have been used for decades now for time synchronization. They are useful, since they can extend the limits of precise time synchronization far beyond the horizon. VLF and LF transmissions (notably OMEGA and LORAN) have been used in the past to convey time information over the horizon, but they have limited capabilities. LORAN can achieve the greatest precision only within the limits of groundwave propagation, a few hundred kilometers. OMEGA has worldwide coverage, but relatively poor performances for timing, only a few tens of microseconds.

The simplest technique using a satellite for time transfer (synchronization or dissemination) is the *one-way technique* (Fig. 1); the satellite is used as a radio relay, or transponder. The signal is transmitted from A to the satellite and from the satellite relayed back to B, which is located well beyond the line of sight of A.

The synchronization equation (see Fig. 1 for symbols) is:

$$E = \text{time}(A) - \text{time}(B) = T_D - T_M$$

and, since T_M is measured, then T_D must be estimated, or computed, given the orbit of the satellite and the location of A and B. Uncertainties in the satellite orbit and ground locations of A and B are the main causes of error for the one–way technique.

Many variations of this technique exist. In one, a clock onboard the satellite replaces the ground transmitting station. Synchronization can even be accomplished, when two stations are simultaneously in view of the satellite, without having a real clock on the satellite, provided that some kind of easily identifiable pulse is transmitted by the satellite (*passive synchronization*)[14].

Using this technique (Fig. 2), two ground clocks can be synchronized by comparing the times of arrival of the same pulse emitted by the satellite[14]. This method is a natural extension of the passive TV synchronization method, widely used to synchronize clocks on a national scale in many countries.

Let the satellite emit a pulse at an arbitrary time t_0. The propagation delay from the satellite to "A" is $T_D(A)$, and from the satellite to "B" is $T_D(B)$; these delays must be known by computing the range at t_0 and applying corrections for tropospheric and ionospheric delays (Fig. 2).

At the location of the clock "A", the pulse emitted by the satellite is received at $T_M(A)$; computing $T_D(A)$, "A" is able to evaluate t_0 in its own time scale.

The same occurs at the location of the clock "B"; another evaluation of t_0 is carried on, but this time it is in the "B" time scale. Obviously the two will not be identical, because of the error E between the two clocks: the difference between the two determinations of t_0 will give a measure of E.

It can be proven that uncertainties in the ephemeris of the satellite, which produce errors in the range estimates, are greatly reduced by the differencing technique[14], resulting in smaller errors in the time synchronization. This fact has been successfully exploited in the "common–view" technique using GPS satellites[15].

If the satellite carries a stable *oscillator onboard*, it may produce a repetitive stream of pulses, with no requirement placed on the degree of synchronization of these pulses with any time scale. As long as these pulses are stable in frequency, and a count is maintained onboard the satellite (and eventually transmitted via telemetry to the ground stations), then the previous synchronization scheme can be extended to clocks not in common–view of the satellite (Fig. 3).

The onboard satellite oscillator acts as a flywheel only for the time required by the satellite to fly between one site and another. Its frequency must be stable only over this limited amount of time. This makes possible to use this technique to synchronize precise atomic oscillators with simple onboard crystal oscillators.

This is the satellite extension of a technique proposed several years ago by Besson, of using aircraft to carry around flying clocks. In 1971, Joseph Hafele of Hewlett Packard and others were the first to fly cesium clocks around the world to prove the Special Theory of Relativity. Aircraft have been used also in other experiments (involving relativity) by C. Alley and co-workers at the University of Maryland.

If the oscillator is stable, and the counting devices following the oscillator itself have provisions to be synchronized to an external time scale (for instance, UTC), then the satellite can broadcast precise time in the form of pulses (markers) with related coded information (Fig. 4), in such a way that is possible:

- one-way time dissemination;
- one-way absolute synchronization (referenced to the onboard time scale, so that a user needs only to receive the satellite transmission to precisely set and synchronize his clock);
- one-way relative synchronization (between two users, either in common view or not, using the stability of the satellite clock as a time flywheel).

These techniques were widely used with the TRANSIT/NNSS satellite system and in the GPS/NAVSTAR, as a timing spin-off from the implementation of satellite navigation systems.

However, all the preceding techniques:

- One-way, satellite acting as a repeater;
- Passive synchronization;
- Satellite carrying an oscillator;
- Satellite carrying a clock;

rely on computed ranges and propagation delays to achieve time transfer: this is a basic limitation of these techniques. A method to accurately measure the propagation delay is very desirable, especially if this can be done with the same precision by which time events are measured.

This is the idea behind the *two-way synchronization* techniques. Both stations, "A" and "B", are active, transmitting their own time signals and receiving the signals transmitted by the other (Fig. 5).

If the satellite is really stationary, when "A" receives the pulse transponded back by "B", then "A" has a measurement of twice the propagation delay between "A" and "B". Here we suppose that the two paths (from "A" to "B" and "B" to "A") are truly reciprocal and this, in practice, may not be the case.

Now that a direct measure of the propagation delay is available at "A", this can be transmitted back to "B" and "B" uses the delay to correct its timing measurements and retrieve the synchronization error E, instead of having to compute the delay from range measurements.

In practice, things are more complicated, but the method is one of the most accurate and precise ever being used for time synchronization. Only laser-based synchronization methods, thanks to their higher bandwidth, can achieve better resolution and accuracy. The disadvantage is related to the fact that a complete transmitting/receiving equipment must be available at the two sites.

This was a bit of a problem in the past, when satellite communication meant bulkier antennas and apparatus. However, with the present day technology, this is feasible with smaller VSAT antennas and Direct Broadcasting Satellites, and indeed experiences have already been taken place in the United States, at the NIST and at the U.S.N.O.

Laser communication links present a wider bandwidth than is possible with RF links. However, they are not as much as efficient in terms of signal to noise ratio. Moreover, a light signal can be relayed back by a mirror or by a retroreflector. Precision pointing of a mirror in space is a difficult task. The retroreflector provides an easy and accurate reference direction of reflection, the only problem being that the light is reflected exactly back to the transmitter site. The problem can be solved by placing a photon detector, a stable oscillator and an event counter onboard the satellite, in addition to the retroreflector array.

Every user (Fig. 6) transmits an intense pulse of light at a known time; which can be precisely measured against the local time scale. The pulse transmitted by the user "A" arrives at the satellite, detected by the photodetector and time tagged in the local time scale of the onboard clock. At the same time, the retroreflector array reflects part of the original pulse energy back to the ground, when it is detected and the round trip time measured accurately.

Since the transmit time and the propagation delay are known, the time of arrival of the transmitted pulse at the satellite can be computed in the station "A" time scale. Also, the transmitted pulse arrival time is measured in the satellite time scale "S" and, by taking into account the propagation delay, we have a measurement of the synchronization error $E(A - S)$ between the time scale of "A" and the satellite.

Another user "B", shortly after "A", makes a measurement, performing the same procedure, and is able to recover $E(B-S)$. By taking the difference between the two measurements yields the synchronization error between "A" and "B". The time scale of the satellite disappears in the differencing.

The frequency stability of the onboard oscillator, in the short time between the arrival of the pulse from "A" and the arrival of the pulse from "B", must be such as to not degrade the timing accuracy of the measurement. If the time elapsed between the arrival at the satellite of the two pulses is only a few hundred milliseconds, it can be shown that a good crystal oscillator can provide enough stability not to degrade the synchronization at the subnanosecond level.

This technique has been implemented in the **LASSO** (LAser Synchronization from Stationary Orbit) concept. A first attempt to carry a LASSO package into orbit was done with the SIRIO-2 satellite and failed, due to a launching accident. Later, a LASSO package was successfully orbited onboard the ESA Meteosat–P2 satellite.

The LASSO experiment was proposed by M. Lefebvre et al. of the Centre National d'Etudes Spatiales (CNES), Toulouse (France). Based on a presentation at the 1972 COSPAR meeting in Madrid, the European Space Agency (ESA) accepted a proposal from the Bureau International de l'Heure (BIH) to pursue a related space mission.

The aim of the LASSO technique is to provide a repeatable, near–real–time method for long distance (intercontinental) clock synchronization, with nanosecond accuracy.

The LASSO payload is composed of retroreflectors, photodetectors for sensing light at two wavelengths (from ruby and doubled Nd–YAG laser emitters) and an ultrastable oscillator to time–tag the arrival of laser pulses; these time–tags or "datations" are transmitted to the ground via telemetry.

The LASSO technique is based on the use of laser ground stations firing monochromatic light pulses at predicted times, directed toward the synchronous satellite. An array of retroreflectors onboard the spacecraft sends back a fraction of the received signal to the originating laser station, while an electronic device onboard the spacecraft detects and time-tags the arrival of the laser pulses.

Each station measures the time of transmission and the two-way propagation delays of the laser pulses, and computes the one-way propagation time between the station and the spacecraft. Then, the offsets between the clocks that provide the time reference at each of the laser stations can be computed from the data collected at the spacecraft and at the ground stations.

With reference to the timing diagram (Fig. 6) for two stations, we have (corrections are neglected):

$$E = (Td_A - Td_B) + (Tp - A - Tp_B) - (Ts_A - Ts_B)$$

where:

- E is the time offset between the two clocks at the stations A and B;
- Td_i are the transmission times of laser pulses from the station i [i =A, B];
- Tp_i are the propagation delays between each station and the spacecraft [i = A, B];
- Ts_i are the times of arrival onboard the satellite of the laser pulses transmitted from the station i [i =A, B];

If: Tr_i are the return times of laser pulses transmitted from the station i [i =A, B],

then the propagation delays Tp_i can be easily computed as:

$$Tp_i = \frac{Tr_i - Td_i}{2} \qquad [i = \text{A, B}]$$

Substituting, we finally obtain the synchronization equation:

$$E = \frac{(Td_A - Td_B)}{2} + \frac{(Tr_A - Tr_B)}{2} + (Ts_A - Ts_B)$$

An interesting variation to the LASSO scheme for optical time transfer was proposed in the past[11]. The idea was to reverse the locations of the optical transmitter and receiver. In the LASSO experiment the transmitting lasers were located on the ground, and the satellite carried orbiting retroreflectors. The proposal to reverse the roles, putting the laser in orbit and inexpensive retroreflectors and detectors on the ground, was aimed to reduce the cost to the user, in hope of providing time dissemination available at metrology centers around the world, and to allow geodetic users of the system to cover wide areas with passive retroreflectors at minimum cost. The difficulty lies in pointing the orbiting laser with the required accuracy. As far as we know, the technique was never pursued, even if it is an interesting concept.

INTERSATELLITE LINKS FOR TIME SYNCHRONIZATION

The Tracking and Data Relay Satellite System (TDRSS) is designed to provide Tracking and Data Relay Service to User Satellites, generally in Low Earth Orbit (LEO), using a constellation of geosynchronous satellites (two operational, TDRS West and East, plus an in-orbit spare) and two ground stations, both located at White Sands, New Mexico.

Fig. 7 (from Ref. 1) shows the geometry involved in the TDRS System. A signal is transmitted (from the user LEO satellite) to one of the two operational TDR satellites which transponds the signal to the TDRSS NASA Ground Terminal (NGT) at White Sands (Fig. 12). The same path is followed in reverse by a signal transmitted from the ground to the user LEO satellite via TDRSS.

When ground stations were used to provide tracking, command, telemetry and data acquisition support to the space missions, an extensive world wide network was required to provide continuity of coverage. In those days, the signals traveling from ground to the satellite (tracking and command) were referred to as the "uplink". Conversely, signals traveling from the satellite to ground (tracking, telemetry and data) were referred to as down0link communications.

This is not so obvious with TDRSS. First, the signal from NGT to the satellite travels upward to the TDR satellite, and then downward to the user satellite, which is in low Earth orbit below the TDRS. Conversely, from the satellite to ground, the signal travels upward to the TDR satellite, then downward to NGT. To avoid confusion, the convention adopted was to refer to the communication link from NGT to the user satellite via TDRS as the forward link, and to the link from the user satellite to NGT via the TDRS as the return link. The TDRS is basically a transponder.

The TDRS is transparent as regard to the communication of data between the user LEO satellite and NGT. However, while the NASA TDRSS was designed to provide Tracking and Data Relay Support to Earth Orbiting Missions, it was not designed to support time and frequency transfer to a User Satellite.

The first satellite needing such a service is an astronomical observatory, the Gamma Ray Observatory (GRO). GRO requires a time-tag of data collected onboard to within 100 microseconds of Universal Time Coordinated (UTC) time scale. Since the onboard oscillator is a crystal oscillator, it needs periodical calibrations, which must be performed from the ground, via the command and telemetry link. To correct the oscillator, however, its phase, frequency offset and aging must be precisely measured with respect to UTC, or against a ground clock referenced to UTC by external means.

In 1975-1976 the Timing Systems Section of the Network Engineering Division at GSFC was charged with this problem. The Applied Physics Laboratory (APL) of the Johns Hopkins University was tasked to aid with a study of possible solutions. The study resulted in what is referred as the DATA INTERFACE APPROACH: to synchronize user spacecraft clocks via the Tracking and Data Relay Satellite System. The technique chosen was the two-way technique.

NOTE: Notice that the User Clock may be either onboard a User Satellite or on the ground: i.e., the technique can be used to also synchronize a second ground station[3] or any Remote Clock, provided that a TDRS-compatible transponder is available at the site[4].

In the two way time synchronization technique[1], two clocks, located at A and one at B (Fig. 5) exchange the time information through a satellite communication link. The time information can be in the form of pulses, bursts of pulses, continuous sine signals or Pseudo Random Noise codes (PRN codes). The basic equation giving the time difference between the two clocks is[1]:

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

where: E is the time offset between the clocks in A and B [actually $E = T(B) - T(A)$]; T_1 and T_3 are the times of reception of the time signal transmitted at the times T_0 and T_2 by A and B.

The corrections δE take into account several factors affecting the 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 (troposphere and ionosphere) and the equipment delays.

Usually a pulse at the rate of 1 pulse per second is the electrical output of a standard clock; the resulting 1 second ambiguity can be easily resolved by looking at the time readout, since one second change in the display is easy to observe, and numerical information can be easily coded, transmitted and decoded as digital data in a one second frame.

The 1 pps pulse output constitutes the time mark of the clock, used to resolve time intervals smaller than 1 second: usually the leading edge of the pulse itself is taken as the on–time reference to increase the resolution of the measurement.

The synchronization procedure used in the TDRSS determines coarse and fine spacecraft clock error with respect to UTC. Coarse error is determined from the spacecraft clock time code to one second resolution; fine error is defined as the residual synchronization error within the 1 second ambiguity period.

We will show, however, that, by relating the ambiguity to the repetition period of the timing pulses used as the time signal, some simplification in the hardware and in the operations may be obtained (see the HYBRID TECHNIQUE).

To perform the ranging measurements (a primary function of the TDRSS is to provide orbital support to the missions), a Pseudo–Random Noise (PRN) Code is generated at the TDRSS Ground Station and modulated on the forward RF link together with the command data for the user spacecraft.

There, the code is received, demodulated and the code epoch precisely measured to reconstruct a second code with the same characteristics of the received code, but with a different bit pattern. Exact time synchronization between the two codes is maintained. This second code is sent back to White Sands via TDRSS.

Being precisely synchronized to the forward–link ranging code, the return–link code provides an easy way to measure the two–way propagation time, so that an estimate of the one–way range between White Sands and the User Satellite is obtained. Since the range from White Sands to the relaying TDR satellite is precisely known (or continuously measured using the same technique), the range from the TDR satellite to the User Satellite is also known.

Even if ranging is not performed continuously, the forward and return PRN codes are present. The PRN codes are an ideal timing signal for time transfer, because of the optimum use of the available bandwidth, the good rejection of external interferences (man–made or natural) and the extreme resolution of the timing measurements due to the high repetition rate of the chip period.

The TDRSS PRN code is periodic, with a code period of about 85 ms, i.e., the code repeats itself every 85 ms. This is the time interval ambiguity associated with the PRN code. Once per cycle, the code generator steps over one easily identifiable state, the so called "All 1's" state, since every tap on the feedback logic of the shift register generating the PRN code is at logic level 1. Notice that an "all 0's" state cannot exist in a PRN code generator, otherwise the code itself will be trivial, being locked in a zero state condition.

In the TDRSS time transfer techniques using PRN codes, the timing signal (or time reference ticks) exchanged between the two clocks to perform the synchronization is the "All 1's" state of the PRN code, and the reference time is measured accordingly on the rising edge of the "All 1's" pulse from the local generator, when the received and locally generated codes are correlated (when receiving), or on the rising edge of the "All 1's" pulse from the local generator when transmitting.

Basically, the APL approach was to use a two–way time synchronization technique, after an initial coarse synchronization was performed to resolve the one second ambiguity. Time tagging of the "All 1's" pulses was required to identify the selected pulse (with about 80 ms ambiguity due to the PRN code repetition rate) within the 1 second coarse synchronization interval. The identification was carried on using the telemetry data stream, since, in principle, epoch timing, telemetry data and frame rates and clocks ticks are asynchronous.

Several techniques were considered[5], including one–way time transfer; however, the improved performances related to the implementation of the two–way technique were evident, and it was decided to implement a synchronization scheme based on the two–way technique, which in its basic form is shown in Fig. 8.

Going deeper into the details of the actual implementation, two situations were taken into account, due to the fact that the return PRN code can be locked to the forward PRN code whether or not a TDRSS ranging function is being performed.

The non–ranging situation requires only an additional time interval measurement onboard the User Spacecraft to measure the transmission time of the reference mark of the transmitted code. This additional measurement must be relayed back to Earth via the telemetry. The remaining of the computations are essentially identical.

Return PRN Code locked to the Forward Code (Technique 1)

The first technique considered assumes that the Return PRN Code (generated onboard the User Satellite) is locked to the Forward Link PRN Code. In Fig. 9 (from Ref. 5) this is shown schematically. To avoid confusion in reading the figure, consider that the second number used in the suffix of the indicated quantities refers only to the number of consecutive measurements performed, and can be ignored, since, in principle, the two–way time transfer can be carried on in one measurement frame.

Defining: $D_1 = D_{11} =$ transmission time of the timing reference from the master (ground) station;

$D_2 = D_{21} =$ time of reception/transmission of the timing reference at the user;

$D_3' = D_{31}' =$ time interval elapsed from the time of transmission to the reception of the timing signal at the master site.

NOTE: D_3' is the two–way propagation delay; the "absolute' time of reception of the timing mark in the master time scale is actually $D_3 = D'_3 + D_1$.

If E_1 is the time offset between the two clocks, we can write:

$$D_1 + t_f = E_1 + D_2 \tag{2}$$

and:

$$D_1 + D_3 = E_1 + D_2 + t_r \tag{3}$$

where t_r and t_f are the forward and return propagation delays.

If the geometry is completely reciprocal, t_r and t_f would be equal and the eqs. (2) and (3) can be simply added to obtain:

$$E_1 = \frac{D_1 + D_3}{2} - D_2 \qquad [D_3 = D_1 + D'_3] \tag{4}$$

which is the basic two-way time synchronization equation, shown also in Fig. 6.2. However, considering the satellite motion and the resulting Doppler effect, we know that this is not true, and in general t_f will be different from t_r.

If this is the case, we can simply use the eq. (2) and write:

$$E_1 = t_f - (D_2 - D_1)[\text{for the technique 1}] \tag{5}$$

The first approximation to evaluate t_f, yielding the classical two-way time synchronization equation (4), assumes full reciprocity, neglecting any satellite motion. In this case, t_f is obtained directly from the two-way propagation delay D'_3.

For the TDRSS synchronization, as in other cases, a more complicated model for the satellite motion is assumed, but this will not be described here.

Return PRN Code not locked to the Forward Code (Technique 2)

The second technique considered is more general, and assumes that the Return PRN Code (generated onboard the User Satellite) is not locked to the Forward Link PRN Code. In Fig. 10 (from Ref. 5) this is shown schematically. Again, to avoid confusion in reading the figure, the second number used in the suffix refers only to the number of consecutive measurements performed, and can be ignored in the following discussion.

Defining: $D_1 = D_{11}$ = transmission time of the timing reference from the master (ground) station;

$D_2 = D_{21}$ = time of reception of the timing reference at the user;

$D_4 = D_{41}$ = time of transmission of the timing reference from the user;

$D'_3 = D'_{31}$ = time of reception of the timing reference at the master site, elapsed from the transmission time

NOTE: D'_3 is the two-way propagation delay; the "absolute" time of reception of the timing mark in the master time scale is actually $D_3 = D'_3 + D_1$

If E_2 is the time offset between the two clocks, we can write:

$$D_1 + t_f = E_2 + D_4 \tag{6}$$

and

$$D_1 + D'_3 = E_2 + D_2 + t_r \tag{7}$$

The suffix "2" of E_2 denotes only the time offset as computed using technique 2. If total reciprocity of the forward and return propagation delays cannot be assumed, we can only write:

$$E_2 = t_f - (D_4 - D_1) \tag{8}$$

Again, t_f must be computed separately, under the assumptions given above.

The TDRSS PRN code generator chip rate and code length result in a repetition period for the full code of about 85 ms; as a consequence, this is also the repetition period of the "All 1's" state of the code.

To identify the "All 1's" state used as the timing marker for the synchronization, a range gating system using the telemetry frame was used. This resulted in some problems, related to the decoding delay of the telemetry frame which, in the TDRSS, is convolutionally encoded on the carrier. This unpredictable delay may create some ambiguity in the "All 1's" state identification, when the two occur very close together.

The problem was solved by adding a second telemetry identifier and resulted in an increase in the complexity of the hardware used to implement the technique.

An error budget was estimated[5] as follows:

SOURCE	ERROR assuming given errors are 1 σ values	ERROR assuming given errors are 3 σ values
Measurements and calculations	6 ns	6 ns (*)
Differential delay at User Satellite	7 ns	20 ns
Differential delay at Master site	7 ns	20 ns
Differential delay of Satellite	10 ns	30 ns
Non–reciprocity in propagation effects	5 ns	5 ns (*)
TOTAL R.M.S.	16 ns	42 ns

NOTE (*): No averaging is assumed

In 1982 a second proposal was put forward by the Gamma Ray Observatory Project Office, regarding the possibility to passively monitor the Gamma Ray Observatory onboard clock simply by using the telemetry return link[7].

The idea was to implement a one–way time transfer technique, based on the telemetry link, with the following budget:

	ERROR SOURCE	R.M.S. ERROR
(a)	GRO clock quantization error	0.28 μs
(b)	Spacecraft delay	—
(c)	Orbit determination error	2.00 μs
(d)	TDRS transponder delay	—
(e)	WSGT equipment delay	1.00 μs
(f)	Telemetry clock reconstruction error	2.00 μs
(g)	NGT quantization error	0.29 μs
(h)	NGT clock error	1.00 μs
	TOTAL R.M.S. ERROR	$\approx$ 3.20 μs

This figure for the total R.M.S. error was considerably higher than that given by the data interface approach. Nevertheless, if maintained, the telemetry interface approach would have been able to satisfy the requirements of the GRO spacecraft with much less hardware and complexity than the more sophisticated APL proposal.

However, the technique was not accepted, because of the risk involved in the decoding of the telemetry data stream: in some of the bit and frame synchronizers used at the time, random slippages of one bit occurred in the clock reconstruction.

Some variations on the schemes proposed for the DATA INTERFACE APPROACH can be envisaged, e.g. by reducing the hardware complexity while maintaining the accuracy of the two–way technique.

The use of a Hybrid Technique was suggested by the fact that, after the two clocks (NGT and user) are synchronized, no need exists to carry on the pulse identification process using range gates and telemetry frame information.

How well two clocks need to be synchronized for this statement to be true?

It can be shown that two clocks (Master and User) need only to be synchronized to within T/4 seconds, where T is the "All 1's" repetition period (i.e., the repetition period of the PRN code).

Since, for TDRSS, $T \approx 80$ ms, then the two clocks need only a initial coarse synchronization within 20 ms. This is well within the capability of a One–Way Time Transfer technique, such as the Telemetry Interface Approach. Therefore, the synchronization of the User Clock (either on a Satellite or on the Ground) can be carried on in two steps:

1. **COARSE SYNCHRONIZATION:** One can use the Telemetry Interface Approach or any other suitable, simple technique to synchronize the User Clock at the 20 ms level (T/4): the One–Way technique is advisable.

The One–Way technique has a definite advantage over trying to perform the full Telemetry Interface approach, since all the propagation delays need not be measured more accurately than a few ms. Range computation from the orbital elements, prediction of atmospheric delays and other delays associated to the equipment may all be neglected.

2. **FINE SYNCHRONIZATION:** Once the coarse synchronization has been performed, using whatever technique is available and convenient, and the two clocks are synchronized within 20 ms, there is no need to identify the "All 1's" pulses.

In this way we should be able to exploit the full capability and accuracy of the Two–Way technique, without the trouble to use the identification procedure (using the telemetry frame marks) and even without the ranging gates, *as long as we rely upon the short term stability ($\tau \leq$ 1s) of the clock that generates the PRN code.*

This approach simplifies the hardware to be built and allows the fine synchronization procedure (2) alone to be used, if the User Clock is maintained to within T/4 seconds.

From an operational point of view, the coarse synchronization must be carried on only initially, when the clock is first switched on. After that, this technique need only be used if a major malfunction should occur and coarse synchronization is lost.

However, for normal timekeeping, only the fine synchronization procedure is to be used.

This adds a substantial simplification to the operational requirements and limits the amount of data to be handled.

The following description is intended to present a possible implementation of the Hybrid synchronization technique. Equipment delays are considered as known quantities, and, in any case, measurable and stable to within the required accuracy. To simplify the equations these delays are, at present, ignored. The coarse synchronization technique will not be addressed, since it is straight forward in its execution; only the two–way fine synchronization will be described.

The reference pulses exchanged between the Master clock (NGT) and the User are the "All 1's" occurrences of the PRN code. The "All 1's" repetition period is T, and it can be shown that, to avoid any ambiguity in recovering the time offset E between the two clocks, these should be initially synchronized with an overall error not to exceed T/4. This is a condition that is readily achievable using ordinary synchronization techniques, and should not present a problem.

During a preliminary investigation, several modes of operation were studied, depending on whether or not the "All 1's" reference mark would or would not be readily available at NGT. In the following it is assumed that the "All 1's" state indicator is available at the master site (NGT): and, as such, various techniques using ranging signals or ground bilateration transponders will not be addressed. In the mode considered here, the "All 1's" signal is available both at the Master Clock and at the User Clock (Fig. 11).

The first occurrence of the "All 1's" after the local second tick at the Master (NGT) occurs at a time T_1, and T is the "All 1's" repetition period. The signal is received at the User at the time T_5 and it is transponded back to NGT, where it arrives at the time T_4 (Fig. 11).

Neglecting the effect due to the satellite motion, the clock offset E is given by the two–way synchronization equation as:

$$E = \frac{T_4 + T_1}{2} - T_5 \tag{9}$$

If T_3 is the first occurrence of the received "All 1's" after the second tick at NGT and T_2 is the first occurrence of the transponded "All 1's" at the User, again after the local second tick, we can write:

$$T_4 = T_3 + n \cdot T \qquad T_5 = T_2 + \frac{n}{2} \cdot T \tag{10}$$

where n is an integral number of cycles of T. Substituting into eq.(9) we have:

$$E = \frac{T_3 + T_1}{2} - T_2 \tag{11}$$

which avoids the use of the range gates to enable the measurements and the identification of T_3 and T_1; a counter is simply started by the local second tick and stopped by the "All 1's" occurrence. However, *special care must be exercised* to handle the modulo–T arithmetic implicit in eq. (11).

The two clocks must be synchronized initially to within T/4 to avoid any ambiguity. Synchronization to T/2 is required because of the division by 2 in eqs. (9) and (11), while initial synchronization to T/4 is further required to give the correct sign to the computed offset (otherwise $E = -5\mu s$ and $E = T/2 - 5\mu s$ are completely equivalent, since a residual ambiguity of T/2 still exists on the computed offset E).

As in the Data Interface Approach (APL), the correction to the basic synchronization equation for the satellite motion is obtained from successive differences in the round trip propagation delays, using the T_3 and T_1 measurements.

The equations will remain the same as those provided for the Data Interface Approach. It can be shown that the linear range variation model is a valid assumption only as a first order approximation; however, it is considered to be fairly effective in dealing with Doppler estimation[11].

The error budget remains essentially identical to the figures quoted for the Data Interface Approach. The main difficulty is related to the calibration of the equipment delays; this remains the main factor limiting the overal accuracy of the Two–Way techniques in general.

In the Hybrid Technique, the coarse and fine synchronization procedures are *completely independent*: as a consequence, the practical implementation of the technique can be broken into steps:

- satellites requiring only coarse time (and maybe these are the majority) *can use the coarse synchronization procedure alone*;
- a satellite requiring more accurate time, will require full synchronization capability: however, in this case, and as long as the clock onboard is kept "on time", the *fine synchronization procedure alone* can be used. The coarse synchronization is to be used only *to set the clock* when it is first switched on, or in the event that some malfunction occurs and time is completely lost at the remote clock;
- to synchronize a *ground clock* the fine synchronization technique alone can be used, since the clock can be kept on coarse time very easily with any other simple and inexpensive techniques already available (LORAN, HF Standard Transmissions, even, in some countries, with radio broadcasted time codes).

The capability to *support a multi–user environment* is stressed by the Hybrid technique. Since no range gates are required (depending upon the relative position of each user), many users can take simultaneous measurements. Then, the time differences can be computed against a single measurement for the forward "All 1's" state and multiple measurements (one per user) for the return state indicators.

Even in this case the coarse synchronization needs only to be used in the event of a malfunction: this feature will help to reduce the operational requirements and, as a consequence, the operational costs.

ADVANCED TDRS PROGRAMS

In the United States, plans are under study to implement an advanced version of the TDRSS; the Advanced TDRSS, or ATDRSS for short, will retain the same basic features of the current TDRSS, having incorporated the timing support in the basic specifications for the system (Ref. 12, para. 5.1, and Ref. 13, para. 3.5.2):

> "... ATDRSS tracking service will provide measurements from which estimates of the USAT (User Satellite) orbit, oscillator frequency bias, and clock bias will be determined."

At the AGT (ATDRSS Ground Terminal), time will be provided to the ranging and communications systems by a Common Time and Frequency System (CTFS), based on a redundant set of cesium frequency standards and time code generators (Ref. 13, sect. 6).

The ATDRSS will support the following time transfer services via the available tracking links via the SMA (S–band, Multiple Access), SSA (S–band, Single Access), KuSA and KaSA (Ku– and Ka–band Single Access) telecommunications channels (Ref. 12, para. 3.5):

- Two–way time transfer, supported via the two–way tracking service;

- One–way time transfer, via the one–way return link tracking service.

In the two–way mode, the time transfer measurement is performed with the following sequence (Ref. 12, para. 5.2.1.d):

1. The AGT measures the elapsed time between a reference CTFS time epoch and the next outgoing forward link range channel PN epoch. The AGT measures the elapsed time between the same reference CTFS epoch and the first return link PN epoch to arrive after the outgoing forward link PN epoch.
2. The USAT places a time tag in the return service data, referring to the departure time of the PN epochs.

The following specifications apply to the ATDRSS two–way time synchronization (Ref. 12, para. 5.3.1.c and para. 5.3.1.d):

- Time Transfer (TT) Measurements Resolution (this is called "granularity" in the specifications): < 200 ns
- TT Measurements r.m.s. Error (also referred as jitter in the specifications): < 25 ns
- Systematic Errors

contribution from ATDRSS:	< ± 35 ns
contribution from AGT:	< ± 30 ns

  [these are the same requirements as for the two–way ranging specifications]
- ATDRSS Delay Compensation [Delay Calibration]: to be provided as part of the timing service
- Time Tagging Accuracy

for ranging data:	< ± 1 μs of CTFS epochs
for Doppler data:	< ± 25 ns of CTFS epochs
for time transfer data:	< ± 5 μs of CTFS epochs
- Timing Accuracy: the reference CTFS epoch times shall have a systematic error < ± 5 μs relative to UTC, and shall be traceable to UTC time within ± 100 ns

For the one–way synchronization, the system specifications state (Ref. 12, para. 5.2.2.c) the following procedure:

1. The USAT will place time tags in the return service data.
2. The AGT shall format the user return service data into NASCOM (NASA Communications Network) data blocks.
3. The AGT shall place time tags in NASCOM data blocks.

In Europe and Japan, other compatible (at least for the S–band service) Tracking and Data Relay Satellites are under study: those are the ESA DRS (Data Relay Satellite) and the Japanese JDRS, planned for the mid–90s.

In Europe, a significant development may delay the planned launch of the first ESA DRS–1: the Advanced Relay and Technology Mission (ARTEMIS) project is well under way, and has been given priority by ESA over the DRS program. The first launch of ARTEMIS (as DRS–0) is scheduled in 1992.

ARTEMIS is a communication technology demonstration satellite, for advanced data relay and land mobile applications. The payloads will be:

- a laser optical data relay communication experiment (SILEX), for high data rate communications;
- an S–band, multiple access data relay payload, for medium data rates, intended to be compatible with the Multiple Access (MA) S–band service provided by TDRSS and ATDRSS;
- an L–band payload, intended for mobile services;
- a number of spacecraft technology experiments, such as ion propulsion and Ni–H batteries;
- an EHF propagation payload, to study propagation effects at high frequencies.

After a nominal 3 years experimental phase, ARTEMIS is intended to become part of the ESA DRS System as DRS–0. Several technologies carried onboard ARTEMIS are interesting: as far as timing is concerned, certainly the SILEX payload may offer unique capabilities to exercise new techniques for intersatellite time transfer.

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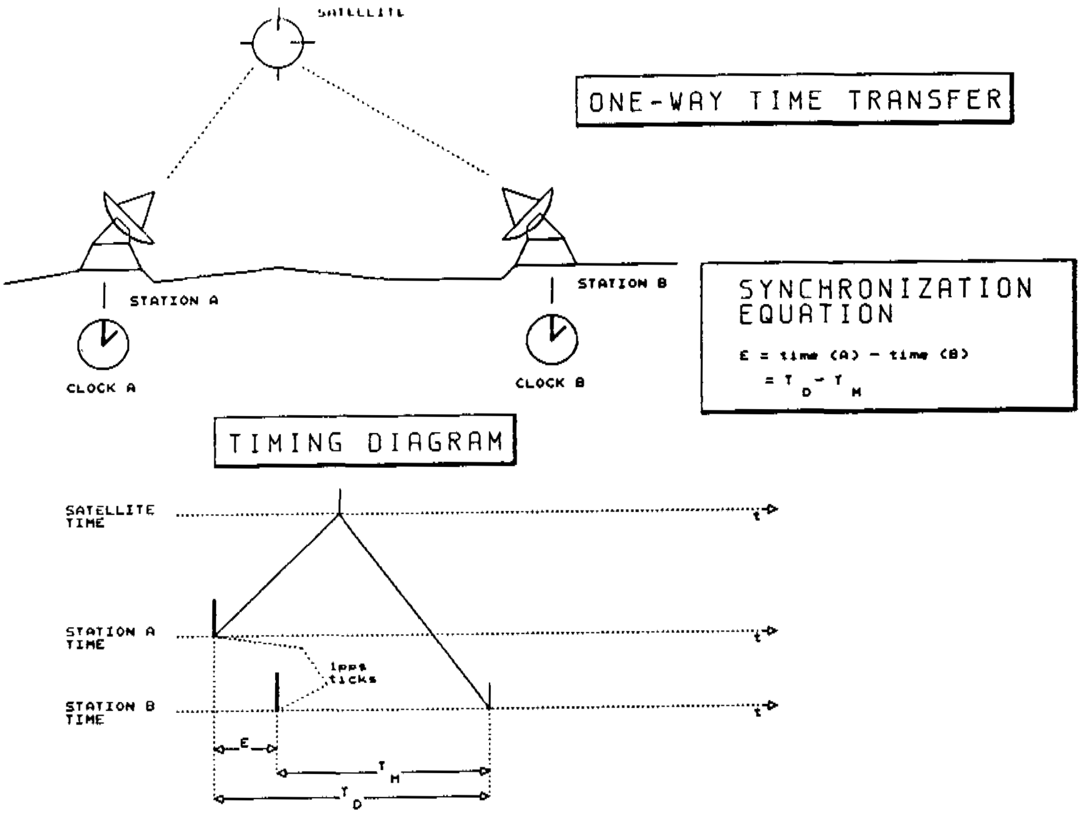


Fig. 1 - ONE-WAY TIME TRANSFER

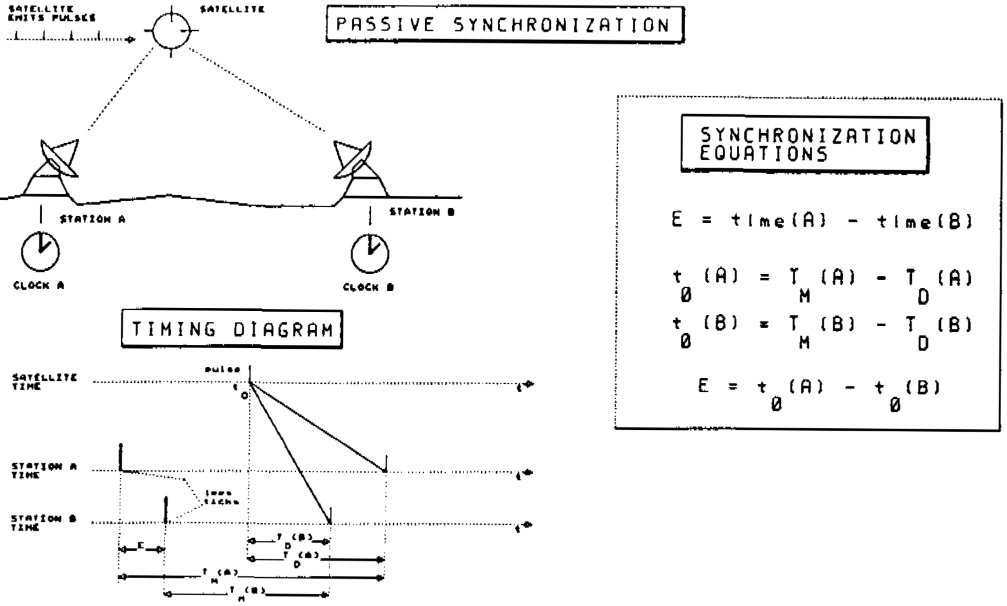


Fig. 2 - PASSIVE SYNCHRONIZATION

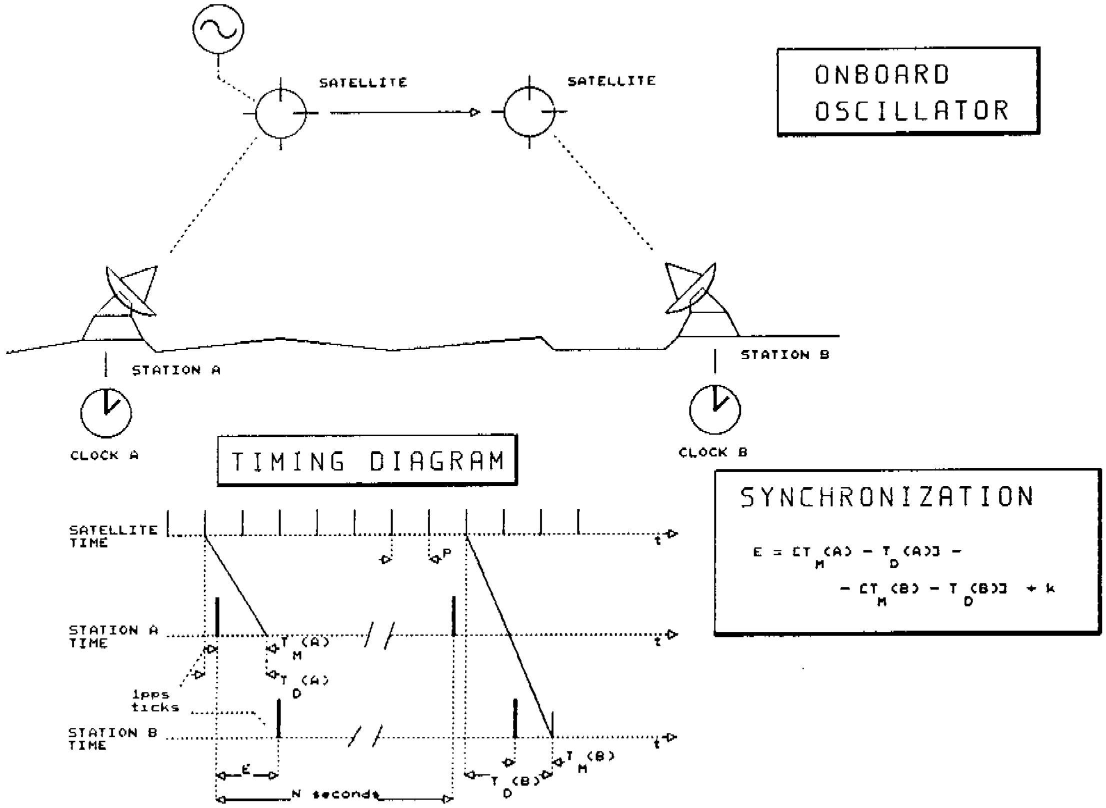


Fig. 3 - SYNCHRONIZATION WITH ORBITING OSCILLATOR

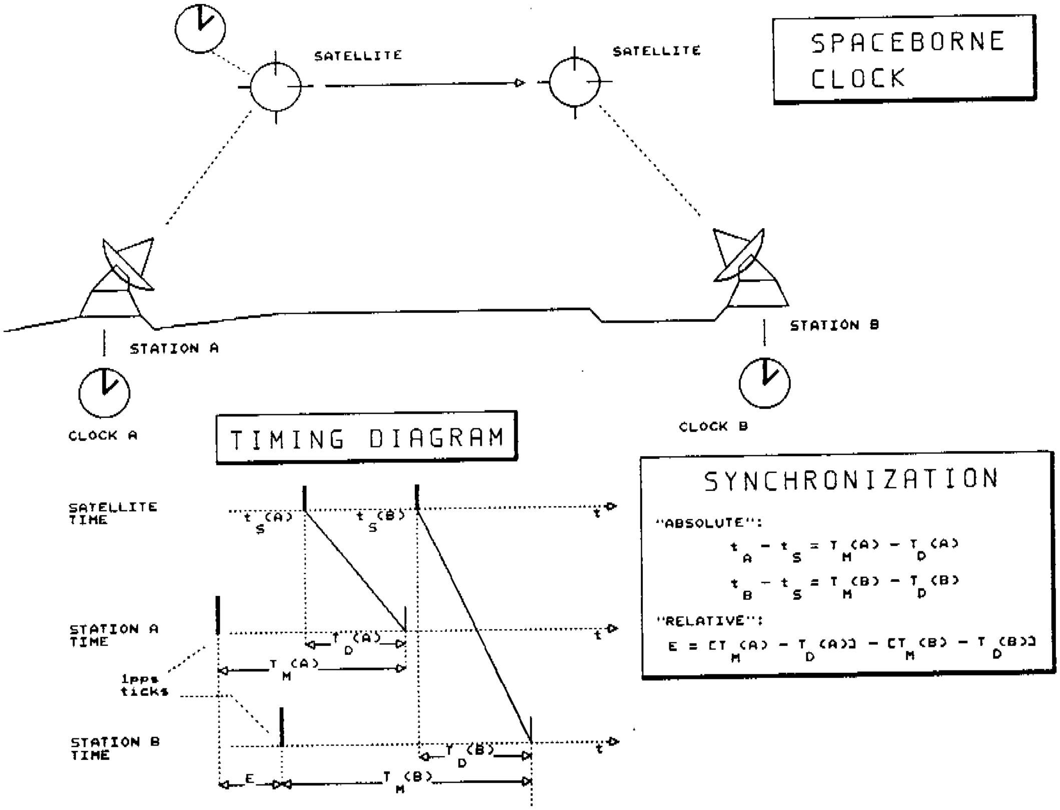


Fig. 4 - TIME TRANSFER WITH ORBITING CLOCK

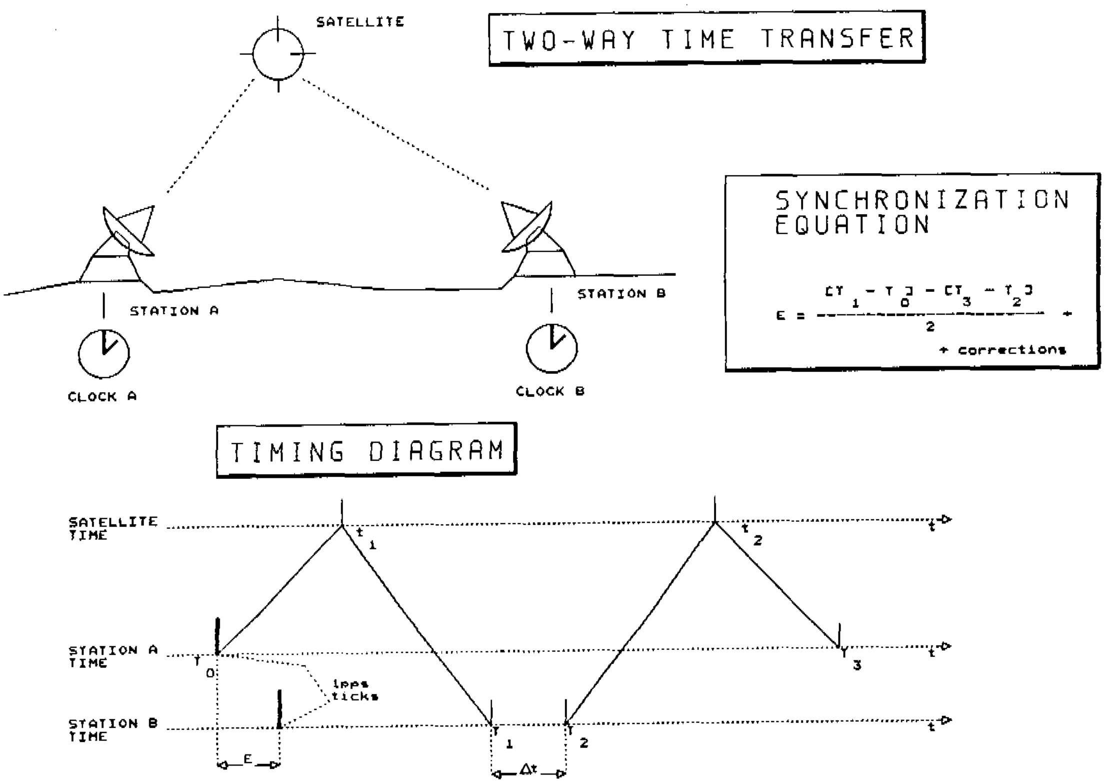


Fig. 5 - TWO-WAY SYNCHRONIZATION

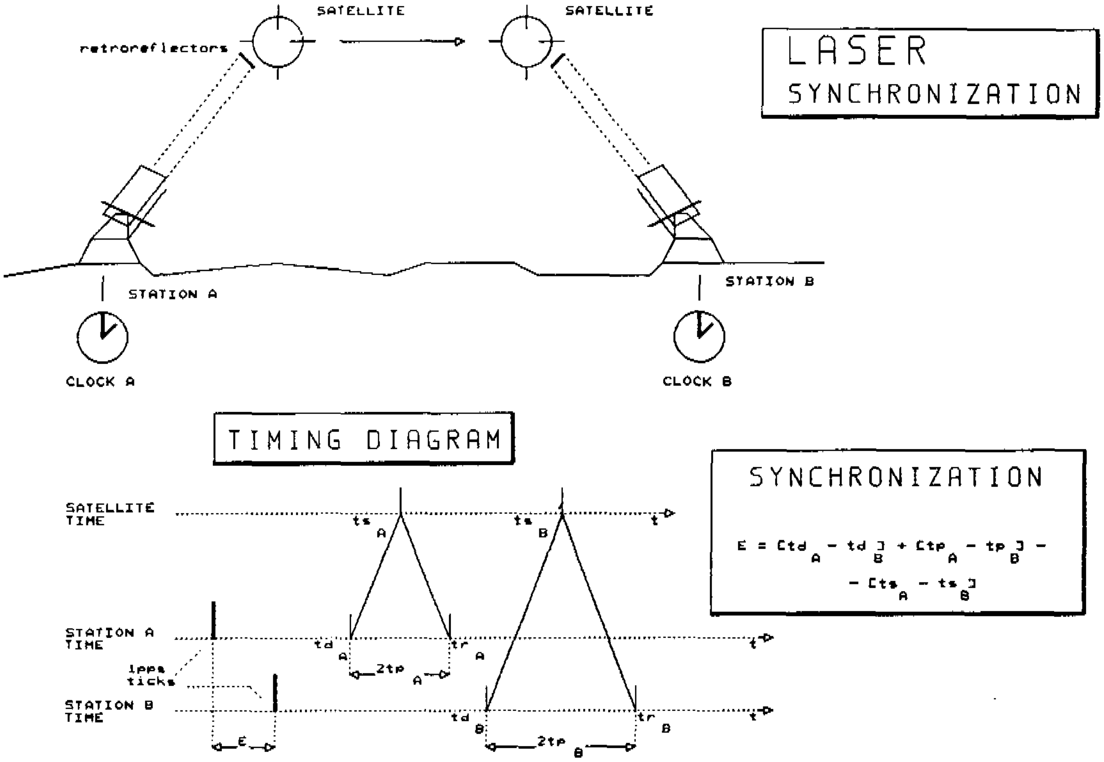


Fig. 6 - LASER SYNCHRONIZATION (LASSO)

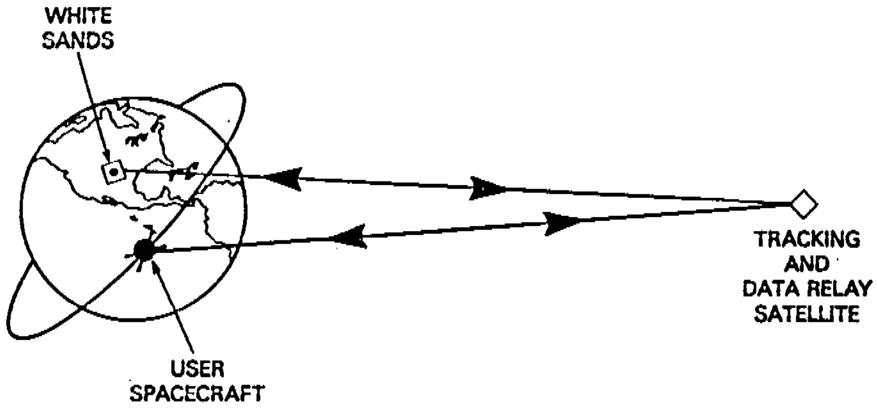


Fig. 7 - Tracking and Data Relay Satellite System (TDRSS) Orbital Geometry (from ref. 1)

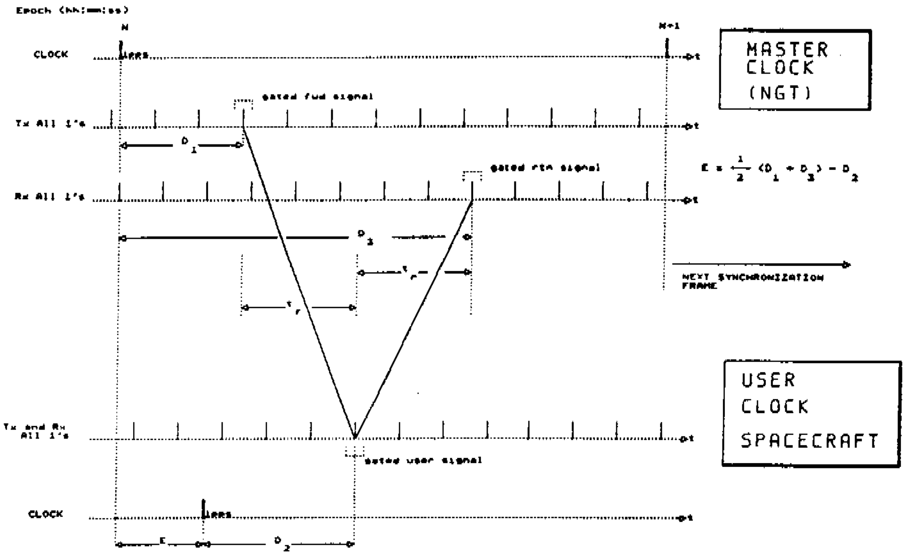


Fig. 8 - TDRSS two-way synchronization: simplified timing diagram (from ref. 1)

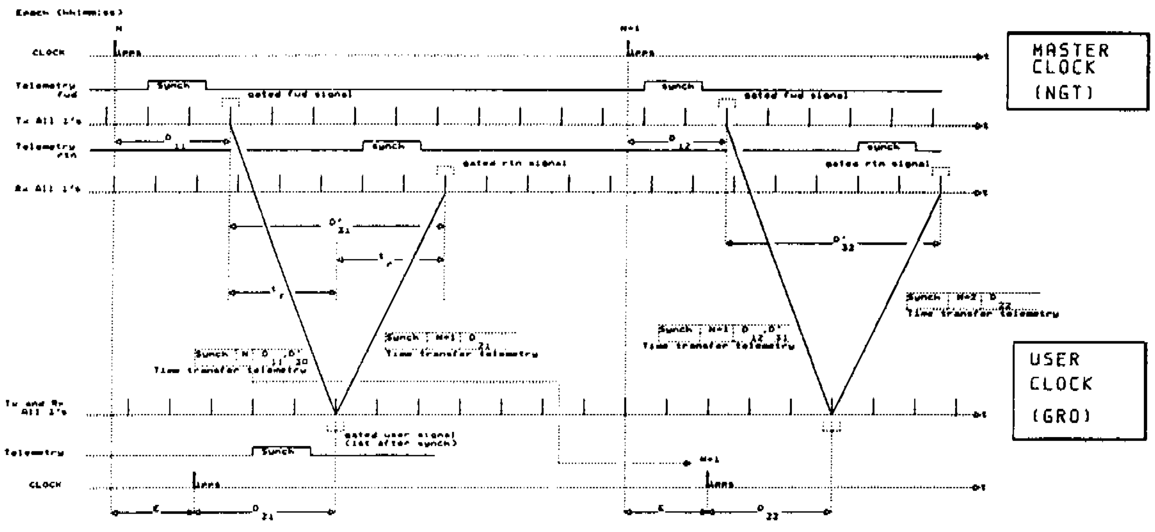


Fig. 9 - TDRSS two-way synchronization - Technique 1: basic timing diagram (from ref. 6)

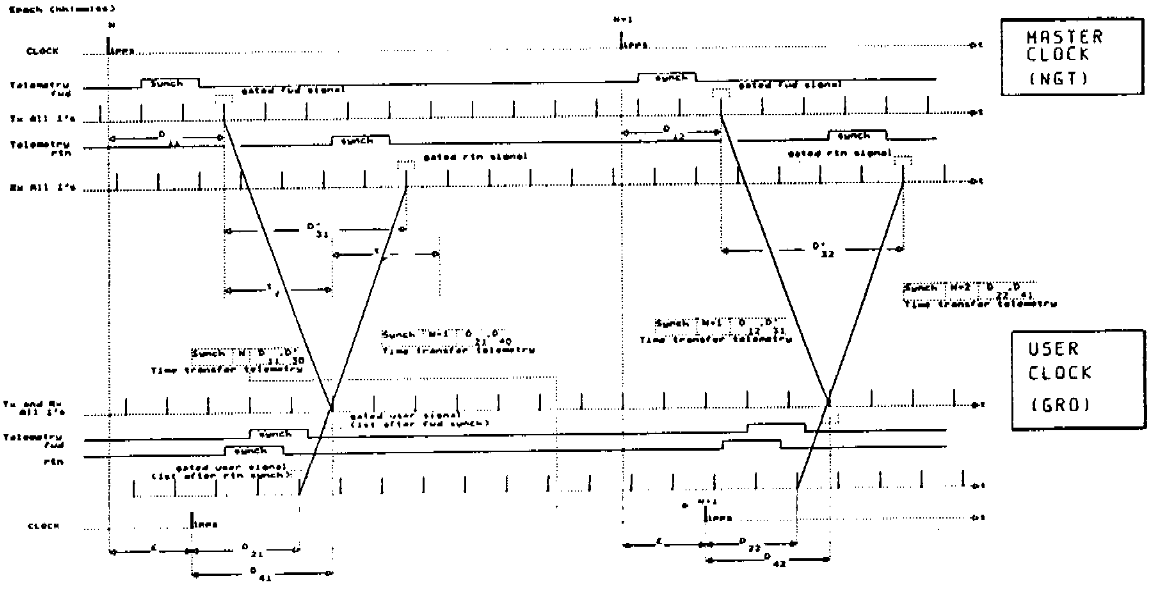


Fig. 10 - TDRSS two-way synchronization - Technique 2: basic timing diagram (from ref. 6)

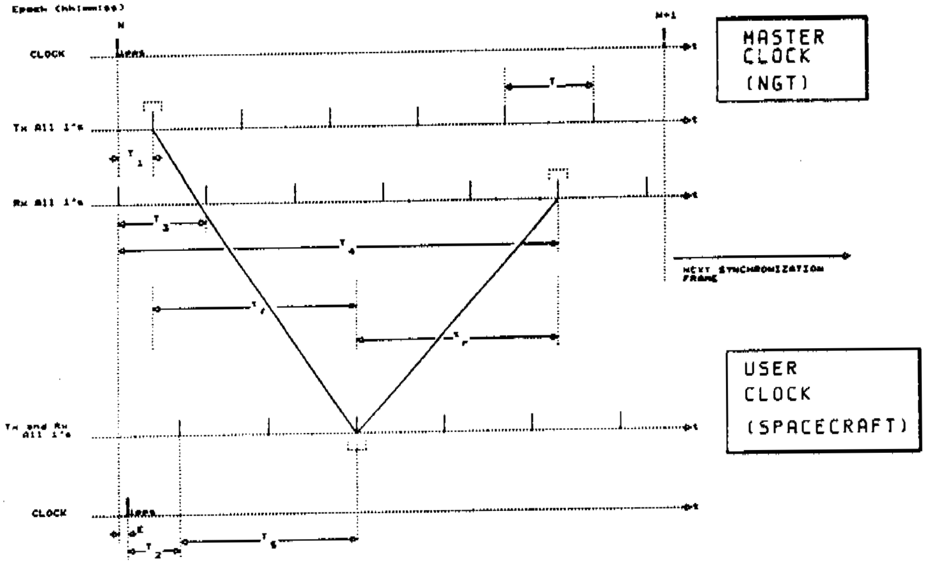


Fig. 11 - Hybrid method, Fine Synchronization: computations carried on with modulo-T arithmetic (from ref. 9)

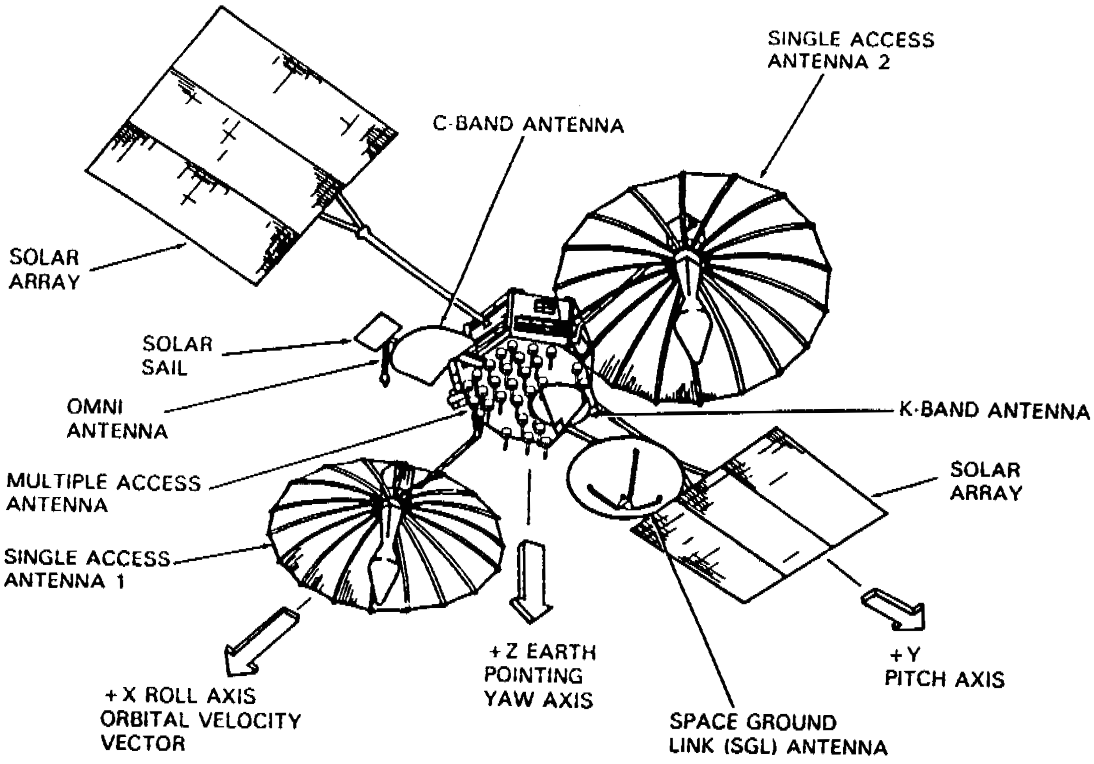
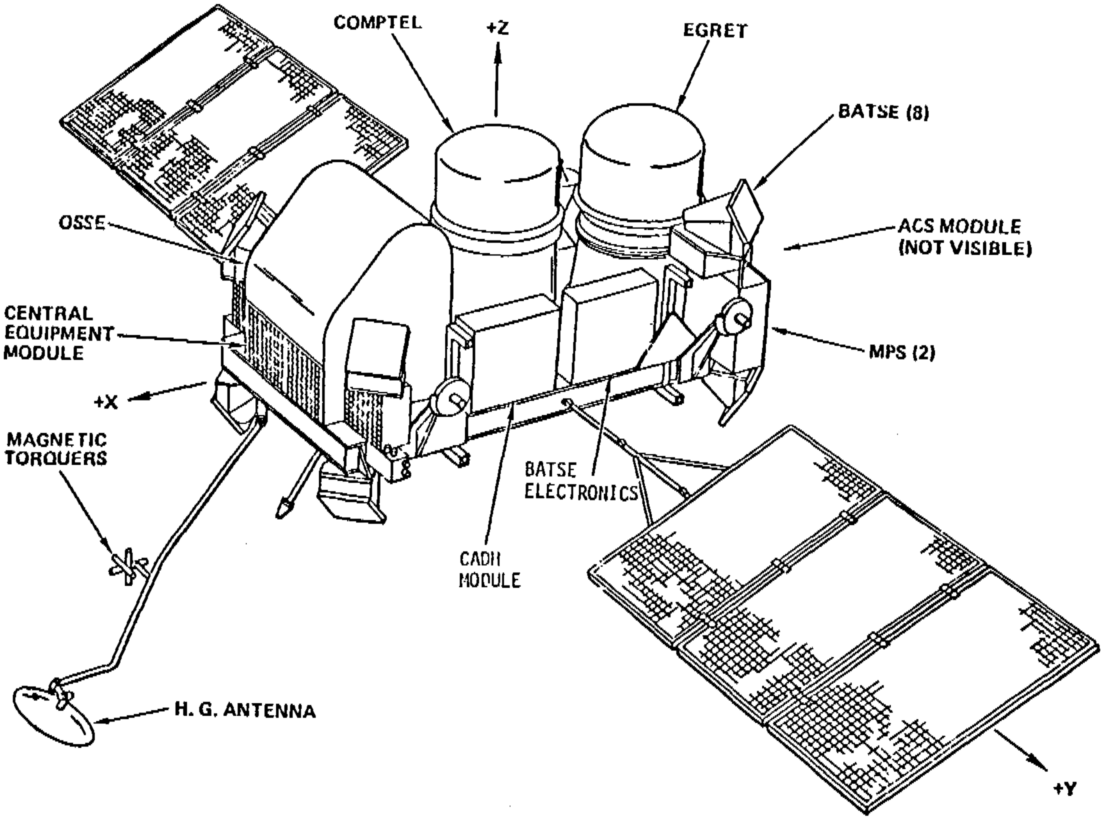


Fig. 12 - The TDRSS Spacecraft

Fig. 13 - The Gamma Ray Observatory (GRO)



Gamma Ray Observatcry