TIMING OF SPACECRAFT DATA

Time Accuracy Requirements and Timing Facilities of the European Space Agency (ESA).

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ABSTRACT

The time accuracy requirements for various ESA satellite missions are analysed; the requirements are grouped by the type of mission. The evolution of satellite timing techniques since 1968 is shown, and the requirements for future ESA missions (until the late 80's) are assessed.

Timing systems and their configuration at various ESA ground stations and the operations control centres are described.

Based on practical experience operational aspects will be presented, covering mainly Time Synchronisation, Time and Frequency corrections and typical problems encountered during routine operations such as routine monitoring, reporting, time/frequency offset calculations and adjustments.

Common time reference techniques operationally used, such as VHF transmission, LORAN-C, TRANSIT and travelling Clocks are compared in terms of availability, reliability and time accuracy.

The equipment performances of standard commercial timing systems, based on Caesium, Rubidium and Crystal oscillators are presented. Based on actual maintenance data acquired in ESA ground stations, the overall reliability of these systems and actual performance parameters in terms of MTBF, MDT, operational availability etc. are shown.

Two studies on future techniques in the field of time dissemination and time synchronisation conclude this paper: The LASSO mission (Laser Synchronisation from Stationary Orbit) and a low-cost time dissemination technique using METEOSAT, the european meteorological satellites, are briefly outlined.

1. INTRODUCTION TO THE ACTIVITIES OF ESA

1.1 General

The European Space Agency (ESA) was set up in 1975, grouping in a single body the complete range of European space activities. These had previously been conducted by ESRO - the European Space Research Organsiation - and ELDO - the European Launcher Development Organisation - in their respective fields of scientific satellite development and launcher construction.

Under the terms of its convention, the Agency's task is to provide, for exclusively peaceful purposes, co-operation among European States in space research and technology, with a view of their use for scientific purposes and for operational applications systems.

1.2 Funding

The general budget and the scientific programmes are funded by the 11 European Member States on the basis of their national income. Other programmes - mainly applications programmes, are optional with varying contributions from different States, depending on their interest and involvement in the respective programme. Examples are the ARIANE launcher development, Spacelab, Telecommunications or Earth Observation programmes.

1.3 Establishments

The headquarters of the Agency is in Paris and there are two main technical establishments - a Technology Centre in the Netherlands, called ESTEC and an Operations Centre at Darmstadt, Germany. The technology centre is responsible for the development of Spacecraft, whereas the operations centre (ESOC) is in charge of the satellite orbital operations.

1.4 Ground Stations

In performing this task, ESOC uses a network of 7 ground stations, linked to the control centre by means of suitable data communications links (Fig. 1).

Carnarvon (Australia), Kourou (French Guiana), Malindi (Kenya), Redu (Belgium), and three specialised stations for the geostationary satellites, Odenwald (Germany), Villafranca (Spain), and Ibaraki (Japan).

The technical role of these stations and the ESOC control centre will be displayed in more detail - in the context of Timing techniques - in the following sections.

1.5 Satellite Missions

A total of 13 scientific ESA satellites were launched from 1968 to date, all of which were highly successful (Table 2). Some exceeded expectations as to both lifetime and scientific return.

The ESA applications satellites were all in the field of Communications or Earth Observation (Table 3.).

More details about these science and applications missions will be given in the following section.

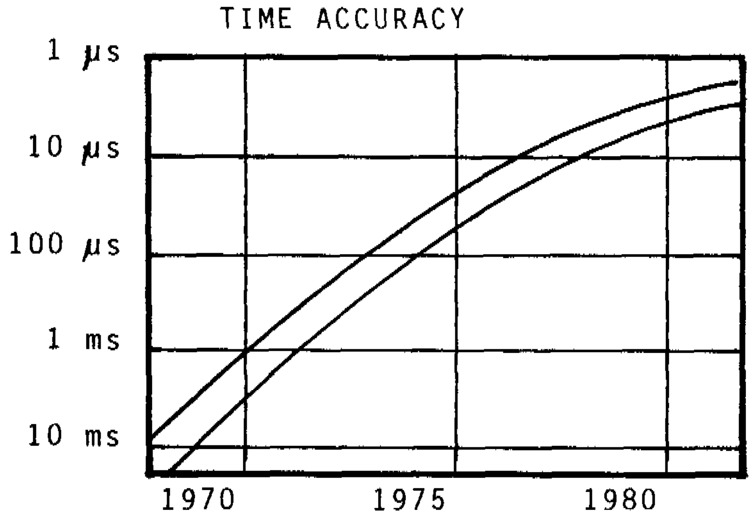
2. TIME ACCURACY REQUIREMENTS FOR SPACECRAFT DATA

2.1 Evolution of Time Accuracy of Station Clocks

Table 1 shows the improvement achieved during the last 15 years in the timing of satellite data.

Whereas VLF or HF time dissemination methods were used for synchronisation of station clocks during the early 70's, LORAN-C and TRANSIT are now the standard reference systems in use. If higher precisions are required, time comparison by means of portable clocks are performed.

This will be explained in more detail in the following section.



Evolution of station clocks time accuracy

TABLE 1

2.2 In tables 2 and 3 the ESA satellite missions are listed with the associated time accuracy requirement. They are grouped into scientific and applications satellites and include current missions and a selection of future missions. From the tables one can conclude that Science Missions are the main driver for High Accuracy Timing Systems. In addition to the absolute accuracy with respect to UTC a good short term frequency stability (typ. 10^{-13}) is required for all future science missions.

In the field of applications satellites the absolute time accuracy is of lesser importance. The criteria of the high frequency stability however also applies to the meteorological and earth observation missions.

Common to all missions the determination of the orbital position is one of the drivers for precise timing of data. For certain future mission, like the Navigation Satellite, this requirement will be in the order of 3 - 10 ns.

ESA SCIENTIFIC SATELLITES

SATELLITE	LAUNCH DATE	MISSION	TIME ACCURACY
ESRO-II/ IRIS	170568	COSMIC RAYS AND SOLAR X-RAYS	
ESRO-IA/ AURORAE	031068	POLAR IONOSPHERE AND AURORAL PHENOMENA	100...
HEOS-1	051268	SOLAR WIND AND INTERPLANETARY MEDIUM	10 ms
ESRO-IB/ BOREAS	011069	POLAR IONOSPHERE AND AURORAL PHENOMENA	
HEOS-2	310172	POLAR MAGNETOSPHERE AND INTER-PLANETARY MEDIUM	10...
TD-1	120372	ULTRAVIOLET ASTRONOMY	1 ms
ESRO-IV	221172	IONOSPHERE AND SOLAR PARTICLES	
COS-B	090875	GAMMA RAY ASTRONOMY	50 μs
GEOS-1	200477	MAGNETOSPHERE	10 μs
ISEE-B	221077	MAGNETOSPHERE AND SUN-EARTH RELATIONS	
IUE	260178	ULTRAVIOLET ASTRONOMY	100 ms
GEOS-2	140778	MAGNETOSPHERE	10 μs
EXOSAT	260583	X-RAY ASTRONOMY	50 μs
HIPPARCOS	1988	ASTRONOMY	5 μs
GIOTTO	1985	HALLEY COMET ENCOUNTER	5 μs
ISO	1990	INFRARED ASTRONOMY	100 μs

TABLE 2

ESA APPLICATIONS SATELLITES

SATELLITES	LAUNCH DATE	MISSION	TIME ACCURACY
OTS MARECS-A ECS-1	11/05/78 20/12/81 16/06/83	TELECOMMUNICATIONS	100..250µs
METEOSAT-1 METEOSAT-2 METEOSAT-OP	23/11/77 19/06/81 198	METEOROLOGY	100..250µs
OLYMPUS	1986	COMMUNICATIONS	100 µs
EURECA	1986	MICROGRAVITY MAT.SCIENCE	100 ms
ERS	1988	EARTH OBSERVATION	100 µs
NAVSAT	1990 +	NAVIGATION	t.b.d.
POPSAT	1990 +	TERRESTRIAL POSITIONING/ KINEMATICS	t.b.d.

TABLE 3

3. OPERATIONS ASPECTS

3.1 Equipment Configurations

Three examples shall illustrate typical timing equipment configurations at ESA ground stations.

3.1.1 Odenwald Station

Fig. 2 shows a diagram of the timing and frequency subsystem in use at our ODENWALD station, the prime station for the meteorological satellites METEOSAT 1 and 2 and the telemetry receiving station for the scientific satellite GEOS.

Two caesium standards are used to generate 5 MHz outputs with a frequency stability of $\pm 5 \times 10^{-12}$.

The 5 MHz outputs are fed into a switching module consisting of two phase shifters, two divider units, and two switching units. The phase shifters provide manual adjustment of the phase of the off-line standard to enable signal switching without any phase jumps. The dividers provide the 1 MHz and 100 KHz outputs for the station. The outputs from the switching module feed four amplifier modules; each amplifier module has sixteen frequency outputs.

Time Code Generators provide further outputs of serial encoded data and 1 Hz pulses to the majority decision unit and master/slave selection unit, which compares the numerous inputs from the different chains and makes a decision which input to use on a 'best two from three' basis. The majority 1 Hz pulse is made available at the output for comparison with the LORAN-C reference.

The time accuracy which is achieved with this configuration is within ± 20 μs of UTC.

3.1.2 Redu Station

Slightly simpler variant of the timing subsystems used in other ESA stations is shown in Fig. 3. It is the timing section of the REDU ground station. This station is the prime TT&C station and control centre for the ECS telecommunications satellites. It further provides back-up support in VHF to all other ESA missions. Since the time accuracy requirements are less stringent, the frequency standards used in this configuration are two Quartz oscillators. They generate 5 MHz, which is compared to a standard frequency derived from a LORAN-C receiver. An error signal is produced, which forms the basis for correction of the station oscillators. The outputs from the two oscillators are taken via a switching module and amplifiers to two time code generators, which in turn supply the time code generator selection module with IRIG-B, PDM, 1, 5 and 10 MHz time signals.

Since the Redu station also includes the control centre for ECS, the timing system includes stop clocks, time displays, and other control centre specific equipment.

With this system configuration the time accuracy achieved is in the order of 50 μs of UTC.

3.1.3 Transfer Orbit Network

Another variant of timing systems is shown in Fig. 4. This configuration is implemented at the equatorially located stations of the transfer orbit network i.e. Kourou, Malindi, Carnarvon. It can be seen that there is not much redundancy built in, apart the double frequency generator, consisting of a Rubidium standand backed up by a Quartz.

Since LORAN-C reception is not possible in the said stations, time is checked against a TRANSIT Satellite receiver. The resultant time accuracy which is achieved with these systems is in the order of 50 - 100 μs.

3.2 Synchronisation of Timing Systems

3.2.1 Synchronisation of the various timing systems described above, with respect to UTC, is achieved by means of VLF reception, LORAN-C, TRANSIT Satellites or Travelling Clocks. Table 4 shows the normal ways of synchronising station clocks and the references used.

Reference / Ground Stations	VLF	LORAN	TRANSIT	TRAVELLING CLOCK
OCC	X			(X)
ODENWALD (Germany)		X		(X)
REDU (Belgium)		X		(X)
VILLAFRANCA (Spain)		X		(X)
MALINDI (Kenya)			X	
KOUROU (Fr. Guyana)			X	
CARNARVON (Australia)			X	

Table 4

3.2.2 VLF Reception of timing signals is in use at all stations for coarse time synchronisation and as back-up reference to the respective higher-precision reference systems.

3.2.3 LORAN-C is the standard time comparison technique at sites where LORAN reception is possible. The time offset of station clocks is determined in the normal way by measuring the interval between the reception of the LORAN-C pulse and the station's 1 pps signal and subtracting the fixed propagation delay. The latter is obtained from USNO (US Naval Observatory), calculated on the basis of the station coordinates, and corrected by means of Travelling Clock measurements.

The time offsets are measured by means of LORAN-C on a daily basis. They are corrected retroactively after availability of the "Series-4" LORAN-C offsets. Typical recordings of these time and frequency offset measurements are shown in the following section.

3.2.4 TRANSIT satellites are used for time synchronisation at our equatorial stations MALINDI, KOUROU, and CARNARVON, where LORAN-C reception is difficult or impossible. The operation of TRANSIT satellite timing receivers is not described here; the principle is assumed to be well known. Two important operational aspects, however, are the simplicity of operation and the reliability of the equipment. In particular in the smaller ESA stations mentioned above, with a typical manning of not more than 5 or 6 M+O Technicians, the fully automatic operation of the Satellite Timing receivers without operator attention is a particular advantage.

The time accuracy achieved by means of TRANSIT time comparison is in the order of 5 μs of UTC.

3.2.5 A Travelling Clock is used for synchronisation of station timing systems, whenever higher precision is required. A home-made portable Rubidium clock is used for this purpose. The autonomy of this clock - limited by the battery capacity - is approximately 4.5 hours. During longer trips the battery has to be recharged - this takes about 1 hour - but for synchronisation of the European ESA sites, the 4.5 hr autonomy is usually sufficient.

The accuracy achieved by time comparison with the portable Rubidium clock is better than 1 μs which is largely sufficient for our present applications.

3.3 Time and Frequency Corrections

The offsets of the station timing systems are determined from daily measurements, using the reference systems outlined above. Examples of time offset recordings are shown in Fig. 5.

Three figures show the typical behaviour of a clock driven by a Rubidium oscillator. You will note the negative frequency drift, characteristic of Rb oscillators. The offsets are determined against LORAN-C as reference. Please note that the recordings are not "Series-4 corrected", i.e. the retroactive corrections of time offsets in the LORAN-C system have not been performed.

From the time offset curve the frequency offset is determined and compensated for from time to time. Time offset corrections are normally not performed by clock-resetting, but through over-compensation of the frequency offset, except if time jumps occur. The obvious advantage of this method is the fact that no excessive deviation of the frequency from the nominal frequency can build up.

In the portable rubidium clock mentioned in the previous chapter, the "time transport" is normally performed when the time offset parabola reaches its horizontal part, thus minimizing the effects of frequency offsets (and thus time drifts) during the time comparison trip.

3.4 Typical Operational Problems

The following is a short summary from the user's point of view of the most frequent problems in operating timing systems at satellite ground stations:

1) Time Jumps

   a) Reason: Equipment failure, mostly power supply of TCG.
   b) Detection: Regular checks of time consistency.
   c) Corrective action: Time reset, correction of time-coded data.

2) Frequency Jumps

a) Reason: Equipment (oscillator) malfunction
b) Detection: Change of time offset drift
c) Corrective action: Frequency adjustment or corrective maintenance.

3) Incorrect Frequency Setting

a) Reason: Operator error or incorrect calibration of frequency adjustment.
b) Detection: Excessive time drift or drift in wrong direction.
c) Corrective action: Frequency correction, Establishment of frequency "calibration curve".

4) Wrong Leap Second Introduction

a) Reason: Operator error (mostly)
b) Detection: Course time check by means of VLF.
c) Corrective action: Time correction with full synchronisation (VLF, LORAN-C, possibly Travelling clock).

5) LORAN-C Reference Incorrect

a) Reason: Receiver locked on wrong cycle of LORAN pulse.
b) Detection: Travelling clock time comparison.
c) Corrective action: Resynch of LORAN receiver.

6) LORAN-C Propagation Delay Error

a) Reason: Error in calculation of propagation delay, wrong coordinates.
b) Detection: Travelling Clock.
c) Corrective action: Correction of fixed delay for LORAN chain.

4. EQUIPMENT PERFORMANCE

The reliability of the timing systems described above is continuously being monitored at the ESA ground stations. From equipment failure records over the past 4 years some performance parameters are summarised below.

Two categories of timing systems were analysed:

- Three systems based on Rubidium clocks, and
- One system based on a Caesium standard.

All systems were in continuous operation.

The results are as follows:

TYPE OF CLOCK	MTBF	MTTR
Rubidium	2100 h	113 h
Caesium	1700 h	503 h

From these figures it is concluded that systems based on Caesium clocks have a slightly higher failure rate than Rubidium clocks. The main difference, however, is in the MTTR which is 4...5 times longer for Caesiums. Mainly due to their higher complexity these systems required frequent corrective maintenance intervention by the manufacturer, which caused long times to repair.

5. TIME DISSEMINATION VIA METEOSAT (STUDY)

5.1 Introduction

A study was carried out on the possibility to use the existing METEOSAT satellites for time dissemination. Similar to the GOES time dissemination system, which uses the DCP (Data Collection Platform) interogation function, a method was worked out which could provide a similar service with an accuracy and stability in the order of 10 μs, with a target of 2...3 μs. The METEOSAT system could thus bridge the gap between the performance of a commercial Rubidium standard and a prime standard, at a cost of less than $10,000.

5.2 System Concept

The time dissemination system proposed consists of the following elements (Fig. 6):

- A satellite, carrying a transponder of reasonable propagation delay stability, and having an orbit determination system allowing position determination to within about 100 m.

- A ground station which can at any moment be supplied with satellite position information. The station should be equipped with a timing subsystem which allows timekeeping to the microsecond accuracy. The station will transmit timing and position information to the spacecraft.

- User stations. These receive the timing message, apply a correction for the propagation delay to their specific location, and set a local (running) clock accordingly.

- A monitoring and calibration facility consisting essentially of a set of user equipment located at a primary timing reference.

In order to avoid operational conflicts the additional occupation of the satellite communication link should be limited to one percent. Timing transmission will therefore take the form of updates: At regular intervals a message is transmitted containing essentially an "event" occurring at an instant, identified in Universal Time. The user equipment will note the local time at reception of the event and from the difference (corrected for propagation delay) it will calculate and implement a correction to the locally generated time.

A detailed description of the system is contained in Ref. (1).

6. LASSO MISSION: LASER SYNCHRONISATION FROM STATIONARY ORBIT

6.1 Introduction

The concept of the LASSO mission is briefly outlined. This mission was designed to be flown on the SIRIO-2 Spacecraft. Due to a malfunction of the ARIANE launch vehicle the satellite was destroyed during the launch in Sept 1982. In the meantime the LASSO mission has been taken up again and is now planned to be integrated into the METEOSAT-3 payload, due to be launched in 1985.

6.2 Principle of Operations

Fig. 7 illustrates the synchronisation of two atomic clocks, e.g. one in the United States and one in Europe. Each clock triggers a laser pulse from a nearby laser station towards the satellite at a predefined time. The satellite sensor and oscillator assembly will then time-tag the arrival of the two pulses. Assuming equal distances between the laser stations and the spacecraft, any difference in arrival times of the two pulses will be proportional to the synchronisation offset between the atomic clocks. This measured difference can be transmitted along with the satellite's telemetry to the ground for clock synchronisation.

In practice the earth - satellite laser propagation time varies with the distance between the participating station and the satellite. To allow the stations to calculate this distance and perform the necessary corrections for the propagation delay, the satellite is equipped with so-called "Retro-reflectors", i.e. mirrors which reflect the incoming laser pulse back to its originating station.

This principle is shown in Fig. 8, where tA and tB are the departure times of the laser pulses, TA and TB are the propagation delays, R is the interval measured on-board the satellite. From these values the required clock correction C is calculated, according to the formula

$$C = tA + TA + R - TB - tB$$

The precision of the clock comparison to be obtained is obviously dependent on the precision to which each term of the above equation can be measured; in principle, it can be as good as 1 ns.

In the time available it is obviously not possible to describe in detail all the elements and the operational set-up of the LASSO system. This information can be found in Ref (2).

REFERENCES

(1) Transmission of Precision Timing by METEOSAT
ESOC/GEED/Studies Branch
GEED/7030/EEL/SLE

(2) SIRIO-2 Programme
ESA SP-1039, August 1981

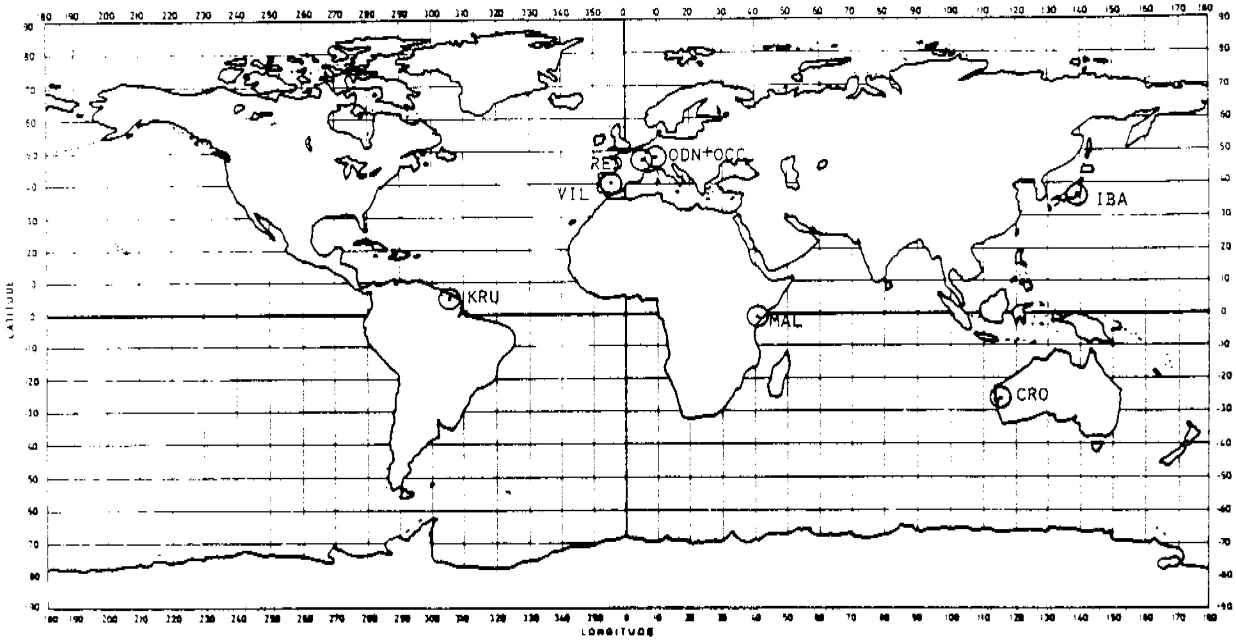


FIG. 1. ESTRACK GROUND STATIONS

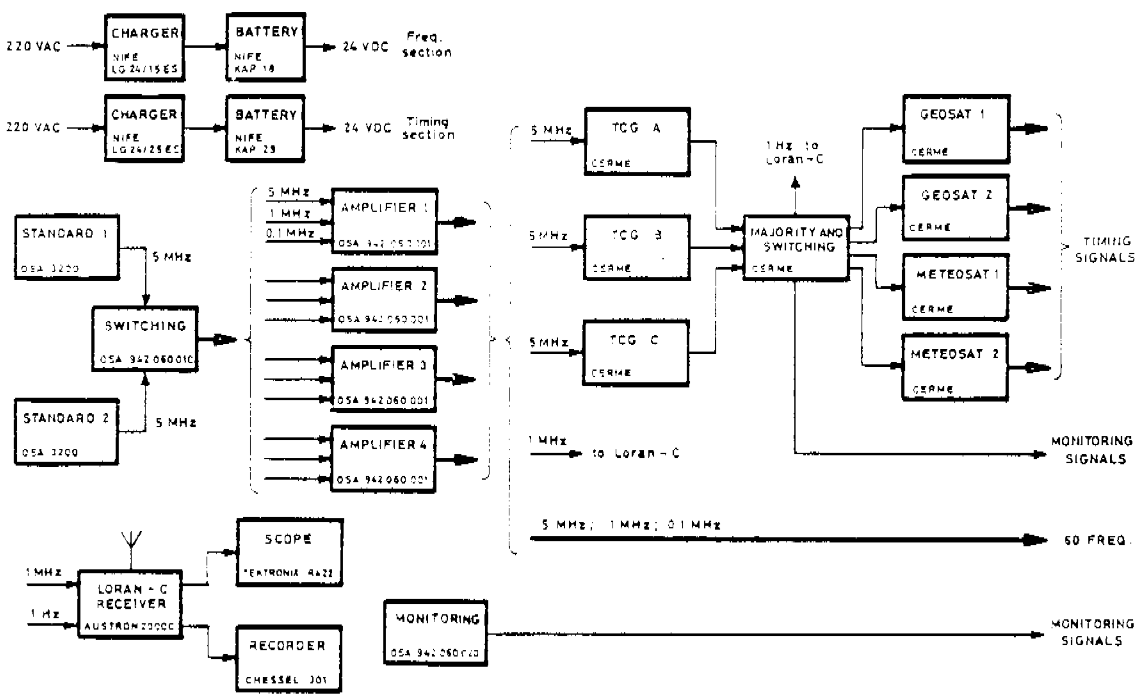


FIG. 2. BLOCK DIAGRAM FOR GEOS-METEOSAT GROUND STATION

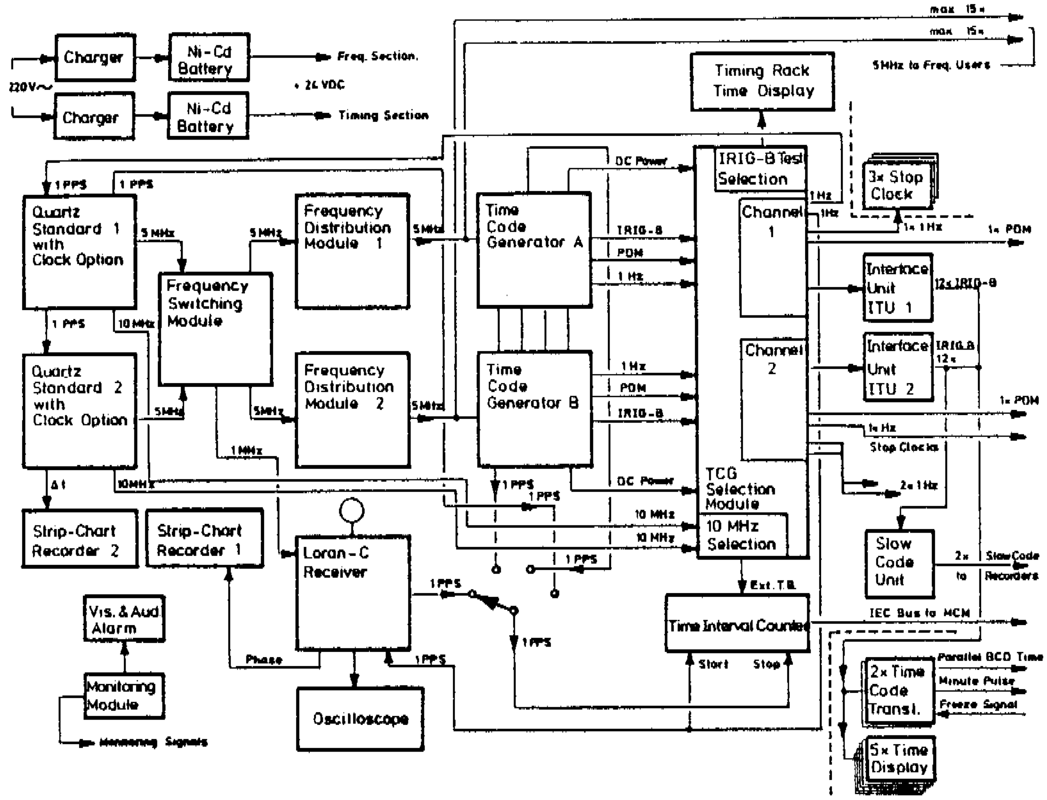


FIG. 3. REDU FREQUENCY AND TIMING SUBSYSTEM BLOCK DIAGRAM

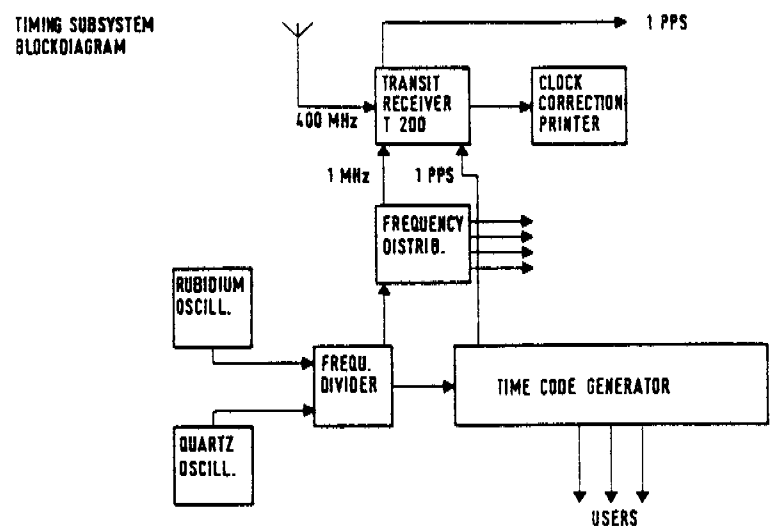


FIG. 4. TRANSFER ORBIT NETWORK STATION

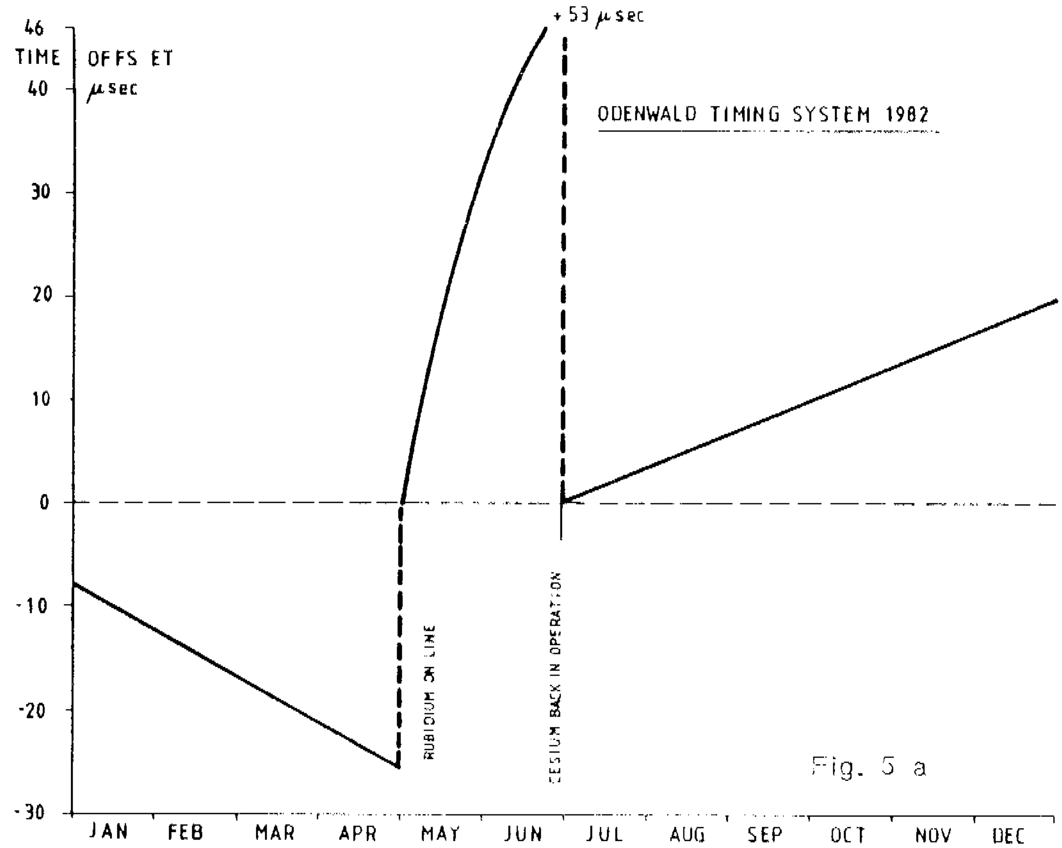

46
TIME
OFFS ET
40
μsec
+53 μsec
ODENWALD TIMING SYSTEM 1982
30
20
10
0
-10
-20
-30
RUBIDIUM ON LINE
CESIUM BACK IN OPERATION
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 5 a

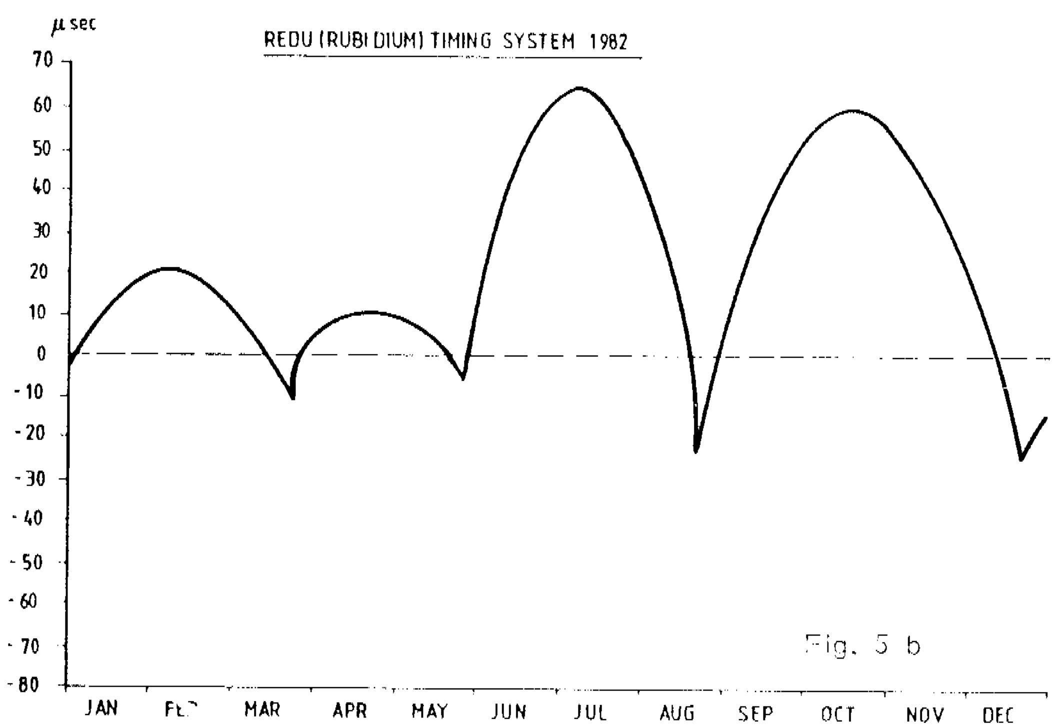

μsec
REDU (RUBIDIUM) TIMING SYSTEM 1982
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
JAN
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 5 b

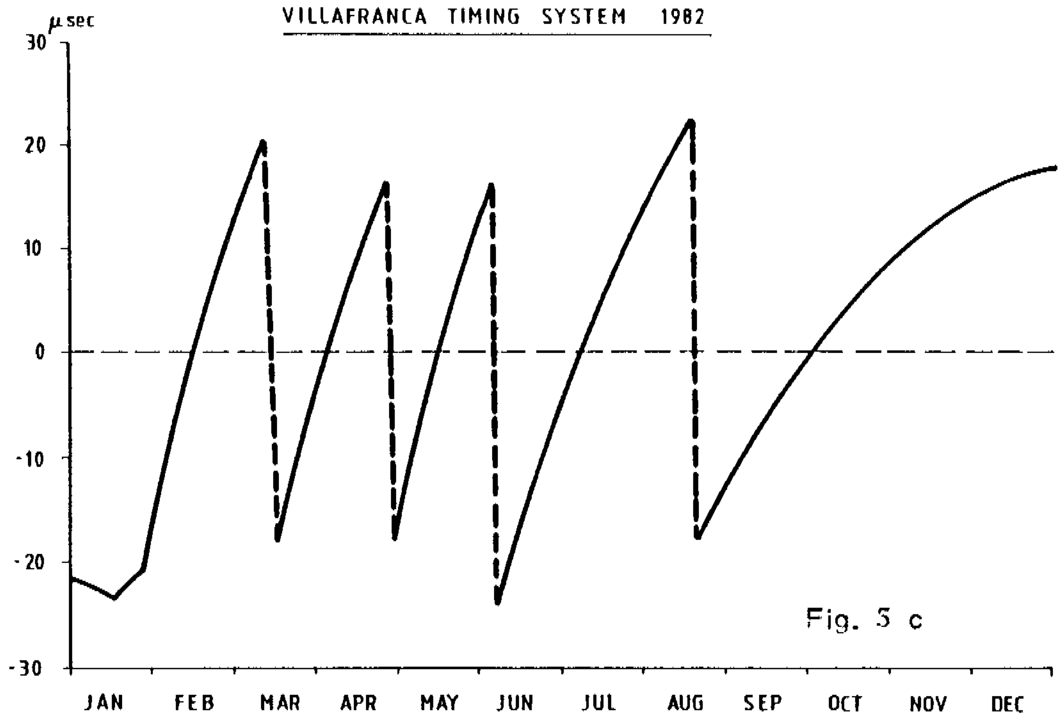
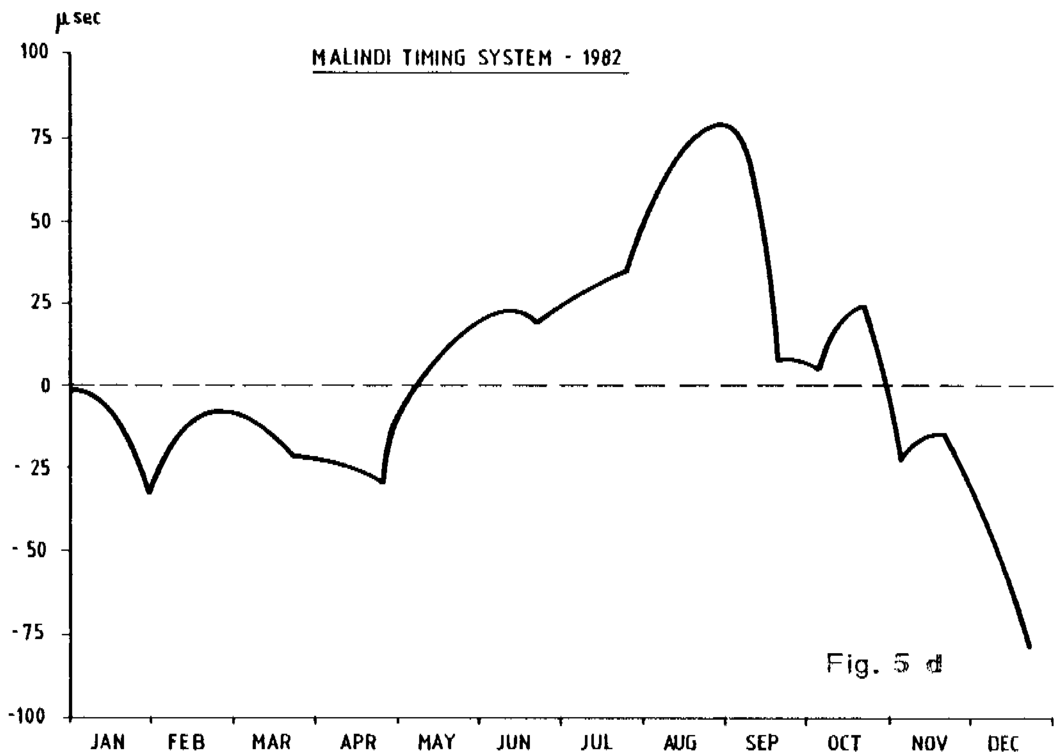

VILLAFRANCA TIMING SYSTEM 1982
μ sec
30
20
10
0
-10
-20
-30
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 5 c


MALINDI TIMING SYSTEM - 1982
μ sec
100
75
50
25
0
- 25
- 50
-75
-100
JAN
FEB
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MAY
JUN
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SEP
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Fig. 5 d

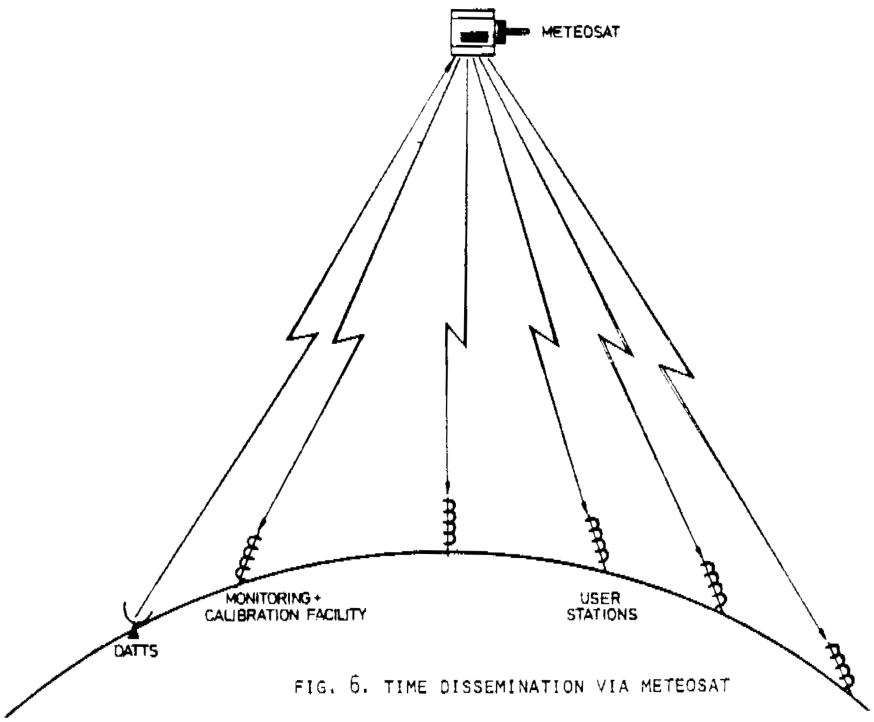


FIG. 6. TIME DISSEMINATION VIA METEOSAT

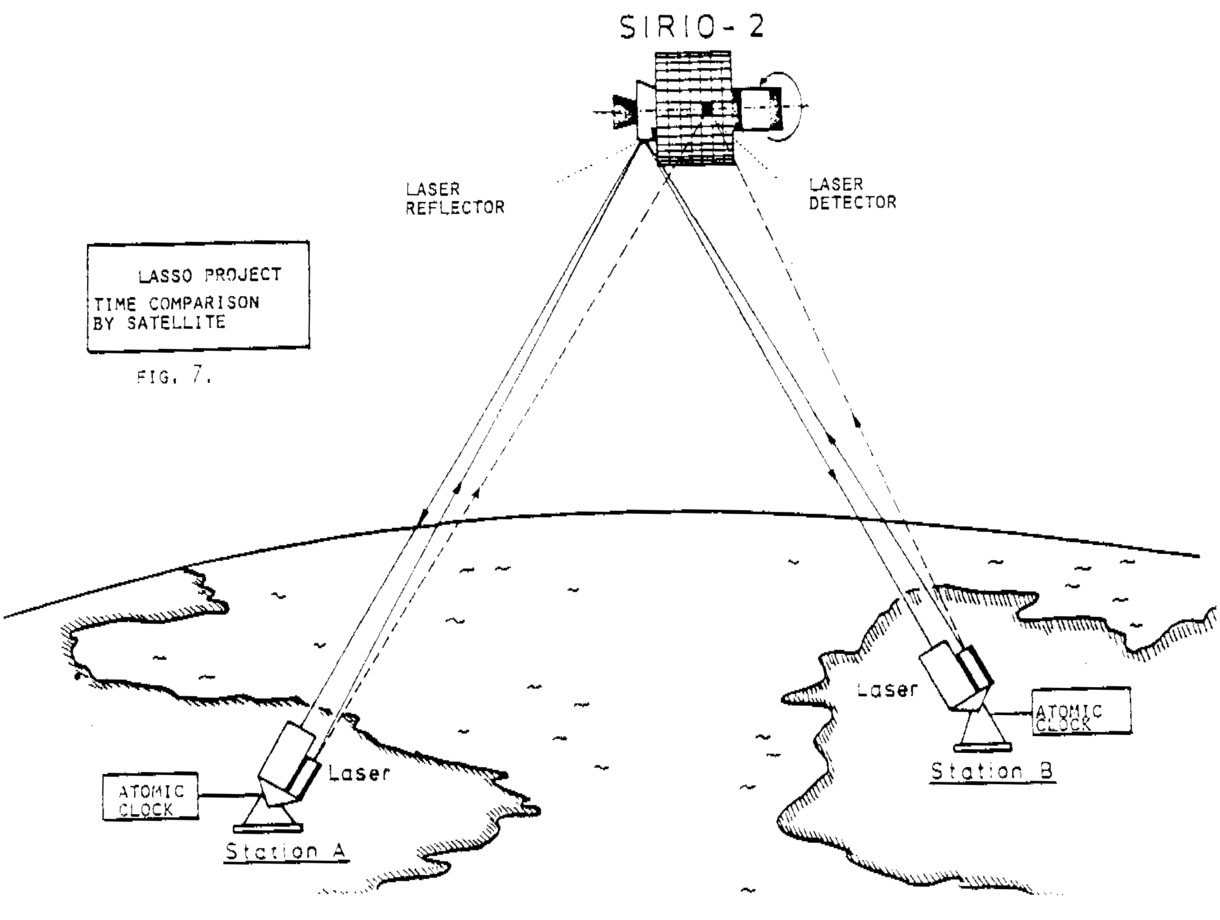
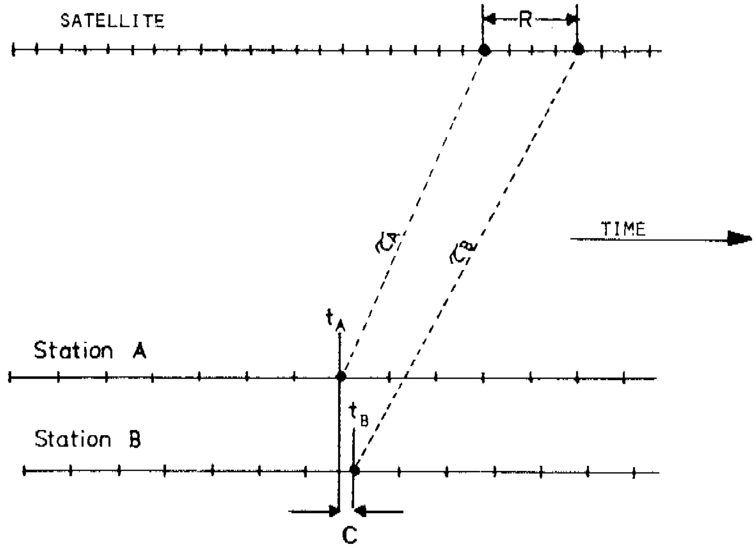


FIG. 7.



$$\boxed{C = t_A - t_B + \tau_A - \tau_B + R}$$

FIG. 8. TIME COMPARISON BETWEEN STATION A AND B

QUESTIONS AND ANSWERS

None for Paper #20.