TELEMETRY
ON FRENCH BALLISTIC MISSILES AND EUROPEAN LAUNCH VEHICLES EVOLUTIONS AND PROSPECTS

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I.- INTRODUCTION

The development of ballistic missiles and launch vehicles in the last twenty five years has required the engineering, perfecting and introduction of suitable testing and measuring facilities, more particularly telemetry equipment.

We purpose to recall the major milestones of the evolution in this field of techniques throughout that period and to try to define some prospects for the future.

We do not pretend to give a historical account, but only our thought on an industrial experience that we have lived through. Therefore, we entreat the reader’s indulgence for the non-exhaustive character of this paper and perhaps for some unintentional errors or distortions.

II.- FRENCH BALLISTIC PROGRAMMES AND EUROPEAN LAUNCH VEHICLES(fig.1)

The ballistic missile and launch vehicle programmes began in France, in 1960, by the starting of a programme of “Basic Ballistic Studies” intended to acquire the technical and industrial knowledge required for initiating the development of the deterrent Strategic Nuclear Force.

This first programme of basic studies (1960-67) resulted in the operation of the SAPHIR two-stage launch vehicle which synthesized all the functions (propulsion, attitude control, guidance and reentry) of the intermediate range ballistic missile (IRBM) and in the development of the DIAMANT launch vehicle, the previous stages being carried out by other test vehicles : AGATHE, TOPAZE and EMERAUDE.

After the RUBIS sounding rocket, this series of vehicles - “the Precious Stones” - was crowned by the development of the first French launch vehicle : DIAMANT A ‘1st successful launch: 26-11-65).

From these were derived the military weapon systems (SSBS: Ground-to-ground strategic ballistic missile, and MSBS:sea-to-ground ballistic missile) and the DIAMANT family of launch vehicles (DIAMANT B, DIAMANT PB4) .

Simultaneously, in 1964, ELDO (European Launcher Development Organisation) and ESRO (European Satellite Organisation) were created to develop heavy launch vehicles and satellites as part of a European co-operation.

After the failure of EUROPA I and EUROPA 2 launch vehicles mainly for industrial organisation reasons, the ELDO programme was given up (April 1973) .

The development of the European ARIANE heavy launch vehicles was subsequently resumed within a different framework: CNES prime-contractorship for the account of ESA which took over the missions of ELDO and ESRO.

After the successful launches of ARIANE I and ARIANE 3, the launch of ARIANE 4 scheduled to take place before the end of this year, the developments of ARIANE 5 and the HERMES spaceplane are being prepared.

III.- MEASUREMENTS ONBOARD MISSILES AND LAUNCH VEHICLES

III.-1 - Aims of measurements

The aim of telemetry chains onboard missiles and launch vehicles is to provide real-time or delayed information for:

1°) controlling pre-flight and flight operations;

2°) detecting and locating malfunctions, determine their cause and remedy them;

3°) validating and improving design (calculation models) and development methods.

The following remarks should be made :

- the first two objectives are overriding
  (safety and malfunction detection);

- one measurement often serves several purposes. With certain exceptions, the metrological characteristics required for each one are different. We must either increase measurement ranges or make choices and trade-offs.

- operational military missiles are not equipped with telemetry chains. Therefore, the latter do not participate in the missile control.

III.-2 - Increase in the number of measurements (Figure 2)

It is almost a commonplace to state that the number of measurements taken on missiles and launch vehicles under development is evergrowing.

This increase is due to the evergrowing complexity of the systems and to the necessity of making test flights as profitable as possible.

- the development logics for the major ballistic or launch vehicle programmes have become more comprehensive. The unit cost of a complete assembly keeps growing. The number of flight tests before operational use decreases. Four qualification launches for ARIANE I, 3 three for Ariane III, IV and V. For the HERMES spaceplane, it is no longer feasible to define a boundary between development and operational phases.

- This procedure has been made possible by finer and finer modelling, by the behaviour of missile or launch vehicle sub-systems. The existence and representativeness of these models are limited, either by our calculation means - methods or machine capabilities - , or by our scientific knowledge.

- The progress of techniques and technologies enables us to accommodate and transmit more and more onboard measurements. Now, their number is most often limited by financial considerations - interest vs. cost of measurements - rather than by technical considerations of accommodation or transmission capability.

- With the extension of digital guidance techniques to the attitude-control and sequential functions, the number of numerical measurements has increased, but not the number of interfaces because this change has taken place within one sub-system.

On the HERMES spaceplane, this situation will change with the increase in self-contained digital sub-systems.

IV.- MEASUREMENT CHAIN

The measurement chain, from the acquisition of the values to be measured to their feed-back, is shown in Figure 3.

Except in case of recovery, measurements are transmitted to the ground by radio-link. Temporary onboard storage of information permits:

1°) to palliate radio-link black-out during certain flight phases (under-water course, stage separations, reentry).

2°) to reduce link capacity by taking advantage of the ballistic phase during which few measurements are interesting so as to transmit the measurements taken during the propelled phase.

3°) to transmit at a low rate the measurements taken at very-high rates in transitory phases (ignition, separation shocks) and thus to take measurements that would be either too dimensioning or incompatible with transmission chains.

V.- EVOLUTION OF MULTIPLEX SYSTEMS - Figure 4

V.-1-Selection of the AJAX standard

At the end of the 50's, a number of telemetry systems had been developed in France for aircraft or missile applications. Among these pioneers, we must mention the telemetry systems developed by SFIM, ONERA, SAT-TURCK, APX, Sud-Aviation LPA..

None of these system was compatible and all of them were tubed systems.

In 59-60, the starting of the French ballistic programme was going to create an important need of equipment. Subcarrier systems were an absolute must. But what standard had to be chosen?: SFIM, ONERA, SAT-TURCK or the U.S. IRIG inter-launch site for which Sud-Aviation LPA had already made some developments?

The method department of the CEV (flight test center) was instructed to study the problem and, after a comparative survey, came to the conclusion that none of those standards was really better than the others from a technical viewpoint. The IRIG had a greater number of subcarriers, but the bandwidths per channel were smaller. The overall transmission capacities were on the same order of magnitude.

A new standard, the AJAX standard, which used the IRIG standard-proportional bands with the exception of some minor variants, was selected (Subcarrier G at 125 GHz for 10 KHz large bandwidth transmission). The development of the equipment constituting the measurement links was decided by the CEV and undertaken in French industrial establishments. This equipment was miniaturized by the replacement of tubes by transistors.

At the present time, I believe that this choice - confirmed on several occasions - was judicious. It made it possible to resort to imports, should French industrial developments fail to comply with the time-scale or should their costs be out of proportion with the limited scope of some requirements. At the end of the developments financed by the Government, it placed French industrial establishments in a more favourable position for export.

V.-2- 1959-1964 PAM (mechanical) - FM SAT TURCK

The AJAX items of equipment released for manufacture in 59 - 60 by ROCHAR, SFIM, SAT, Sud Aviation LPA, etc.., were not available for the first launches of the "Precious Stones" series.

As a temporary measure, the existing SAT-TURCK tubed equipment was used. It gave full satisfaction. On several occasions the equipment recovered after a launch was reused after overhaul.

V.-3- 1964: PAM (mechanical or electronic ?) -FM AJAX

The AJAX standard appeared in 1964 on the RUBIS and SAPHIR two-stage rockets.

All the multiplex items of equipment to the AJAX standard were made in the forms of fully transistorized modules.

In view of the number of measurements to be transmitted (a few hundreds) and of the number of compatible subcarriers (18 as a maximum, 13 to 15 in practice), temporal commutation of measurements on 3 or 4 subcarriers was used : PAM/FM multiplexing.

Mechanical switches (LEDEX, SFIM, VACTRIC, GDI) and electronic switches (Sud-Aviation Cannes, LRBA), competed for a long time, showing the same number of disadvantages.

The switching of low-level measurements brought about big difficulties (switching noise and influence of common potentials). Eventually, electronic switching was selected in the mid-60's .

V.-3 - 1966 : TELEMAQUE - PCM feasibility

The feasibility of PCM telemetry was demonstrated as early as 1966 by the development, by INTERTECHNIQUE under RADIATION licence, of a TELEMAQUE proto-type unit ordered by the CEV, based on the multiplexing of all the measurements of a SAPHIR test vehicle.

A PCM transmission link replaced three AJAX links advantageously !, except for two or three vibration measurements.

Together with the functional model of the test vehicle, this prototype made it possible to study the problems in connection with brief measurement sampling: internal impedance of sources, balancing of impedances vs. ground , etc., and thus to determine new wiring rules (SUD-AVIATION CANNES).

V.-7 - The TEUCER standard

The transmission of vibration measurements with proportional-band standards was not satisfactory from the users' viewpoint. By definition, bandwidths and transit times were variable from one channel to another, thus making correlations between measurements difficult. Moreover, the number of measurements that could be sent on a transmitter was too small. This led to the elaboration of constant band standards, less satisfactory as regards the crosstalk dynamics. The corresponding equipment appeared for the first time in the United States. Several standards presented by various manufacturers competed on the market: EMR, DCS, AIAA, etc.

In France the choice of PCM telemetry was accompanied by the adoption of constant-band subcarriers : the NRZ PCM in the lower part of the video spectrum, the sub-carriers in the upper part. We were lucky when we had to select the standard. Just as we were about to make a decision, we learnt that the IRIG was doing the same. The decision was thus delayed, and so TEUCER, the AJAX's brother, was IRIG.

V.-8 - TELEMAQUE PCM and TEUCER

The TELEMAQUE PCM and the channels to the TEUCER standard were used for the first time in 1970. With a comparable RF bandwidth, its effective transmission capability was about three times greater.

V.-9 - 1974:“Essai”PCM; 1976: CANNES PCM (240 Kbits/s).

However, in comparison with the FM equipment (proportional or constant band), the Telemaque PCM presented two disadvantages: its cost and its lack of modularity. Each application required a specific development and the evolutions of measurement plans were uneasy.

To palliate that drawback, manufacturers proposed some items of equipment constituted by plug-in modules developed according to the same principle as AJAX modules (Intertechnique “Essai” PCM and SAT PCM).

Another approach, a more ambitious one, was a PCM system consisting of a set of boxes specific to each function, connected by a BUS line, the measurement plan specific units and the format being programmed in a PROM according to its use; this was the CANNES PCM (1).

This system was used as a basis for the design of a delayed-output electronic equipment allowing to repeat the measurements in the PCM message with a delay on the order of one second. This permitted to get rid of a brief radio-link black-out during certain phases of a missile flight (operation of pyrotechnic systems, separation).

The “ESSAI”PCM was used for the first time in 1974, the CANNES PCM in 1976.

V.-10 - 1980 :CANNES PCM (400 Kbits/s)

The maximum rates of PCMs were initially limited by the speed of analog/digital coders to 125 Kbits/s for the ESSAI and TELEMAQUE PCMs, and then to 240 Kbits/s for the initial version of the CANNES PCM. In 1980, this limitation disappeared. The CANNES PCM rate was brought to 400 Kbits/s, which is the maximum value authorized by the definition of the BUS link.Fig. 5 and 6.

The increase of the coder operating rate to 400 Kbits/s led to a reduced sampling time. In order not to reduce the accuracy of low-level measurements (20 mV range of measurement), this implied constraints on the impedances (between terminals and of common mode) of sources and wirings beyond which it was not attempted to go.

The CANNES PCM with TEUCER channels is currently used for ARIANE III and IV launch vehicles.

V.-II - 1987:CANNES PCM (2 Mbits/s)

The use of the PCM for transmitting large bandwidth channels permitted to delete the links reserved for FM multiplex and thus to reduce the number of links required; as a minimum : one per object having a “life” of its own, through the use of the maximum capacity of the transmission channel. Figure 7.

At the present time, a PCM system with a transmission speed of 2 Mbits/s managing 5 CANNES PCM BUS lines is under development.

VI.- AS A CONCLUSION... AFTER ?

With the CANNES PCM, since 1974 we have had at our disposal a telemetry system consisting of a range of specialized units developped, perfected, modified in accordance with the specific requirements, progress or constraints induced by the ultra-fast technological development of digital electronic components, which are all COMPATIBLE since they are connected by a BUS whose specialized dialog procedures (fig. 5 and 6) for the acquisition of measurements by peripheral units have been retained.

So far, several hundreds of CANNES PCM units have been launched and a BUS link failure have never occurred.

This telemetry system is quite suitable for the acquisition of measurements on the various sub-units of big missiles and launch vehicles. Its use on ARIANE V is anticipated and, in all likelyhood, it will be possible to use it on HERMES.

What will be the evolution of the CANNES PCM range or of similar systems ?

We believe that it will have a twofold aim:

1.- For peripheral acquisition units :

- a versatility for analog and all-or-nothing measurements;
- the integration of sensor ancillaries;
- the introduction of decentralized programmable systems;
- the creation of local measurement processing units (shock response spectrum, Fourier analysis);

2.- For the central unit, probably a gathering and a sophistication integrating all the following function into a single unit:

- management of the various acquisition formats used in flight;

- compression of acquired information;

- formatting of information for transmission or storage;

- management of transmission and storage link resources.

Initially, the rules will be pre-recorded as a function of flight phases, and subsequently it will be possible to select then automatically, taking additionally into account the evolution of parameters.

In what form will this information be formatted for transmission or storage?

In the systems integrating several digital acquisition units interfacing independent sub-systems, the NASA "package" standard seems to be more suitable than the conventional IRIG sequential standard. Ground processing is easier.

The rate limitations of the required computerized ground decommutation systems are extended beyond the rates acceptable by transmission channels.

For HERMES, CNES anticipates to retain this standard with VITERBI and REED SOLOMON error correcting codes.

Specific multiplexers have not disappeared. They are an absolute must when the measurements to be acquired are concentrated and when the volume reduction is essential.

The integration limit is more financial than technological. Wiring and connection techniques remain major obstacles to miniaturization. The latter requires a reduced number of items of equipment and dismountability connectors.

The approaches to specialized macrocomponents and pre-distributed circuits seem to be attractive. For the time being, a requirement justifying the initial investment is still missing.

(1) CANNES is an acronym which means: Codeurs Analogiques Numériques à Nombres d'Entrées Selectionnables (Analog digital coders with selective numbers of entries) . It also alludes to the role played in its design by some engineers of Aérospatiale Cannes.

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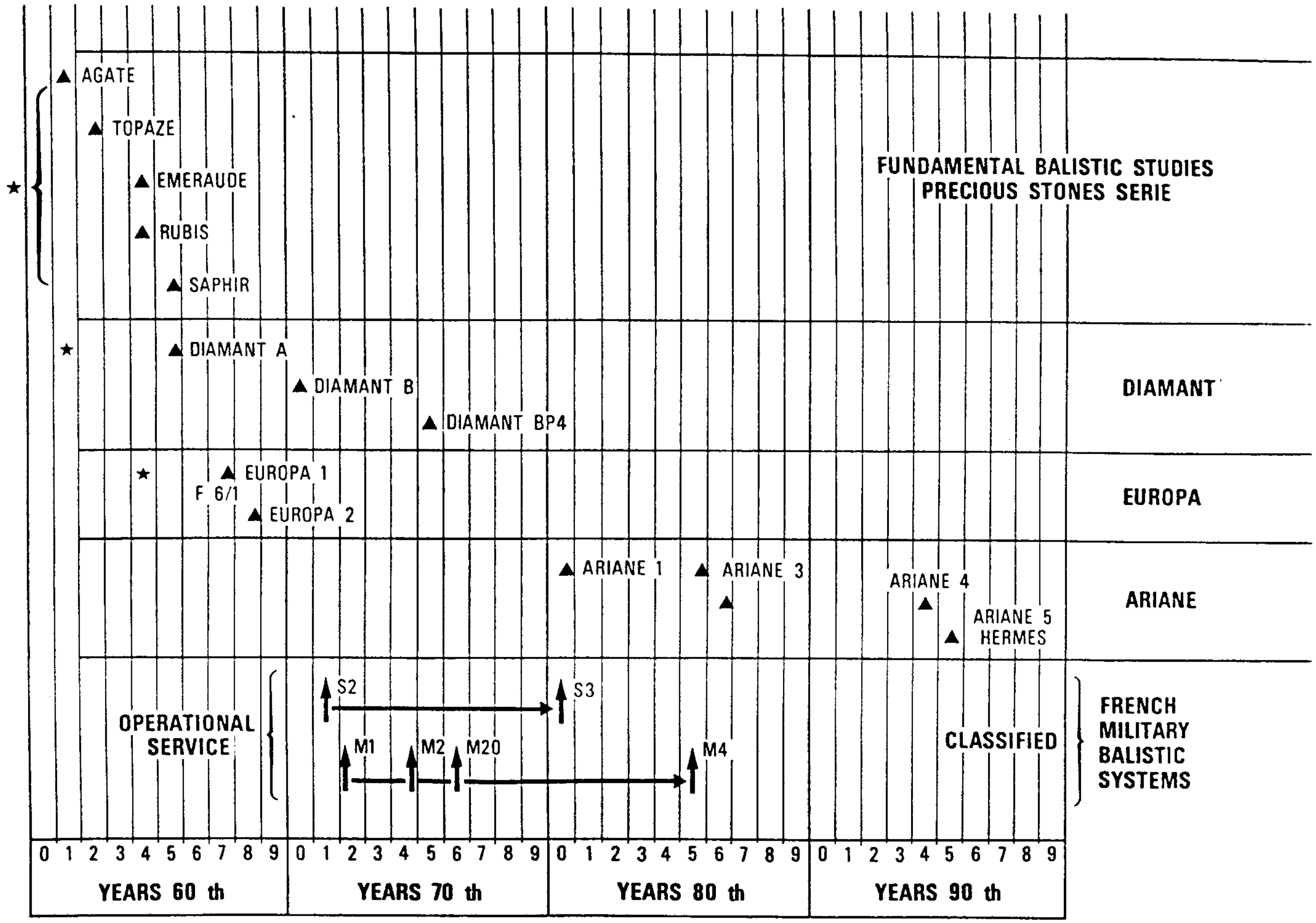


AGATE
TOPAZE
EMERAUDE
RUBIS
SAPHIR
FUNDAMENTAL BALISTIC STUDIES
PRECIOUS STONES SERIE
DIAMANT A
DIAMANT B
DIAMANT BP4
DIAMANT
EUROPA 1
F 6/1
EUROPA 2
EUROPA
ARIANE 1
ARIANE 3
ARIANE 4
ARIANE 5
HERMES
ARIANE
OPERATIONAL SERVICE
S2
S3
M1
M2
M20
M4
CLASSIFIED
FRENCH MILITARY BALISTIC SYSTEMS
0 1 2 3 4 5 6 7 8 9
YEARS 60 th
YEARS 70 th
YEARS 80 th
YEARS 90 th

Figure 1.

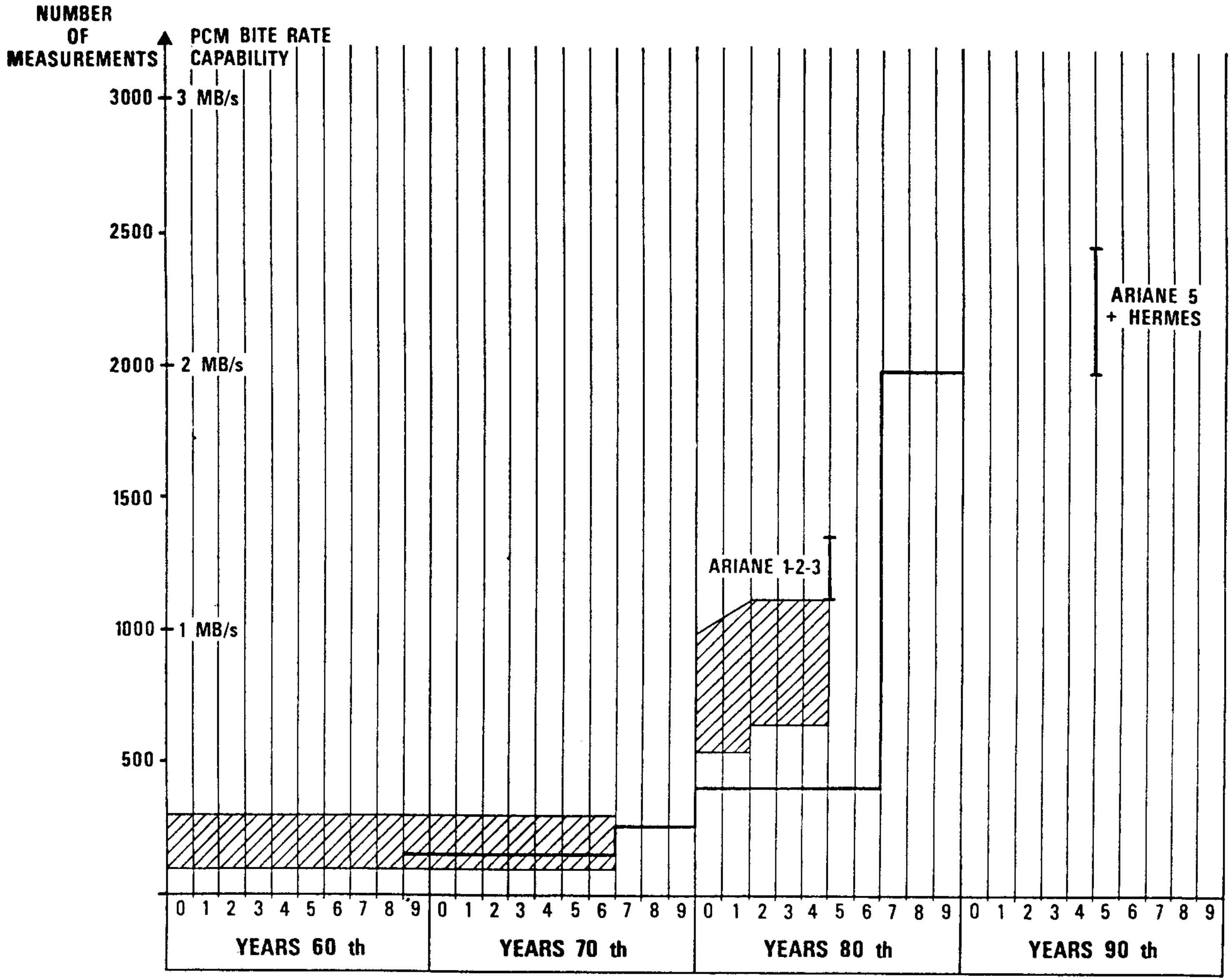
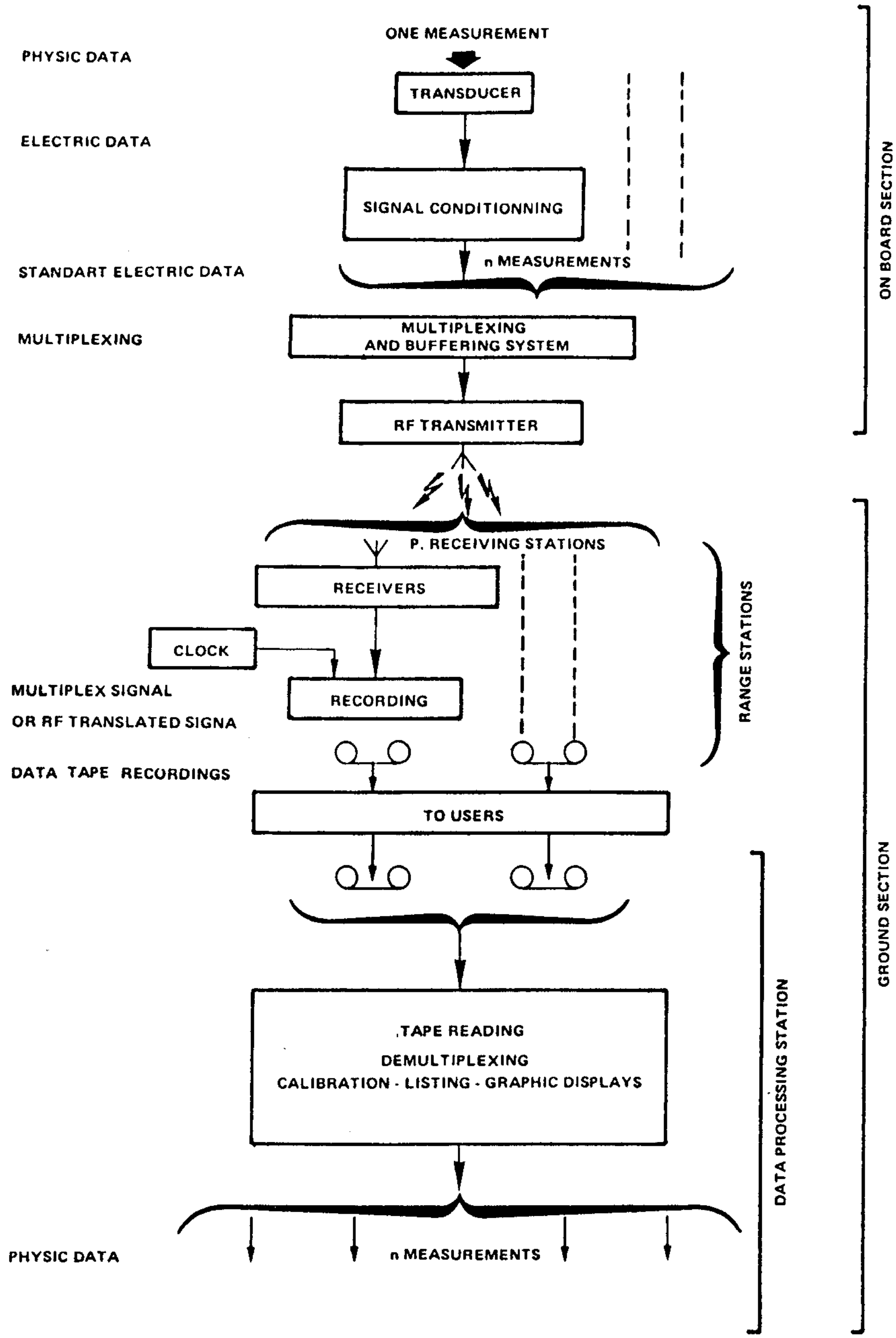
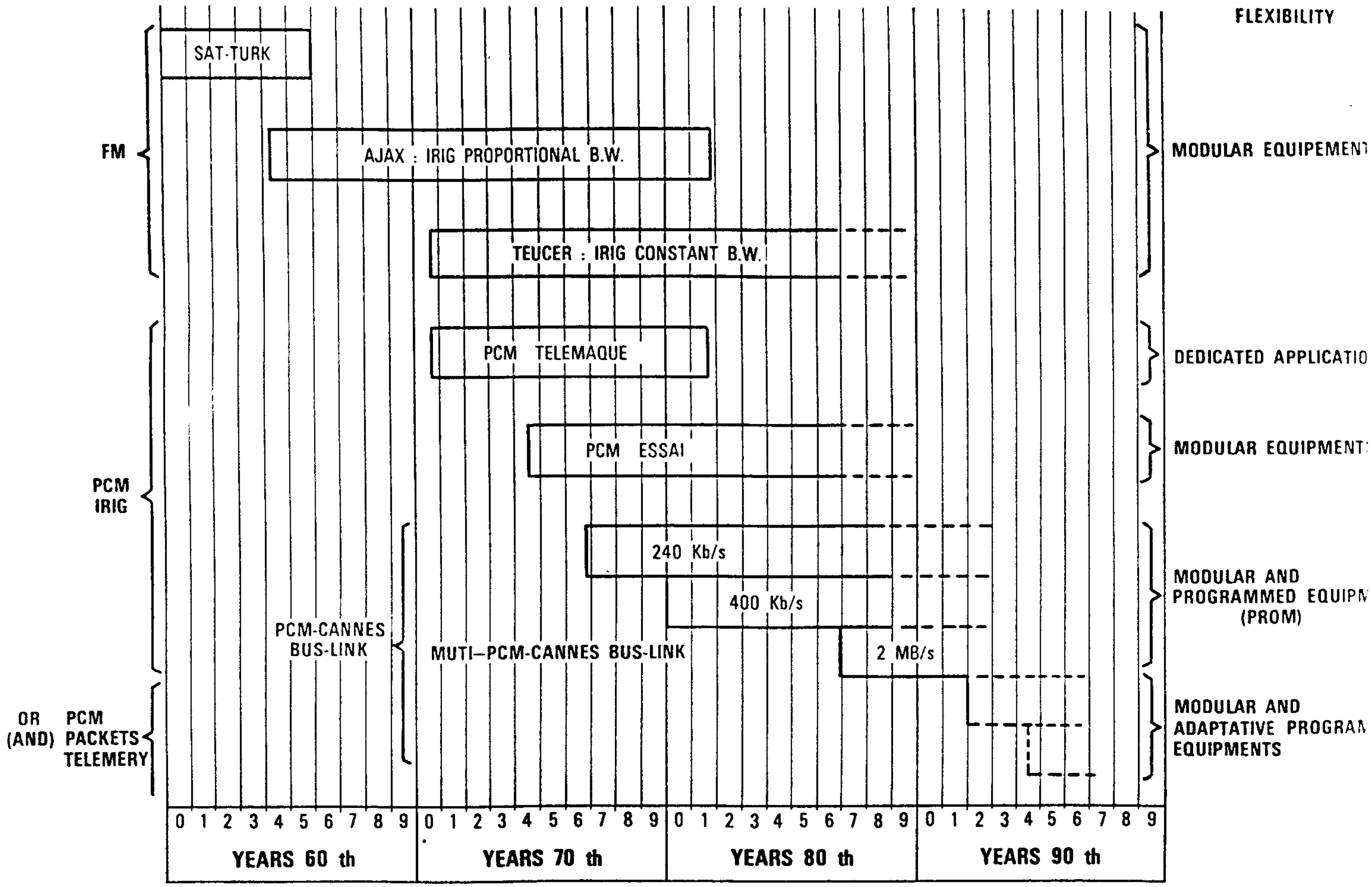

NUMBER OF MEASUREMENTS
PCM BITE RATE CAPABILITY
3000
3 MB/s
2500
2000
2 MB/s
1500
1000
1 MB/s
500
ARIANE 5 + HERMES
ARIANE 1-2-3
0 1 2 3 4 5 6 7 8 9
YEARS 60 th
0 1 2 3 4 5 6 7 8 9
YEARS 70 th
0 1 2 3 4 5 6 7 8 9
YEARS 80 th
0 1 2 3 4 5 6 7 8 9
YEARS 90 th

Figure 2.



IN FLIGT MEASUREMENT CHAIN - GENERAL SYNOPTIC

Figure 3.



FLEXIBILITY
FM
SAT-TURK
AJAX : IRIG PROPORTIONAL B.W.
MODULAR EQUIPEMENT
TEUCER : IRIG CONSTANT B.W.
PCM TELEMAQUE
DEDICATED APPLICATIO
PCM ESSAI
MODULAR EQUIPMENT
PCM
IRIG
240 Kb/s
400 Kb/s
2 MB/s
MODULAR AND
PROGRAMMED EQUIPM
(PROM)
PCM-CANNES
BUS-LINK
MUTI–PCM-CANNES BUS-LINK
OR PCM
(AND) PACKETS
TELEMERY
MODULAR AND
ADAPTATIVE PROGRAM
EQUIPMENTS
0 1 2 3 4 5 6 7 8 9
YEARS 60 th
YEARS 70 th
YEARS 80 th
YEARS 90 th

Figure 4.

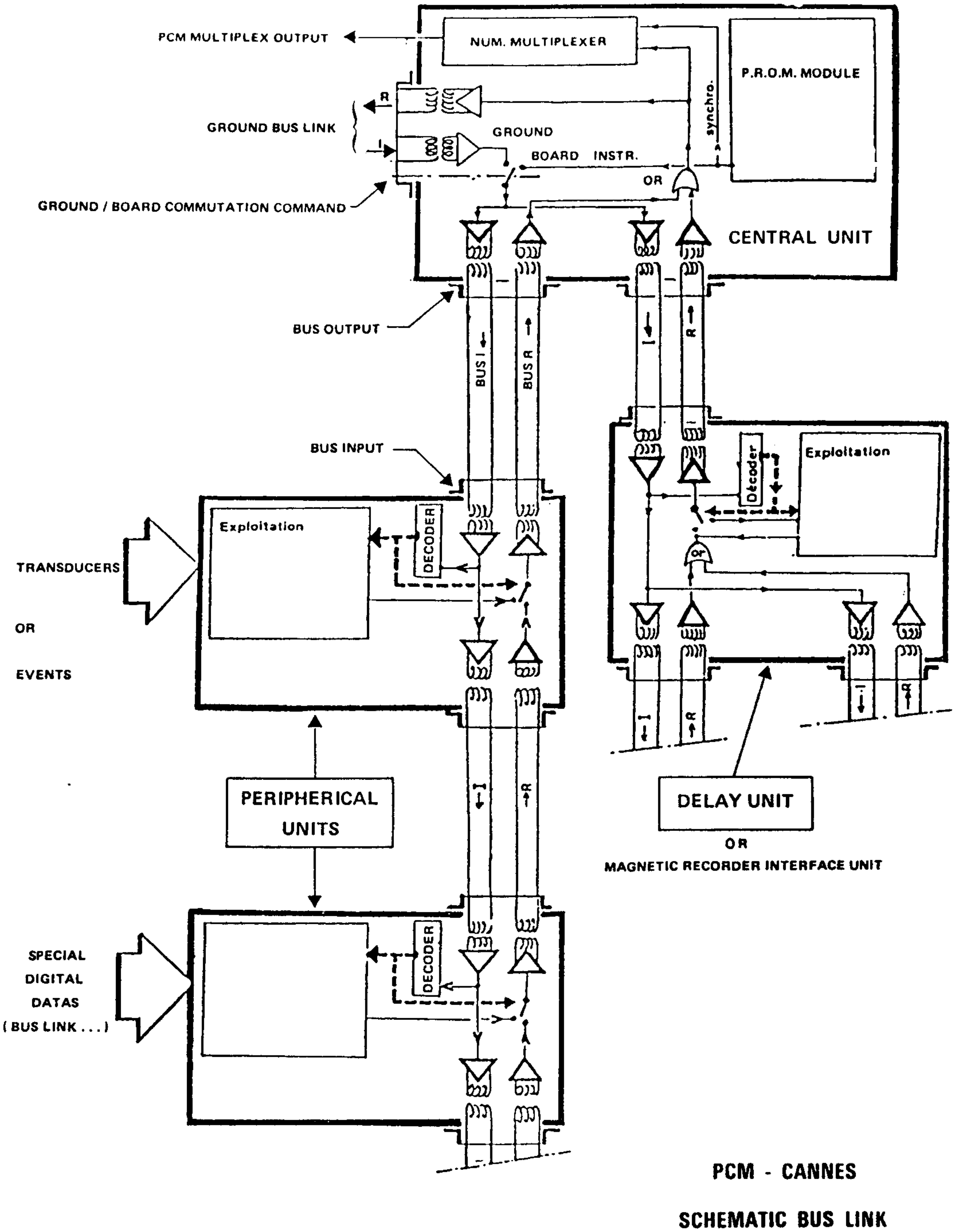
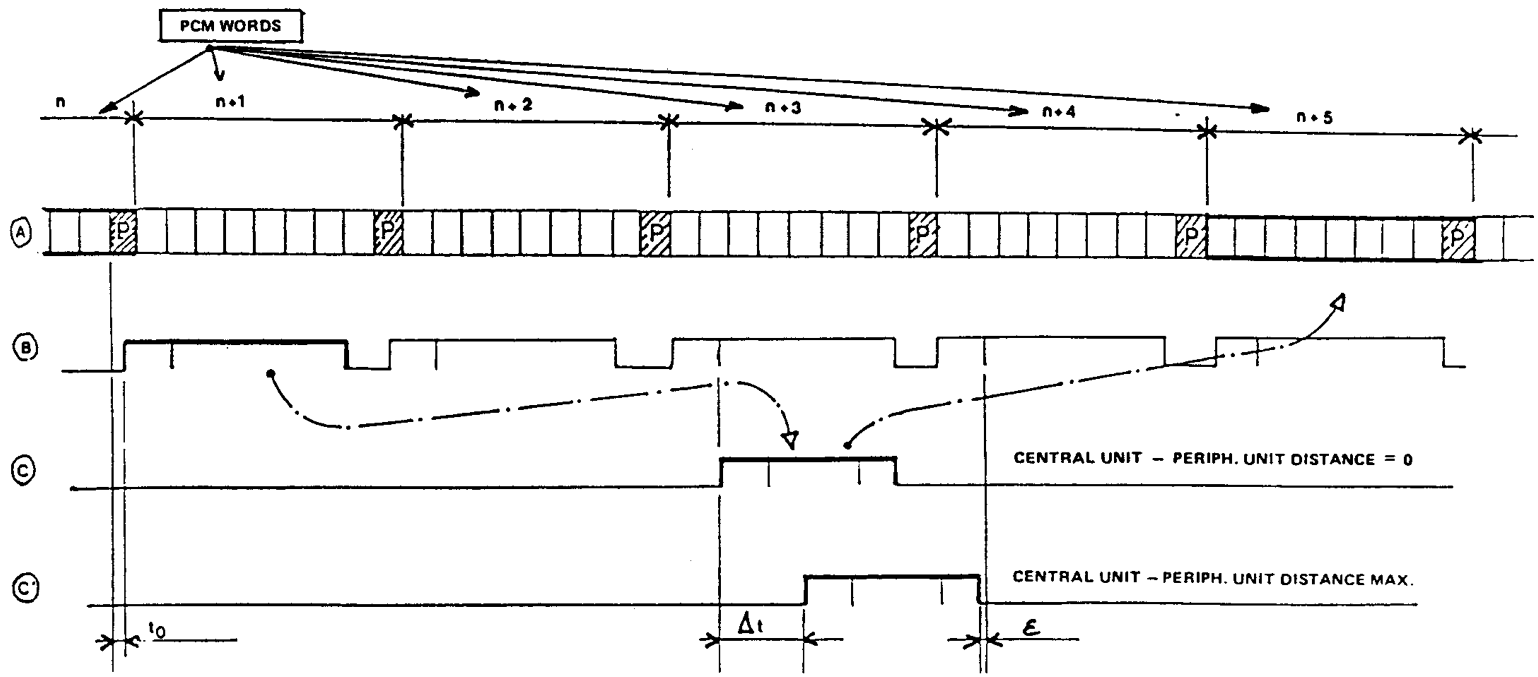

PCM MULTIPLEX OUTPUT
NUM. MULTIPLEXER
P.R.O.M. MODULE
synchro.
GROUND BUS LINK
GROUND
BOARD INSTR.
OR
GROUND / BOARD COMMUTATION COMMAND
CENTRAL UNIT
BUS OUTPUT
BUS I
BUS R
BUS INPUT
Exploitation
DECODER
Décoder
TRANSDUCERS
OR
EVENTS
PERIPHERICAL UNITS
DELAY UNIT
OR
MAGNETIC RECORDER INTERFACE UNIT
SPECIAL DIGITAL DATAS (BUS LINK ...)
PCM - CANNES
SCHEMATIC BUS LINK

Figure 5.



A = CENTRAL UNIT PCM MULTIPLEX OUTPUT

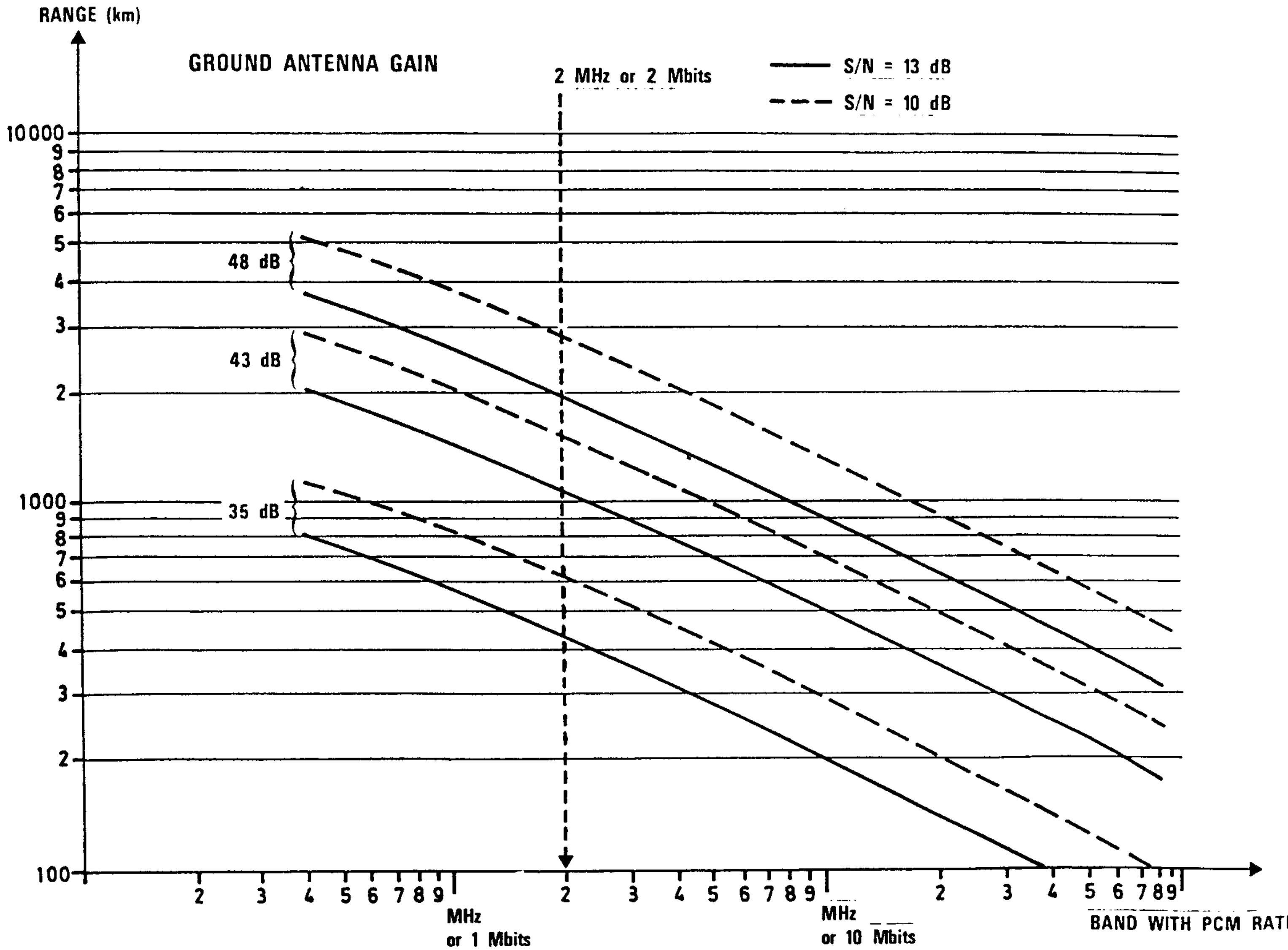
B = CENTRAL UNIT INTERROGATION BUS OUTPUT

C AND C' = BUS ANSWER

NOTA : IN THIS EXAMPLE $R_{BB} = R_{BU} = 400$ kbits/s

PCM 'CANNES - 400' BUS SIGNALS

Figure 6.



RANGE (km)
GROUND ANTENNA GAIN
2 MHz or 2 Mbits
S/N = 13 dB
S/N = 10 dB
10000
9
8
7
6
5
4
3
2
1000
9
8
7
6
5
4
3
2
100
48 dB
43 dB
35 dB
2
3
4
5
6
7
8
9
MHz
or 1 Mbits
2
3
4
5
6
7
8
9
MHz
or 10 Mbits
2
3
4
5
6
7
8
9
BAND WITH PCM RATE