SPECIAL FEATURES OF THE TRANSMISSION SYSTEMS OF THE SATELLITE ESRO II/IRIS

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Special Features of the Transmission Systems of the Satellite ESRO II/IRIS

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In this pamphlet devoted to the ESRO satellite IRIS, it appeared advantageous to include an article describing the special features of the transmission systems by means of which the stations of the ESRO network keep permanent contact with the satellite once in orbit.
Discussion will first center on the telemetry system used by the satellite to transmit to the ground the result of its observations and then describe the commanding guidance system whereby the satellite receives and executes the guidance control commands required by the mission.

The Telemetry System.

1. The Mission Requirements

The basic options were taken concerning the telecommunications systems of the IRIS satellite during the course of the year 1964 following agreement on the requirements of the mission as far as telecommunications were concerned.

Although it was the first in a series of satellites christened at that time "Small Satellites" within the scope of the general program of the Organization, the IRIS satellite appeared to be relatively demanding as far as telemetry and command guidance were concerned. Since the general subject of the scientific mission was the study of corpuscular radiations emitted by the sun, the data provided by a typical experiment consisted of several series of numbers indicating the quantity of particles collected by the sensors in a given time, each number series being characterized by the particle type collected (proton, electron, particles) or by its energy level. By considering each series of numbers as an independent information "channel", the set of the 7 experiments installed on board corresponded to 22 digitized canals making up the main flow of data.

To these main channels there corresponded a still greater number of secondary data channels required for the correct interpretation of the results. These concerned the telemetering of the data required for the calibration of the sensors (such as the temperatures, the currents and supply voltages of the scientific sensors). By adding to these secondary scientific channels the data channels with technological character for the interpretation of the behavior of the satellite in the true sense (i.e. of its vital equipments such as the attitude control systems, etc...), a total of 64 channels for ancillary data was counted. These channels transmitted analog data which meant they did not deal with numbers but with the state of a continuously varying magnitude.

The high number of data channels and the digital character of the main data flow reflected therefore the requirements of the "IRIS" mission. In addition to these first observations, the method to be followed for data acquisition had an important bearing on the configuration of the telemetry system. Moving on a low orbit, the satellite would only be visible from a terrestrial station for a limited time (at the maximum approximately 15 minutes). Permanent observation of the scientific events would therefore require a very high number of ground stations unless we resorted to a technique for recording data on board the satellite. It was therefore decided that the satellite would make a permanent recording of its observation during the time of one orbit and would retransmit it off-line during its transit above a station. Computations of orbit and visibility beginning from the four stations of the ESRO network established that, if the satellite could retransmit within a period of 3 minutes all the data collected during one orbit (or approximately 96 minutes), more than 90% of the results observed would be collected by the ESRO network stations alone. This method of acquisition was the determining factor in setting up the telecommunications system.

Indeed, it made necessary:

- the presence of a recorder aboard the satellite,

- two telemetry links, one of which would be permanent and used sporadically for satellite observation during its transit above a station. The other link, triggered by command guidance, would be used for the transmission of data contained in the recorder,

- the use of two transmitters for each of the two links since one was operating with time compressed data and the transmitted flow of data recorded was 32 times greater than the flow of data in real time, hence making illogical the use of the same transmitter for these two links.

In summary, and seen from the special viewpoint of telecommunications, the IRIS satellite had the appearance of a small space observatory whose requirements were comparable to those of the NASA satellites of the OSO series (Orbiting Solar Observatory) which required long years of development and whose first success was recorded in 1965.

2. The Basic Options

The similarity of the basic requirements tended to imply similarity in basic options, i.e., there were going to be dictated for the IRIS satellite solutions close to solutions used for the OSO satellites which, at that time, were still in the developmental stage. Also, there was no lack of cautions passed on to the ESTEC experts, generally coming from technicians of the Member-States of the Organization, but also from certain NASA experts against acceptance of premature solutions which would require a considerable technological effort from European industry and would increase perceptibly the risk of holding back the IRIS satellite program.

Nevertheless, none of the technological solutions already developed in the Member-States could satisfy the mission requirements. The systems developed by the telemetering of sounding rockets, based on frequency multiplex, were poorly adapted for transmission of digital data. In addition, their extension to the number of canals required could not be considered within reasonable limits of weight and power consumption. One other system which, at this time, was of great interest to the ESTEC technicians was the PFM system, used almost exclusively on satellites already constructed or in the project stage in the European national programs. This system is based on a time multiplex of data channels (meaning that samples from different information channels are transmitted sequentially over a single channel and in a determined order), each data sample corresponding to a brief signal in a frequency whose value corresponds conventionally to that of the quantity to be measured.[1]

Its acceptance could not have involved any technological risk but its operation within the scope of the requirements for the IRIS satellite proved to be impossible. In brief, it can be stated that the coding of data samples by frequency pulse is a "slow" process, since each pulse has to be transmitted for a time sufficiently long

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[1] It is this succession of frequency pulses whose acoustic reproduction provides a melodious succession of tones, i.e., the "beep-beep-beep"... often attributed to be the traditional language of satellites.

for its frequency to be collected and since the data storage capacity of the system is very reduced within the reasonable limits of size of the radio frequency spectrum. More important, in the case of the IRIS satellite, the acceptance of the PFM system would have led to an unjustified congestion of the available frequency range and would have required an unacceptable length of magnetic recording tape aboard the satellite.

It was at the end of 1964, and as a logical consequence of the preceding considerations, that the basic options concerning the telemetry link of the IRIS satellite were decided and sanctioned during a conference attended by experts from the Member States establishing a valid tradition for future ESRO missions:

- The radio link would be of the PCM type, i.e., that the data would be transmitted in binary coded form.

- The two states of the carrier wave corresponding to the binary values 0 and 1 of a data element would be characterized by the phase of this wave (phase modulation of the carrier), this method allowing the use of techniques of coherent demodulation known for their low acquisition threshold.

- The continuous emission in real time could be utilized as a beacon for satellite direction finding systems. This option imposed a minimum control of the frequency spectrum of the carrier wave and, in particular, the use of a sub-carrier. The modulation of this latter by digital data would be of the FSK type (abrupt frequency changes), and not of the PSK type more conventional since that time. This last option was taken up out of fear, which was subsequently justified, that suitable means of acquisition would not be available in time at the ground.

- Finally, within the scope of the PCM system accepted, the data, analog in nature, would have to be digitized aboard the satellite and all data would then be recorded magnetically aboard the satellite in digital form.

The description of the embarked telemetry equipment, forming the subject of the following paragraph, only makes up one brief illustration of the manner in which these basic options have been implemented in the case of the IRIS satellite.

3. Description of the Embarked Telemetry Equipment of the IRIS Satellite.

Figure 1 is a simplified schematic diagram of the embarked telemetry system of the IRIS satellite.

The input devices consist of two commutators of which one carries out the switching of analog channels and the other the switching of digital channels. These commutators can be thought of as electronic rotary switches which successively put each input, i.e., each telemetry channel, in contact with the output for a very short time. The latter action could take place in an unvarying sequence and be endlessly repeated. At their outputs there appear therefore two uninterrupted data "sample" sequences from different channels. After removal, the analog samples are digitized (or coded in binary form) and the two pulse trains, outputting from the digital commutator and from the analog-digital "converter" respectively, are overlapped into each other to form the "PCM message" proper.

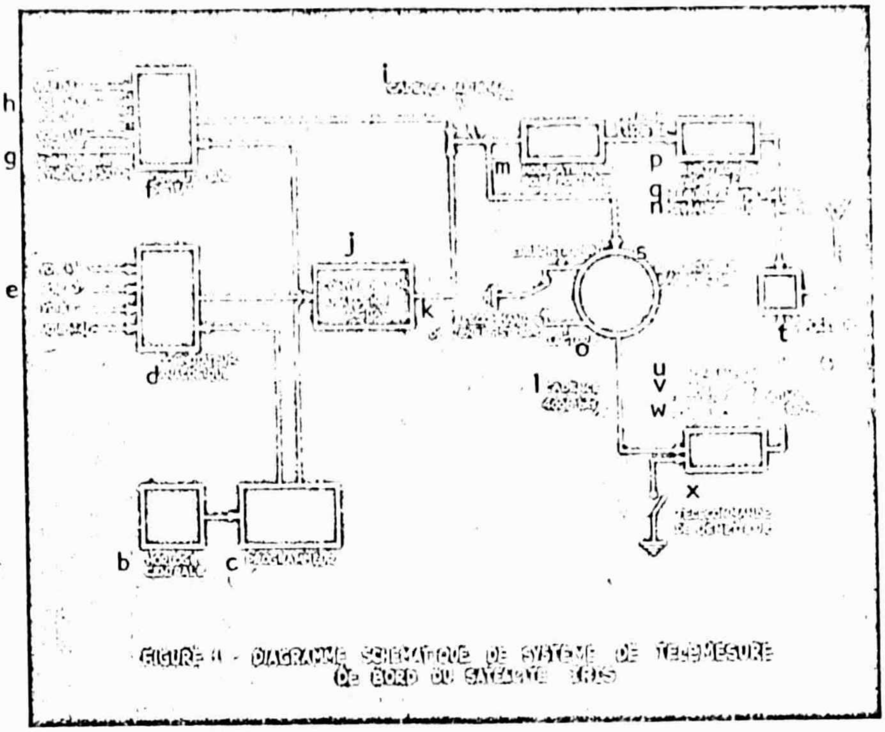

Figure 1. Schematic Diagram of the Embarked Telemetry System of the IRIS Satellite.

b-central clock
c-programmer
d-analog commutator
e-channel no. 1, channel no. 2,
  channel no. --, channel no. 42
f-digital commutator
g-synchornization signals
h-channel no. 1, channel no. 2,
  channel no. --, channel no. 28
i-rate: 128 bits/sec
j-analog-digital converter
k-recorder remote control
l-rate: 4096 bits/sec
m-sub-carrier modulator
n-recording

n-recording
o-readout
p-real-time transmitter
q-frequency: 196.890 MHz
r-power: 0.2 watts
s-magnetic recorder
t-diplexer
u-off-line transmitter
v-frequency: 136.050 MHz
w-power: 2 watts
x-transmitter command guidance

All these operations are cyclic and each cycle makes up an element of the formattted message in which each sample is represented by at least one sample. This last reservation comes from the fact that the sampling rates of the different channels should be proportioned to the more or less rapid variation rate of the parameters depicted. By way of example, the telemetry format of the IRIS satellite is made up of a sequence of 256 measurement samples in which the slowest channels are presented by a single sample and the most rapid channel by 32 samples. The sequencing time for a complete format is 16 seconds and the data rate is 16 8 bit words or 126 bits per second.

The PCM message is then expedited in two directions. In the first place, it is applied to the modulation input from a sub-carrier modulator which produces a sine-wave signal transporting the data in the form of frequency shift keying (the two frequencies described corresponding to the binary data are 1280 Hz and 1408 Hz).

This signal is used to modulate the phase of a radio wave at the frequency of 136.890 MHz, generated in a transmitter whose operation is, in principle, continuous (transmission in real time).

Parallelly, the PCM message is applied to the recording input of the magnetic tape recorder. The off-line transmission of recorded data is accomplished by using a transmitter with greater power (2 watts as opposed to 0.2 watt for the real-time transmitter), transmitting a radio signal at the frequency of 136.050 MHz and whose input is normally connected to the output readout of the recorder. This operation is actuated and terminated by means of command guidance acting simultaneously on the recorder and the transmitter in an off-line mode.

The channel sampling operations are controlled by a programmer preparing and distributing the multiple synchronization signals required. All these signals are derivatives, by means of division of frequency and count, from one single reference signal produced by a central clock (or oscillator) with a precision equal to 10^{-5}

(the error is on the order of 1 second per day). It is beginning from this clock that the identification numbers of the formats are also prepared, forming continuous succession and which, inserted into successive formats, allow the reconstitution of the sample removal time frames and to associate them with the precise position of the satellite on its orbit.

This description is very cursory and many relatively important characteristics of the equipment are not shown. For example, the remotely controlled switches intended to ensure changeover of transmitters in the event of defective operation of one of them, the generating systems of synchronization codes intended to allow locating the origins of the different formats, the time switches restoring the recorder to the recording position and disconnecting the high power transmitter in the event no command control link is operative, etc...

Figures 2 to 9 are photos of equipments illustrating some of the characteristic details of the actual production of the main units of the schematic diagram of Figure 1. The most important units are discussed below:

a) The Encoder

The encoder in the true sense includes all the elements of Figure 1 with the exception of the magnetic recorder, the transmitters and the diplexer. In spite of their diversity of functions, devices such as the programmer, commutators, analog-digital converter, etc., can be produced beginning from a relatively limited number of basic circuits, all subject to the same mechanical design. This latter, moreover, makes up one of the chief problems in the design of an electronic equipment for space use. The stresses applied to the satellite by the rocket during launch require equipment of unusual sturdiness which moreover should not be produced to the detriment of system weight.

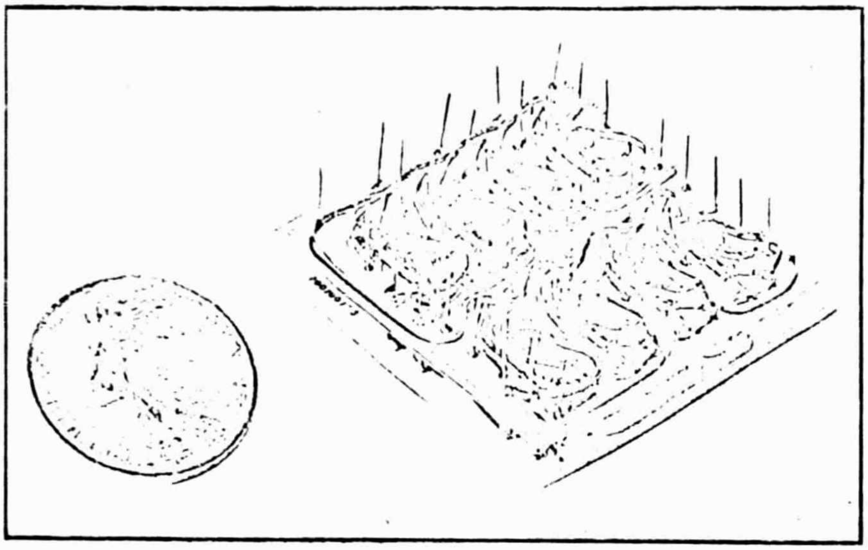

Figure 2. Basic Module of the Encoder (before covering).

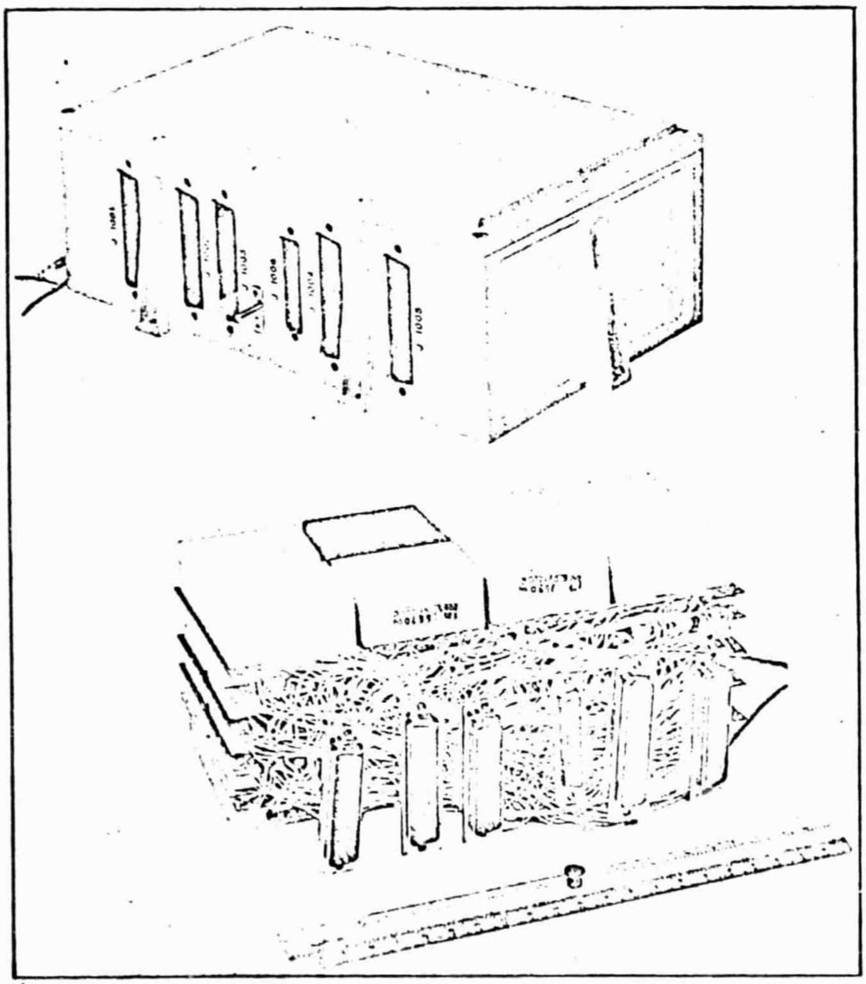

Figure 3. Open View of the Encoder Showing the Stacking of the Five Plugboards Carrying the Modules.

In the special case of the IRIS satellite, the components of the different circuits are assembled and interconnected by soldering in modules of the "Codwood" type (vertical arrangement of the components between two horizontal plugboards as illustrated in Figure 2). These modules are stiffened by casting them completely in a synthetic insulating material (a polyurethane foam). These modules are installed eight at a time on an insulation plugboard, the interconnections assured by printed circuits on the two plugboard surfaces. The system of 40 circuits required for the production of the electronic functions of the encoder appears in the form of two identically shaped plugboards shown on Figure 3. These 5 plugboards are stacked in an aluminum casing carrying the connectors on one of its surfaces (Figure 4).

One of the typical characteristics of the mechanical production of the encoder is the placing under pressure of the 5 plugboards by the interposition of plates of compressible material whose thickness is in excess of the available height of the casing in such a way that it is impossible to fit the cover on the casing unless a force approximately equivalent to a ton is applied. This "prestressing" system endows the system with the mechanical stiffness necessary to pour the system into a synthetic substance which would increase its weight and compromise its accessibility.

Other typical characterisitcs of the encoder are its weight equal to 3 kg, its electrical consumption less than 0.6 watts and above all its reliability. Starting from the characteristics of the components used, the probability of survival of this equipment beyond a period of one year could be predicted with 95% accuracy, a prediction not always invalidated after 3 months of orbital flight.

b) The Magnetic Recorder

The magnetic recorder is one of the essential devices of the satellite since its operation allows a continuous observation, if not in real time, of the scientific phenomena seen over the whole length of the satellite trajectory.

The design of a magnetic recorder poses above all problems of a mechnical nature consisting in ensuring the uniform movement of a magnetic tape over the recording and playback heads. The principle of the mechanical system for transport of the IRIS recorder tape is very special and was developed exclusively for use aboard satellites, chiefly those of NASA (the contributions of such American firms as Raymond and Lockheed Electronic should be mentioned here).

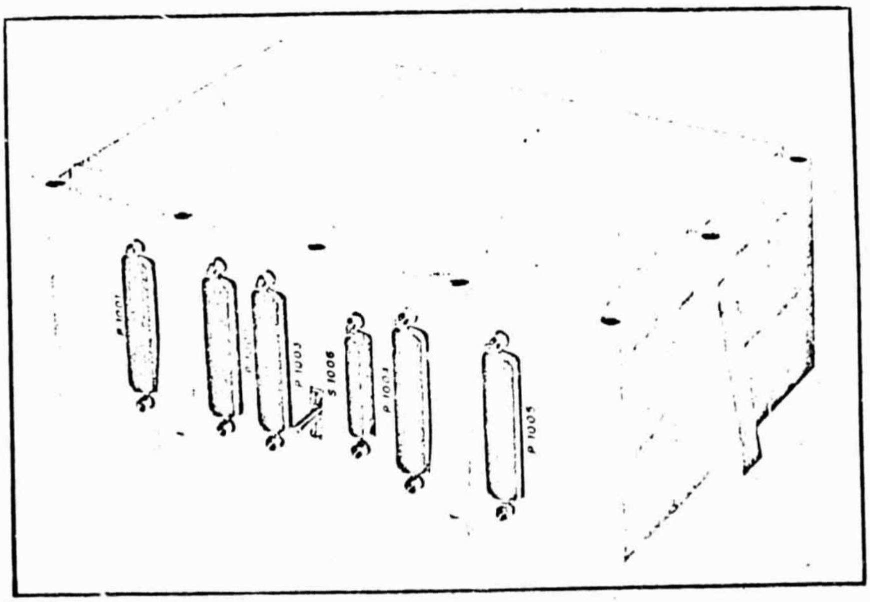

Figure 4. View of the Encoder When Closed.

The magnetic tape makes up a closed loop. The two tape origins are joined end to end and the length of the tape corresponds to a recording capacity sufficient for all the data collected during one orbit. Under these conditions, the "recording" and "playback" operational cycle do not require reversal of the direction of movement of the tape. After the recording of one complete orbit, the tape regains its initial position and the readout of the recorded data can begin immediately and the data from the orbit is re-read in a chronological succession identical to that of its recording.

The essential problem is the storage of the tape whose length, in the case of the IRIS satellite, is 50 m owing to the recording capacity required. This tape is wound compactly on a single reel which, for the production of a closed loop, assumes that the tape passes continuously from the inside spiral winding to the outside spiral winding, jumping over all the other spiral windings of the reel. The kinematics of the tape is then the following: since the reel is free on its axis of rotation, a tension is applied to the tape on the end coming out of the inner spiral winding. This tension induces a rotation of the reel which is in the direction of wind of the tape in continuation of the peripheral spiral winding. There is produced in this way a continuous movement, the tape being drawn from the center of the reel and "re-wound" to the outside, and whose characteristic is that it requires a relative sliding of the tape from one spiral winding to the other. This sliding should ideally preserve for all the segments of the tape a constant linear rate no matter what the radius of the spiral winding of the segments considered. Figure 5 shows a view of the open recorder. The reel supporting the tape is very visible there as well as the path of the tape passing from the inside to the outside of the reel.

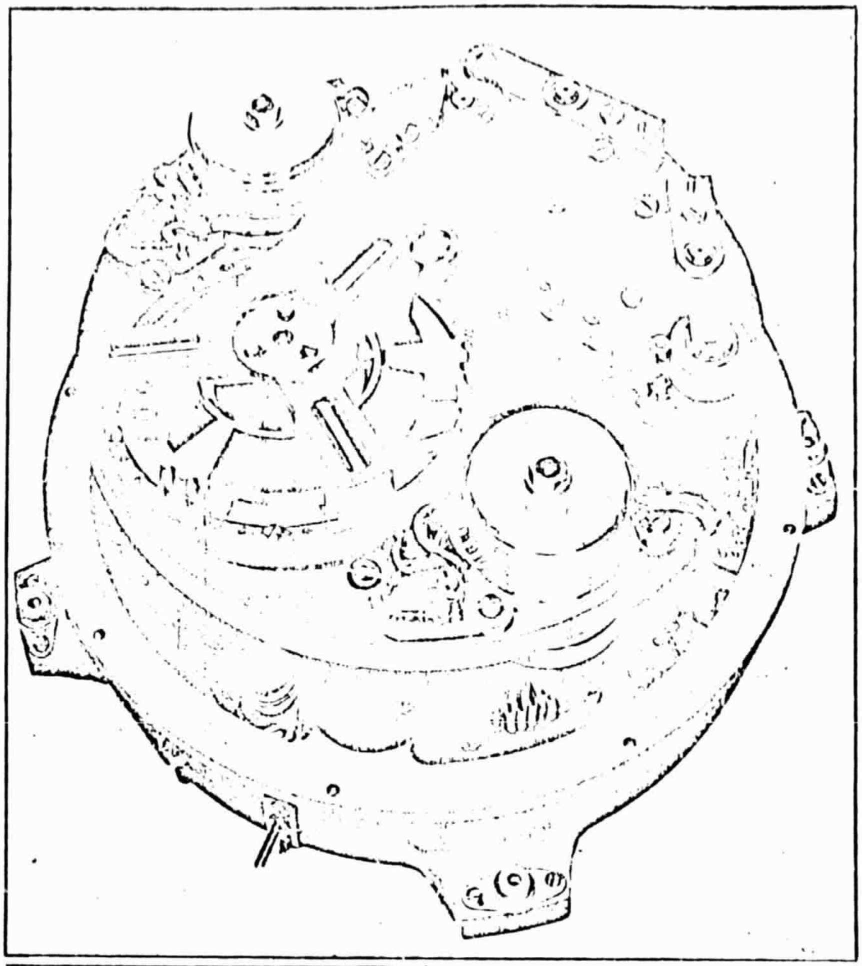

Figure 5. View of the Open Recorder Showing the Mechanical Drive System of the Magnetic Tape.

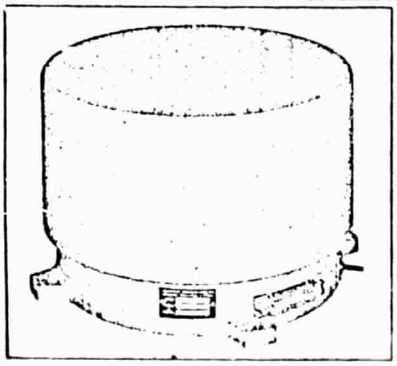

Figure 7. View of the Closed Recorder.

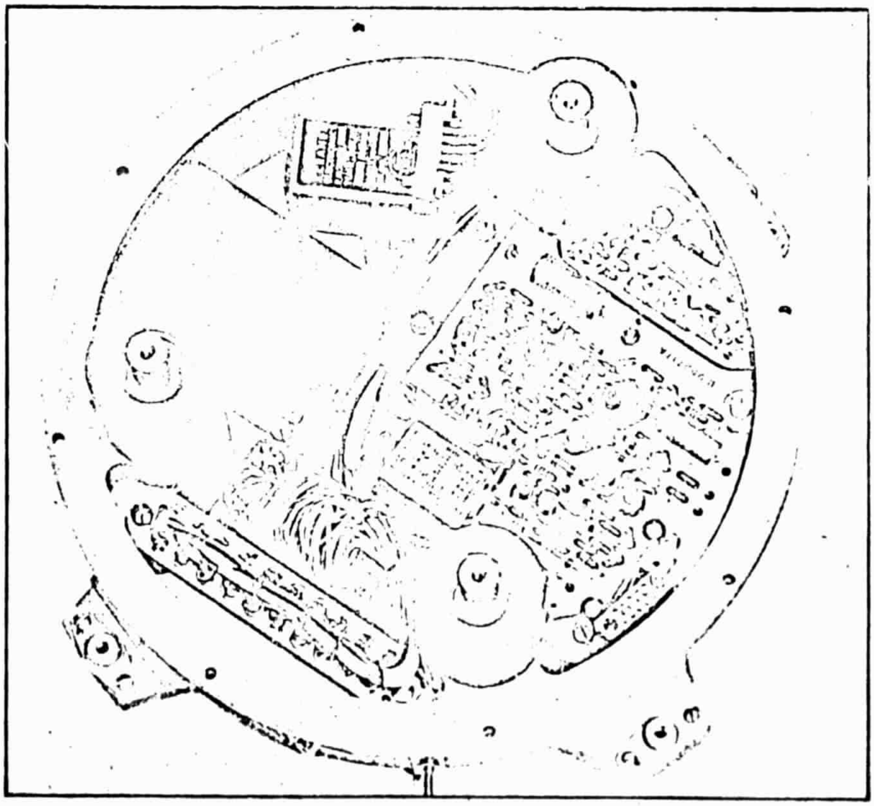

Figure 6. View of the Recorder Showing the Cushioned Supports.

This sliding of the tape on itself is the major disadvantage of this system since it requires a lubrication of the tape whose quality essentially conditions the regularity of the movement. Except for this, the system has many advantages: storage of the tape in an ideally compact form, mechanical simplicity coming from the absence of a system for reversal of direction of movement, preservation of the kinetic moment and of the center of gravity of the system (the passage of the tape from one reel to another could, for example, unbalance the satellite), automatic preservation of the last recorded data, etc. In total, this winding principle allows, in the case of the IRIS satellite, recording a data quantity equal to 1 million bits for a total recorder weight equal to 3 kg. It should be mentioned that recent studies carried out in Europe have shown that the capacity of this recorder could be extended to 20 million bits with no perceptible increase in weight. This capacity would cause it to be usable in the majority of missions presently projected. This explains the efforts already invested by the Organization and those planned for involving the development and adaptation of this recorder to new missions.

c) The Transmitters

The transmitters are illustrated in Figures 8 and 9. They are produced in the form of compact circuits entirely covered by plastic insulating material. Their design should present no special problems since the main specifications for transmission frequency (range 136-137 MHz) and for radiated power (2 watts and 0.2 watt) are not more severe than the corresponding specifications of transmitters already embarked on sounding rockets in many of the national European programs. The development effort chiefly emphasized the reduction of equipment weight (brought down to approximately 300 g for each transmitter), the obtaining of a sufficient duration of life by the use of selected components and above all the improvement of power efficiency. This latter worry clearly concerned the larger powered transmitter whose total consumption was successfully brought down to less than 6 watts. This performance, moreover, could only have been obtained by a thorough optimization study of the last stages, since the obtaining of a good efficiency was in conflict with other essential characterisitics such as the stability of the transmitter, its capacity for absorption of a reasonable rate of reflected power, its degree of protection against external short-circuits, etc.

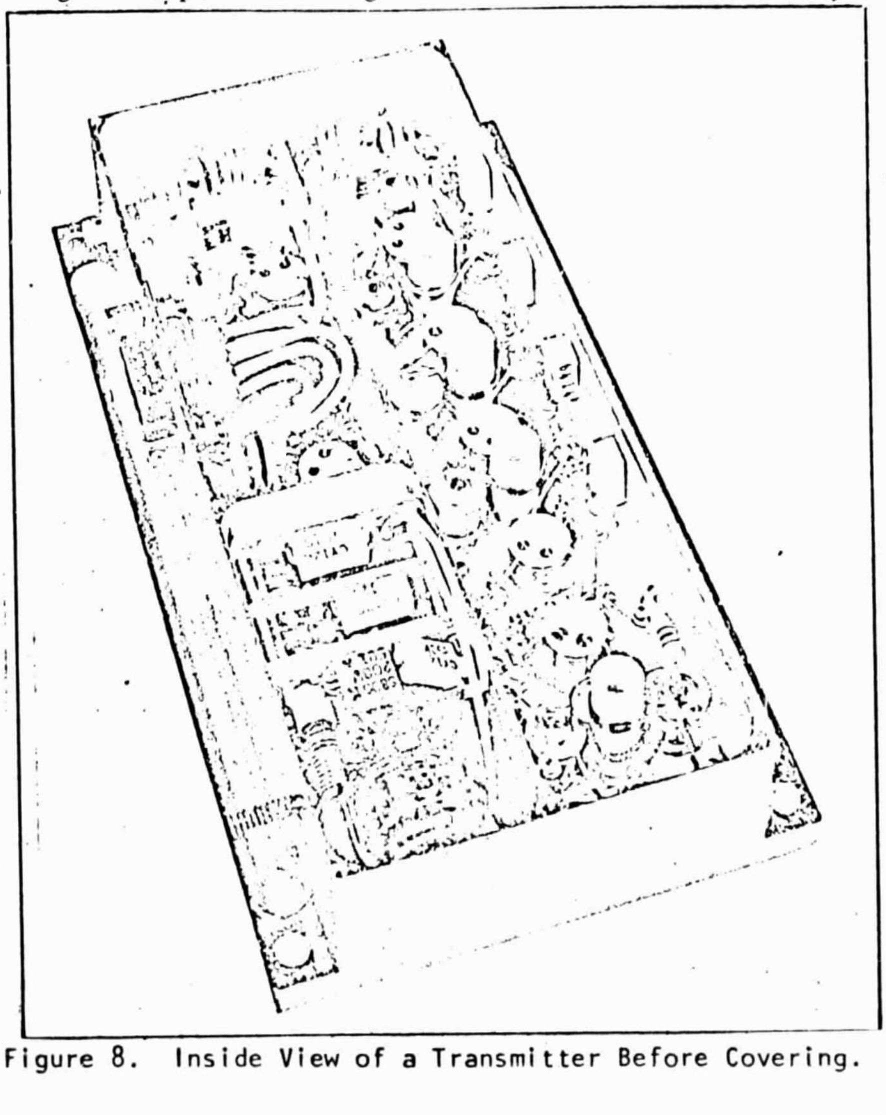

Figure 8. Inside View of a Transmitter Before Covering.

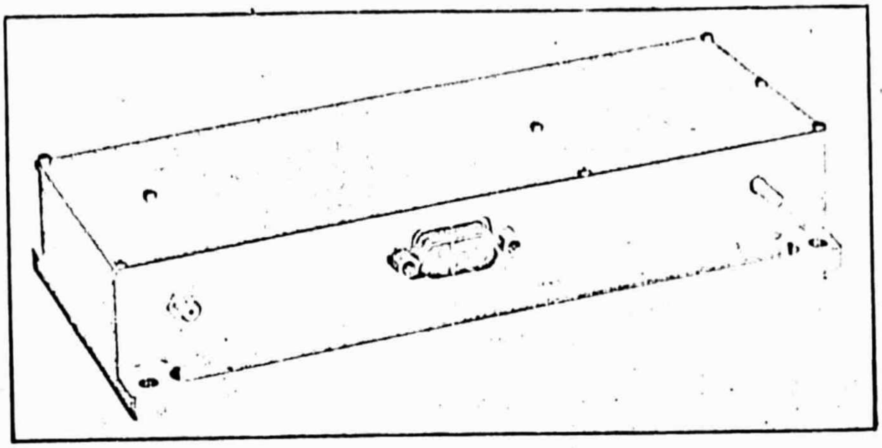

Figure 9. View of a Transmitter When Closed.

4. Problems Encountered

This paragraph will briefly review some of the problems met during development and perfection of the telemetry system limiting discussion to the essential devices which are the encoder and the recorder. It would be tedious to mention the multiple problems posed by the advanced character of the basic options and whose predictable character allowed making all the arrangements for solving them on a timely basis. The effort of the technicians involved will be appreciated more beginning with the illustration of some problems which were unpredictable and especially troublesome and whose solution was required within the limits of an already remarkably loaded program. The first three months in orbit of the IRIS satellite is permanent proof that all these problems were solved satisfactorily. The IRIS telemetry system still oerates flawlessly without perceptible deviation from its rated characteristics.

a) The Encoder

The encoder, in all its operational parts is made up of small circuits which are not too important from the point of view of electrical performance. On the other hand, the simultaneous operation of all these circuits with the reliability required as important an equipment (the deterioration of the encoder would spell the end of the mission) demands the utilization of especially well chosen components. For many of these components, it was necessary to resort to the American market. It was rather quickly noted that this market too had its limitations if requirements were laid on for good operation for a year and a ruggedness sufficient for withstanding stresses applied to the equipment during launch. The impasse was created by an accumulation of unfavorable circumstances: the high number of components used (requiring an exceptional reliability from each one of them), the especially powerful stresses from the "Scout" launch vehicle, the factor of amplification by resonance of the satellite structure, the coincidences between characteristic vibration ranges, etc. At one time, the stresses applied to the components appeared as if they would reach a level of 200 g (the vibrations would therefore have applied to the components tension and shearing stresses of an intensity equal to 200 times their weight). No manufacturer could be found who was able to guarantee a service life of one year for components previously submitted to this test.

The impasse was resolved by the systematic and stubborn improvement of all factors concerned and also by a perceptible decrease in the safety margins made possible by a more precise knowledge of the stresses and their amplification processes. It is therefore possible to mention as especially praiseworthy the effort made in the direction of reduction of resonance amplification factors of the telemetry equipment itself. This effort consisted in a complete overhaul of methods for assembling circuits and ended in the solution described above.

The solution of these problems had, however, considerably retarded the placing of orders for a great number of American components and the supply situation for the flight models became worse as a result of a general crisis which lasted all during the year 1966 in the American market for high reliability components. It is at this time that the realization became acute as to the danger of a dependence on an uncontrolled market and where the Organization had no priority at its disposal. The consoling aspect of all these vicissitudes which required feats of organization in order to make up for the incurred delays is that they were the cause of the birth of many ideas on the problem of qualifying European electronic components for space use. These are ideas which should now become a reality in the near future.

Another problem dealt with the methods for assembling specific components especially vulnerable to workshop handling. After assembly and coating of the modules, it was noticed on a sporadic basis that some of the transistors, although handled with customary care by trained personnel in an air-conditioned and dustfree environment, had ceased to operate correctly. Beyond the damage undergone by the loss of the whole module, these observations caused some uncertainty as to the intrinsically good state and future service life of the transistors which apparently continued to operate normally. It was finally discovered that these transistors were especially sensitive to the electrostatic charges accumulated on their electrodes, this accumulation being made possible by the dryness of the air-conditioned environment. It was therefore necessary to reinspect the physical composition of the atmosphere in which the different operations took place. The solution to this problem was very fortunately found in time in order to be used in the manufacture of the flight units.

b) The Magnetic Recorder

It can be stated very briefly that all development efforts bearing on the mechanical system of a recorder are centered on an ideally regular movement of the tape and that all development efforts bearing on associated electronic circuits tend to minimize the effects of the irregularities latent to the nature of the data. This need for regularity is especially constraining in the case of a digital recording of which the IRIS satellite makes up the first European example. In reality, the playback signals are only a succession of pulses whose "framing" with respect to an ideal clock marking off the mean "rhythm" of the pulses (and which, moreover, is to be reconstituted on the ground beginning from the signals themselves) allows determination of the binary value "0" or "1". Any irregularity of tape movement deflects specific number of pulses from the ideal "framing" with respect to the reconstituted clock and compromises the quality of the information. Some irregularities create difficulties in the synchronizing of the ground equipments, made worse by the presence of noise on the link, and others, more pronounced, lead to the total loss of the data.

The magnetic recorder of the American firm Lockeed Electronic was used as the base of the IRIS satellite recorder development program. It appeared at the time that this recorder possessed, by its mechanical design, a regularity of movement sufficient to justify allocating it a digital recording capability according to the conditions defined by the mission. In reality, the final development of this recorder was going to be found to be one of the most critical points of the little program.

NASA was experiencing at that time serious difficulties in the development of its PCM recorders for scientific use. The few examples of actual operation while in orbit indicated a very short average service life, much shorter than the service life of a year desired for the IRIS satellite.

A first effort consisted in a complete examination of the recorder circuits. It was the opinion of NASA experts, shared by the Organization technicians, that these circuits, such as they had been designed up until then, did not achieve maximum performance in the reconstruction of data played back from an irregularly driven tape. Other circuits, based on other methods of digital acquisition were possible to design and they were taken under sutdy. It was finally a European solution which won out and presently gives complete satisfaction on board the IRIS satellite.

The essential problem, nevertheless, remained the procurement of a "naturally" regular mechanical drive. A major difficulty appeared very late in the program when it was noticed that some recorders, although properly inspected and tested, were suddenly displaying an alarming rate of irregularities and that, if this tendency continued to become progressively more pronounced, the data was going to be completely destroyed. The technicians of both ESRO and NASA worked toward the solution of this puzzling problem for many weeks. Since they were convinved that an especially troublesome flaw was involved, the technicians developed a systematic research program which finally concentrated its attention on the analysis of the inner environment of the recorder. It was noted at that time that there was a relatively long-range chemical deterioration of the lubricant of the magnetic tape owing to the effect of some gases coming from the synthetic product coating the electronic modules. It was possible to take appropriate corrective action after the analysis of these coating products and degassing the electronic modules before their installation in the recorder. The contribution of the Organization engineers to the solution of this problem was definitive.

There still remained the problem of ensuring survival of the recorder over the mechanical stresses of the launch. At the beginning of the program, the recorder had been delivered equipped with a standard cushioned mount which had been deemed sufficient for its protection. Just as it had been with the encoder, an accumulation of unfavorable circumstances revealed the inadequacy of this mount. It was only following systematic research conducted by the specialized ESTEC division that a support perfectly adapted to the operational conditions of the IRIS satellite could be defined and developed.

In sum, the program of design and development of the recorder had many vicissitudes but also was quite instructive. From now on, the recorders of future ESRO missions, including ESRO I, will be entirely of European design and the propsects for improvement seen by European engineers should normally allow the adjustment of the recorder used on the IRIS satellite to the most demanding scientific missions.

The Command Guidance System

1. The Requirements of the Mission and the Basic Options

The IRIS satellite is capable of reacting to 36 different command guidance orders. This number can surprise the reader who has just read the several pages above where the unique requirement was made clear for two different commands intended to put the satellite into a position for recording or off-line retransmission of its observations. In reality, many command guidance orders were introduced owing to technological requirements, most of them, moreover, having been sufficiently exploited up until the present. The difference commands can be classified in the following manner:

- 10 commands have the function of modifying the operation of the different experiments, either in order to basically change the type of measurement performed or to put them in the "calibration" position.

- 7 commands have the function of connecting or disconnecting the experiments from the power supply systems. These command guidance orders allow bypass of experiments and immunizing them from each other in case a poorly performing experiment should run the risk of affecting the others.

- 8 commands direct the operation of the attitude and stabilization control system of the satellite.

- 5 commands allow the organization of the electric power supply system of the satellite. For example, these orders allow placing the satellite in "economical" operational mode or even allow substitution of an emergency device for a malfunctioning one.

- Finally, there are 6 commands assigned to the telecommunications system. They have the objective of placing the system in a position for recording, re-transmitting off-line, or substituting one of the two telemetry transmitters for the other, etc.

It was only at the beginning of 1965, when the project had reached a rather advanced stage, that the mission requirements were known precisely, this occurring upon completion of the satellite total system design.

Owing to its requirements as far as command guidance was concerned, dealing with 36 different commands, the satellite also deserved, just like the telemetry system, its designation as a "small space observatory". Without being sensational, these requirements made less feasible the continued acceptance of the system used up until that time within the scope of the national European programs. This latter system, originating moreover from a NASA standardized system, operated by means of transmission of "tones", one command corresponding to the transmission of a sustained frequency characterized by its value. The capacity of the system was limited to specific quantity of commands, hence different frequencies. There were not more than about ten of the latter and it appeared illogical to try and extend the system to a larger number of them. In addition, it was predicted that subsequent ESRO missions would have higher requirements than those of the IRIS satellite. The acceptance of another system, based on a coding method allowing distinction to be made of a large number of different commands, was made necessary.

On the plane of basic options, the selection of the command guidance system gives the ESRO technicians far less cause for concern and less analytical work than the choice of the telemetering system.

At that time, NASA had already established the norms for a system with a specific 70 command capacity, typically intended for scientific satellites of the IRIS satellite class. It was called "Tone Digital Command System". This system originated from a method of digital coding of the commands and, for their transmission to the satellite, specified a relatively complex method of modulation intended to protect the satellite against interference from any source. This system was perfectly adapted to the mission and all NASA stations were, or were going to be, equipped with corresponding equipments. Hence, it was accepted.

2. Description of the Command Guidance System.

This paragraph does not form a detailed technical description of the command guidance systems. At the very most, some of the system characteristics will be enumerated in order to illustrate their complexity.

The logical design of a coherent group of a certain number of codes composed of "0" and "1" in succession and their sequential transmission by electromagnetic means using some form of modulation present no problem. What does characterize a digital command guidance link are, on one hand, the redundancies intended to ensure the reception on-board the satellite of the transmitted command and, on the other hand, the safety features included in the encoding and the modulation intended to protect the satellite against outside electromagnetic transmissions and erroneous interpretation of a signal received. Here are some examples of the "precautions" taken in the system used for the IRIS satellite:

- The codes utilized had a validity check. They are all composed of four "0" and four "1" (giving 70 different combinations), whose order of succession characterizes the command. The satellite automatically rejects any code which, degraded by interference, is not responsive to this check.

- The modulation itself is a protective factor. The coders are in reality translated into the form of frequency pulses whose length corresponds to the value of the binary data "0" or "1". It is this continuous succession which is transmitted to the satellite in the form of amplitude modulation of the radio carrier. If the design of the on-board acquisition systems of the satellite is correct, this complicated modulation reduces the probability that an extraneous signal becomes confused with a command transmission.

- The sending of a command is preceded by transmission of a coded address intended to "identify" the satellite and hence to present acquisition aboard a satellite of a command intended for another satellite.

- Owing to the need for redundance, the address is repeated twice and the command is repeated three times. Nevertheless, no command is acquired if it does not follow an address within a reasonably short delay.

- The tone pulses are analyzed on board the satellite by counting the pulses and strict tolerances are specified for the numbers of periods which can be interpreted as "0" or "1" values.

Safety factors of all kinds could be multiplied at will except for the danger of complicating the equipment to the point of percetibly increasing the probability of inopportune operation of a protective system which could block passage of the command. The preceding list is not exhaustive but does, however, point out the main protections and, consequently, sufficiently illustrates the complexity of the embarked system.

The on-board equipment is composed of a receiver which, always on the lookout for signals, amplifies and demodulates the signal received from the ground, and from a decoder. The decoder should obviously decode the commands received and distribute them inside the satellite and its most critical circuits should ensure the implementation of the safety factors of the system, performing the count of the period of the signal received, recording the "1" and the "0" values, confirming the validity checks of the codes, etc. Just as it was for the telemetry encoder, functions quite as diversified can be performed by a certain number of possible basic circuits of a same mechanical design. The Figures 10 and 11 depict some typical modules respectively of the receiver and decoder. The 60 modules making up the decoder (or approximately 2,500 components) are arranged on two printed circuit plugboards ensuring the electrical connections between these modules. These two plugboards are housed in two separate casings. The complete receiver-decoder system is represented by Figure 12.

In spite of its complexity, the decoder only weighs 1200 kg (receiver-decoder system weighs approximately 1900 kg), but its most prominent characteristic is its low power consumption, less than 0.1 watt when it is in the "monitoring" state. Indeed, the decoder should always remain capable of reacting to a command guidance transmission. Since the latter are very sporadic in the life of the satellite (the sending of a command takes approximately one second), it would be illogical for reasons of economy of electrical power, to keep continuously under voltage such a quantity of circuits. For this reason, the equipment includes an automatic system for placing its circuits under progressive voltage as soon as it is "sensitized" by the beginning of a transmission.

3. Problems Met

Although in complete agreement with American standards as published by NASA, the on-board equipment is of completely European design and manufacture.

The development program began most confidently since the standards to be followed appeared clear, and defined quite well the goal to be pursured. However, soon difficulties made their appearance. Some of the largest of the latter will be briefly noted below:

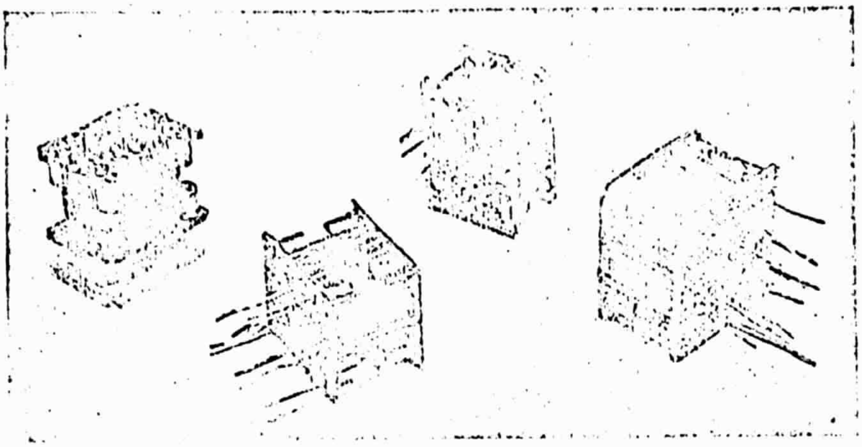

Figure 10. View of Typical Modules of the Command Guidance Decoder (before coating).

Figure 11. View of Some Modules of the Command Guidance Receiver.

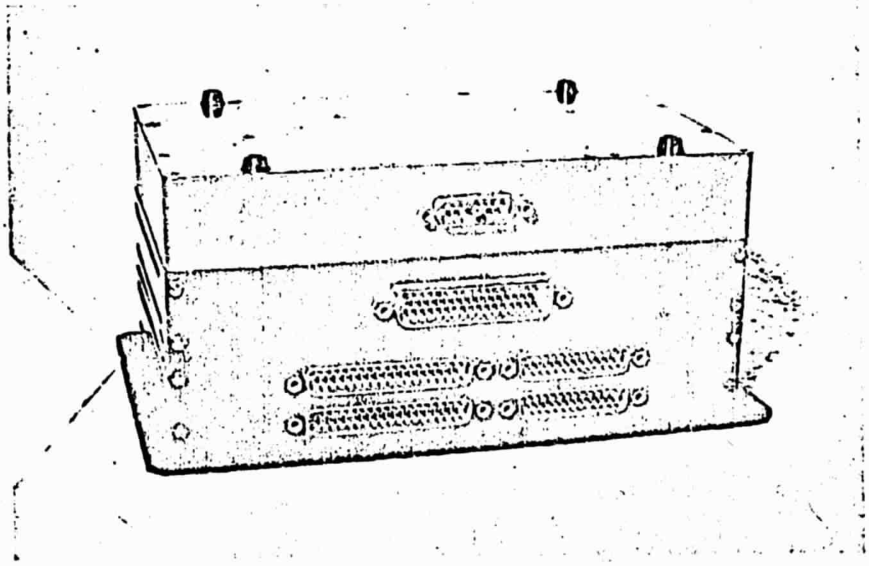

Figure 12. View of the Command Guidance Receiver-Decoder System.

First to be mentioned is the problem of acquisition of the PDM pulses. The problem appeared to be almost theoretical in nature. Indeed, on one hand, it is required to filter the train of frequency pulses in order to be able to operate in very severe noise conditions (corresponding to a signal to noise ratio of 6 dB, or at a ratio of twice the mean amplitudes). On the other hand, any filter has the tendency of changing the duration of a pulse and, by the very principle of the system, it is the duration of the pulses which determine their values. This problem was finally solved by a mix of analog and digital technique. However, for a long time it was believed that it was going to be necessary to relax the system specifications, thus certainly reducing its reliability.

Some technological difficulties appeared starting with the construction of the first unit: a crystal filter of American manufacture equipping the receiver was unable to pass the vibration trials even though it had been guaranteed by the manufacturer. It was on this occasion that it was decided to proceed to the qualification tests of a newly developed European crystal filter. The behavior of this latter was shown to be superior to that of its American equivalent (it is, moreover) the first European crystal operating aboard a satellite) and the tests which took place at that time can usefully be recorded in the file of the general problem of qualification of European components for space use.

The integration of the embarked command guidance equipment of the satellite has turned up a series of problems centered around the protection of the receiver. The telemetry transmitters and the command guidance receiver are switched to the single satellite antenna and output signals from the transmitters should be prevented from interfering with the command guidance receiver through this switch.

These signals can be discriminated by means of their respective frequencies but an idea of the filtering qualities required of these switching circuits will be gained by comparing the orders of magnitude implied: the powers of the telemetry signals are repsectively 2 and 0.2 watts and the command guidance receiver has a sensitivity allowing it to react to a signal as weak as -105 dbm, or $10^{-13.5}$. This difficulty is not insurmountable but requires a special watchfulness concerning all the characterisitics of the devices concerned. It can be stated that the experience gained during the electrical integration of the first ESRO satellite makes up one of the most important acquisitions of the Organization.

One of the last difficulties met - and its tragic character originated essentially from the fact that it appeared late in the program - concerned the question of system. During the first feasibility tests of the satellite with the NASA network, it was observed that the IRIS system obstinately refused to obey the commands sent to it. What did happen? The answer is rather uncomplicated. The Organization engineers, at the start of the program, had taken very seriously those protection systems stipulated by the American standards and had given them consideration in their totality. This philosophy had made the receiver-decoder system into a system that was especially insensitive to interferences and to any deformed signals which it could receive. (This insensitivity can moreover be phrased in eloquent terms: during electrical tests, more than one million commands were simulated in all possible conditions of transmission: background noise, tone shifting, frequency shifting, etc., without the decoder outputting one single erroneous command). To this strictness in application of embarked equipment standards there should normally have corre ponded a rather precise conformity of ground command guidance transmission equipments. In the controversy which followed concerning this contradictory incompatability of the on-board IRIS satellite equipment with the ground equipments of the NASA stations, it was finally agreed that it was the latter which did not conform to the standards. It was noticed at the same time that the IRIS satellite was the first to wholly apply the standards of the system.

As a conclusion to all these vicissitudes it can be said that success has sanctioned the quality both of the system adopted as well as the on-board equipment. At the moment of writing of this article, more than 3,000 commands have been sent to the satellite which have all been faithfully carried out.