COMMUNICATIONS BETWEEN SATELLITE AND BALLOONS FOR THE EOLE MISSION

J. P. BOURDEAU, P. DEBRAY, and X. NAMY
CNES—Satellites Division

I - DESCRIPTION OF EOLE

1.1. - Eole mission :

The purpose of Eole experiment is to study the wind distribution in the South Hemisphere and to measure different parameters, characteristics of the atmosphere like temperature and pressure.

This experiment will be accomplished with a fleat of balloons, around 500, flying at a constant level (300 mb). These free balloons plot the motion of the mass of air. Temperature and pressure sensors will be placed on board of the balloon package.

One satellite will interrogate these balloons and receive the different data measured on board. The results obtained during the interrogation will be stored and sent to the ground when the satellite is in view of the ground station.

The orbit will be circular 800 km altitude with an inclinaison at 45°.

1.2. - General description of the spacecraft and balloons equipments :

The satellite configuration is given by fig. 1. Its weight is about 80 kg. The spacecraft is stabilized with respect to the geocentrique using gravity gradient. It is mainly constituted by:

- a structure,
- the gravity gradient system : boom and magnetic dumping materials and attitude sensors,
- a solar generator associated with batteries and converters,
- a telecommunication system at 136-148 MHz allowing the communication between satellite-ground station,
- a core memory used to store the balloons data before transmission to the ground,

– a system which allows :
  - to interrogate the balloons,
  - to receive the balloons information
  - to localize the balloons
  - to process the data transmitted by the balloons.

A brief description of this system will be the main concern of this paper.

The balloons package includes:

– a solar generator associated with batteries and converters,
– a coherent transponder,
– a telemetry encoder,
– an antenna.

1.3. - Specifications of the balloons interrogation system:

The balloons and satellite equipements should be able to localize 500 balloons in about 8 minutes. The accuracies of this localization will be on the order of ± 3 km. During the same time, the parameters measured on board of the balloons must be transmitted to the spacecraft and processed on board, the total accuracy being better than 1 % of the full scale.

The solution of this problem has to be found taking into account the following facts :
1° - the balloon packages will be mass produced at low cost,
2° - the satellite has to be launched by a Scout rocket. It follows that the power and weight on board of spacecraft and balloons is limited.

II - DESCRIPTION OF THE CHOOSEN SOLUTION

The purpose of the satellite-balloon and balloon-satellite link is:

1° - to address a designated balloon
2° - to localize the called balloon
3° - to assure the transfert of information from the ballloon to the satellite.

2.1. - Localization:

Two parameters are measured on board of the spacecraft:

– the angle θ between the speed vector $\vec{V}$ of the satellite and the direction satellite-balloon (through a Doppler measurement),
– the range “d” satellite-balloon.

The locus of the balloons : sphere of radius R + h having as center the center of the earth, R is the radius of the earth, h : the altitude of the balloon. Therefore, the balloon is at the intersection of two spheres and one conus. Two positions are possible : at the next orbit it will be possible to choose the right one (fig.2).

One another hand, the necessity of knowing $\vec{V}$ requests to know the satellite ephemeris and the time of measurement. One stable oscillator placed on board of the spacecraft will be used as a reference for the system.

Doppler measurement The spacecraft transmits a signal received by the balloon. After a coherent change of frequency, this signal is sent back to the spacecraft. The beating frequency of the signals transmitted and received is measured by a counting method.

θ is given by :

$$\cos.\ \theta \simeq \frac{c}{|\vec{V}|} \times \frac{f_D}{2\ f_i}$$

c = light speed

f_D = Doppler frequency

$f_i = \frac{p}{q} f_0$

where f_0 is the frequency transmitted by the satellite
and $\frac{p}{q}$ the transposition ratio of the balloon.

Range measurement Three frequencies modulate the RF carrier radiated by the satellite:

48 Hz define the dynamic range (3125 km)
2304 Hz which define 65,1 km
2688 Hz which define 55,8 km.

For each of the given frequencies, one measures the phase difference between the transmitted and received signal. The processing of the three phases difference allows the knowledge of the range.

2.2. - Interrogation sequence:

The balloons can be interrogated either in a sequentially manner, in this case the 500 balloons will be interrogated one by one, the time allocated for one balloon being 625 ms, or in a programmed manner : in a memory on board of the spacecraft is stored the address of the balloon and the time at which they will be interrogated. In any case, the message is constituted as follows :

Carrier The carrier frequency of the spacecraft is 460 MHz. The frequency is derived from a stable oscillator used as reference for all the measurements on board of the spacecraft. When a balloon reaches the visibility area of the spacecraft, its UHF receiver locks on the phase of the received carrier. When the balloon has decommutated its own address, it transmits back to the satellite the received signal after coherent change of frequency. The frequency transmitted by the balloon is 400 MHz. The satellite receiver is a phase-lock receiver the time devoted to lock being 100 ms.

Modulation Spacecraft modulation. The type of modulation is P.M. The interrogation message for one particular balloon is a 30 bits binary sequence. It is made up of three words :

- one of 18 bits,
- one of 6 identical bits
- one of 6 identical bits complementary of the above defined.
  Bit rate is 48 bits per second.
- 18 bits word : this word can be any of the 511 words
  of 18 bits in which a PN sequence of length 511 bits can be divided in. Using such word as balloon address, one can interrogate 511 balloons, 9 of these 18 bits are used as address, the others 9 are used for error detection.
- PN generator : It is a 9 stages shift register with a feedback obtained through modulo 2 adder on 9th and 5th stages.
- 6 bits words : One is the 6 “0” word. The other is the 6 “1” word. The order of the two 6 bits words can be reversed. For normal operation, the sequence is 6 “0”, 6 “1”. If the order is reversed, this means the balloon has to be destroyed.
- Bits are encoded in burst-blank FSK prior to transmission (figure 3).
- The two frequencies contained in the burst are F_0 = 2304 Hz, F_1 = 2688 Hz.
- It can be notice that F_0, F_1 and the bit rate are the frequencies used for ranging. They are derived from the U.S.O.

Received message by satellite It consists of:

- unmodulated UHF carrier during $\frac{8}{48}$ second.
- PM modulated UHF carrier by the 6 “0” and 6 “1” words received by the balloon and coherently transmitted back to the spacecraft.
- PM modulated UHF carrier by balloon information. Each of these 4 data being transmitted during $\frac{2}{48}$ second.

The balloon information are a time multiplex of the 4 frequencies representing data. Each output transducer frequency is sampled during two cycles of the 48 Hz clocking the balloon. The information bandwith is 7,5 to 10 KHz The total message length is $\frac{28}{48}$ second.

General timing of system (fig.4) Interrogation messages are sent continuously by the spacecraft. Balloon clock is obtained through a phase-lock loop locked on the enveloppe of interrogation messages. Therefore, balloon clock is coherent with satellite 48 Hz giving the assurance of precise location of response sequence with respect to interrogation sequence except for propagation delay which causes an uncertainty of $\frac{1}{48}$ second. The general diagram of the satellite equipmens is given on fig.5.

III - UHF DESIGN :

3.1. - Transmitter and receiver

The major items of the system for Doppler measurement are shown in the fig.6.

- an ultra stable oscillator (Master oscillator which is the frequency reference for the whole system : all frequencies in the system derive from it).
- the transmitter : starting from fr (U.S.O. freq.) it generates f 0 and amplifies it to a proper power 4 watt.
- the receiver : receives and amplifies the signal sent back by the balloon. This receiver has a low noise figure.
- a phase-lock loop : extracts the Doppler frequency from the noise. Basicaly, it is a narrow band filter. Out of the PLL comes out a frequency $f = D_f + f_p$ (f_p: polarization frequency.)
- a counter : it counts f.

A signal coming from the U.S.O. is used as reference signal. Having stated the basic equipment involved in the system, we will now go a bit more in the details of the UHF phase-lock loop that we feel the most original. The precision of the frequency measurement can be estimated through σ_f : standard frequency deviation. There are several causes of error on the frequency measurement, an important one being due to the noisy signal that is received in the satellite. In order to achievea correct location of the balloons 0,1 Hz should be the precision due to the noise in the balloon to satellite link. It has been shown that this type of error can be written :

$$\sigma_1 = \frac{1}{2\pi T} \quad \frac{1}{\sqrt{\frac{A^2}{N_0 \; 2B_L}}}$$

T : time of integration of frequency measurement

$\frac{A^2}{N_0}$: signal to noise power density

$2\ B_L$: Double -sided noise bandwith in front of the counter (i.e. P LL double sided noise bandwith).

We wish to determine $2\ B_L$. The link conditions enable us to take $\frac{A^2}{N_0}$ at least equal to 10 000. Ranging measurement has to be made at the same time and for the same length of time $T = \frac{1}{4}$ s .

Therefore : $0{,}1 = \frac{1}{2\pi \times \frac{1}{4}} \times \frac{1}{\sqrt{\frac{10\ 000}{2\ B_L}}}$

from which $2\ B_L \neq 200$ Hz.

Up to this point, we have examined the PLL in its filter function that is to say when the loop is locked. But before performing its function as a filter the phase-lock loop must lock into the signal. System consideration have led to a time of about 100 ms devoted to locking. The frequency domain to be explored is ± 18 KHz (Doppler) plus instability of VCXO, DC amplifiers, etc ... this gives a sweep frequency speed of about 400 KHz/s.

Such a high speed of 400 KHz/s with a bandwith of about 200 Hz and a low signal to noise power density (10 000) do not enable the loop to lock.

The solution which is adopted is to switch the noise bandwith of the PLL, once the acquisition has been done from a large to a narrow mode. A quadridetector performs the signal recognition in order to stop the sweep and switch to the narrow mode.

3.2. - UHF Spacecraft antennas

Type of the antenna The choice of a vertical, linear polarized balloon antenna with a very high front to back ratio, asks for a very good circular polarization on satellite.

(In balloon-satellite link, the field vector $\vec{E}$ rotates through the Faraday's effect, and so, for minimum polarization-loss the satellite antenna must be circularly polarized).

Likewise in satellite-balloon link, we have to match a lineary with a circularly rolnrized antenna. This ?roperty must occur in the conical angle defined by θ (figure 7).

The conical log-spiral antenna is particularly suitable to solve this kind of problem. It is a frequency independant antenna and is essentially circularly polarized in any direction in which there is substancial radiation. In our case, the antenna is used at 400 MHz (link from balloon to satellite) and at 460 MHz (link from satellite to balloon).

The Eole log-spiral antenna Geometry of antenna (fig. 8 and 9). The basic parameters of the equiangular conical antenna are :

- cone angle $2\,\theta_0 = 20°$ which gives an important front to back ratio for the radiation pattern (in the order of 25 dB). This figure makes it easier to integrate the antenna on the satellite, which, being in a radiation hole does not alter the pattern too much.
- rate of wrap of the arms : $\alpha = 45°$. This angle produces the adequate large conical beam in a cone angle larger than 2 x 62°.
- Number of arms : 4, which are feed with equal voltages of phases : 0, 90, 180, 270° to avoid on the antenna's axis a hole in the radiation pattern. More over, the structure is so that the geometry of the arm and the space between arms is identical, except for a rotation of 45° about a spin axis (self complementary conical antenna). So, we obtain a very good symetrical pattern about this axis.

Feeding system (fig.10) It provides the required phasing of arms and matches the antenna access. It consists of :

- an hybrid junction to insure the quadrature of phases,
- a double wide-band coaxial balun to insure the balance feeding of the opposite arms.

Typical radiation pattern The two frequencies of interest are 400 and 460 MHz.

Due to the presence of the satellite body the pattern at these two frequencies are not the same; in particular the upper part of the satellite acts as a reflector.

At 400 MHz about the axis, the polarization is far from being circular, and at 460 MHz there is a hole in the diagram for θ - 35°. See figures 11 and 12 (Diagrams are done with a rotating dipole). The antenna has been optimised in order to reduce both of these effects at the same time.

IV - RANGING MEASUREMENT AND DATA PROCESSING

4.1. - Range measurement :

Three optimum phase-meters are used. Each of them is of the type described fig.13. One measures the phase of the 48 Hz out of the receiver amplitude detector. It can be

$$\sigma_{\theta_A} = \frac{1}{\sqrt{2\left(\frac{P}{N_O}\right)_A \cdot DA}}$$

$\left(\frac{P}{N}\right)_A$ is the signal to noise ratio/Hz at the receiver amplitude detector output, D_A is the integration time.

The two others phase-meters measure the phase of the 2304 Hz and 2688 Hz at the receiver phase detector output. Taking into account the burst-blank configuration of the signal, we have :

$$\sigma_{\theta_\phi} = \frac{1}{\sqrt{\frac{1}{2}\left(\frac{P}{N_O}\right)_\phi D_\phi}}$$

$\left(\frac{P}{N_O}\right)_\phi$ is the signal to noise ratio/Hz at the receiver phase detector output, and D_ϕ is the integration time.

For $D_A = \frac{10}{48}$ s, $D_\phi = \frac{4}{48}$ s and maximum range :

$$\frac{\sigma_{\theta_A}}{2\pi} = 2\ \% \text{ and } \frac{\sigma_{\theta_\phi}}{2\ \pi} = 1,5\ \%$$

4.2. - Data processor :

Synchronisation Each data is transmitted during $\frac{2}{48}$ second, there is for each data a known duration of $\frac{1}{48}$ second where the data is certainly present.

Data processing. The data processor consists of a phase-locked loop which locks successively on each data frequency. Lock in time is less than $\frac{1}{2}\ \frac{1}{48}$ second which leaves another $\frac{1}{2}\ \frac{1}{48}$ second to get rid of transients and count VCO frequency with a 7 stages binary counter.

In order to get lock in time less than $\frac{1}{96}$ second, Six phase-locks are used. Each of them explores one 6th of the total bandwith. The signal of the first loop which acquires is directed to the counter.

The accuracy of the measurement is given by

$$\frac{\Delta F}{B_f} = \frac{1}{2\pi} \times \frac{1}{m} \times \frac{1}{\sqrt{\left(\frac{P}{N_O}\right)_\phi \times \frac{1}{2\ B_L}}} \times \frac{F_M}{B_f}$$

ΔF is the error,
B_f is 2.5 KHz (information bandwith)
m is the number of periods counted
$2\ B_L$ is the equivalent loop noise bandwith (1250 Hz for infinite signal to noise ratio)
F_M is the maximum frequency : 10 KHz

At maximum range $\frac{\Delta F}{B_f} = 0{,}9\ \%$

The feasibility of this system has been proved in laboratory. Furthermore, the principe of localization using only Doppler measurement in the condition described above has been tested with “Transit”. The Eole program being made in cooperation with NASA, the satellite will be launched with a Scout from WALLOPS ISLAND in 1970.

Eole satellite

Orbital configuration

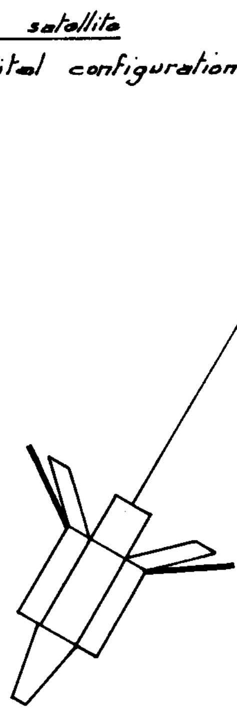
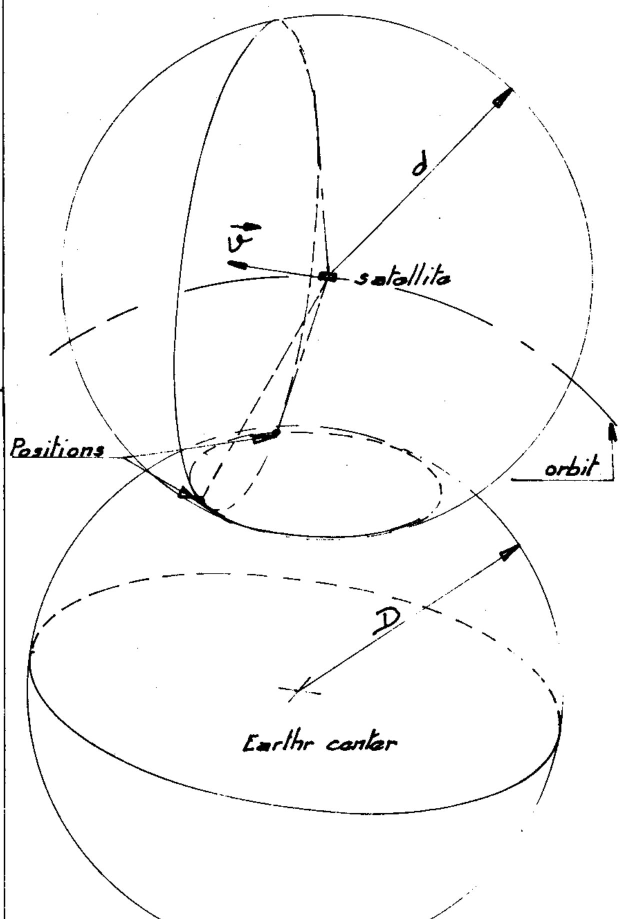


fig: 1



Localisation fig: 2

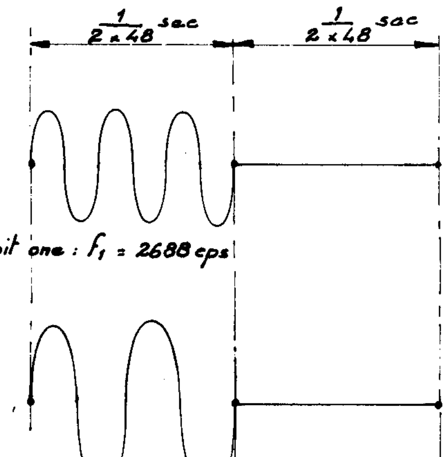


fig: 3

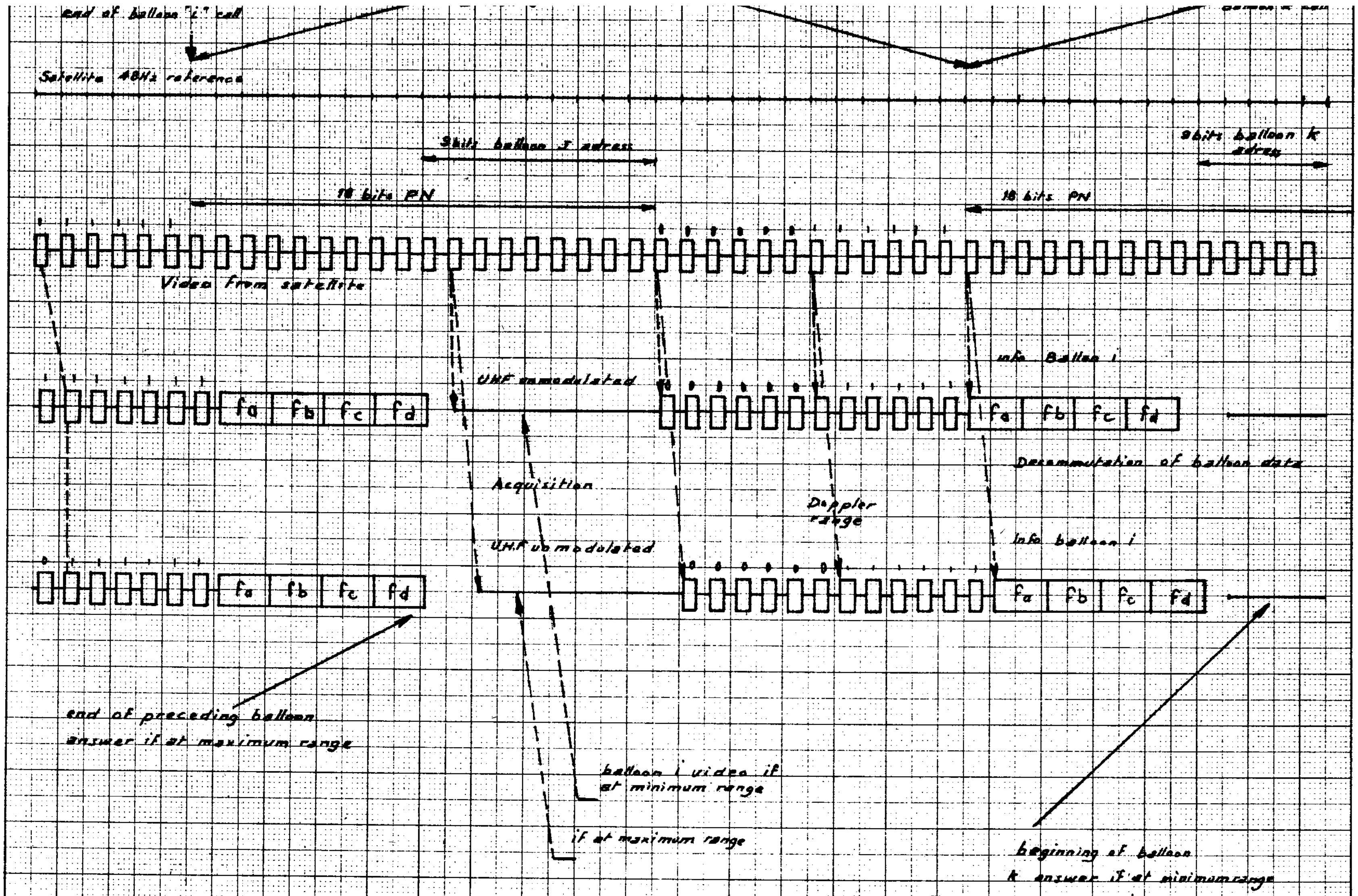
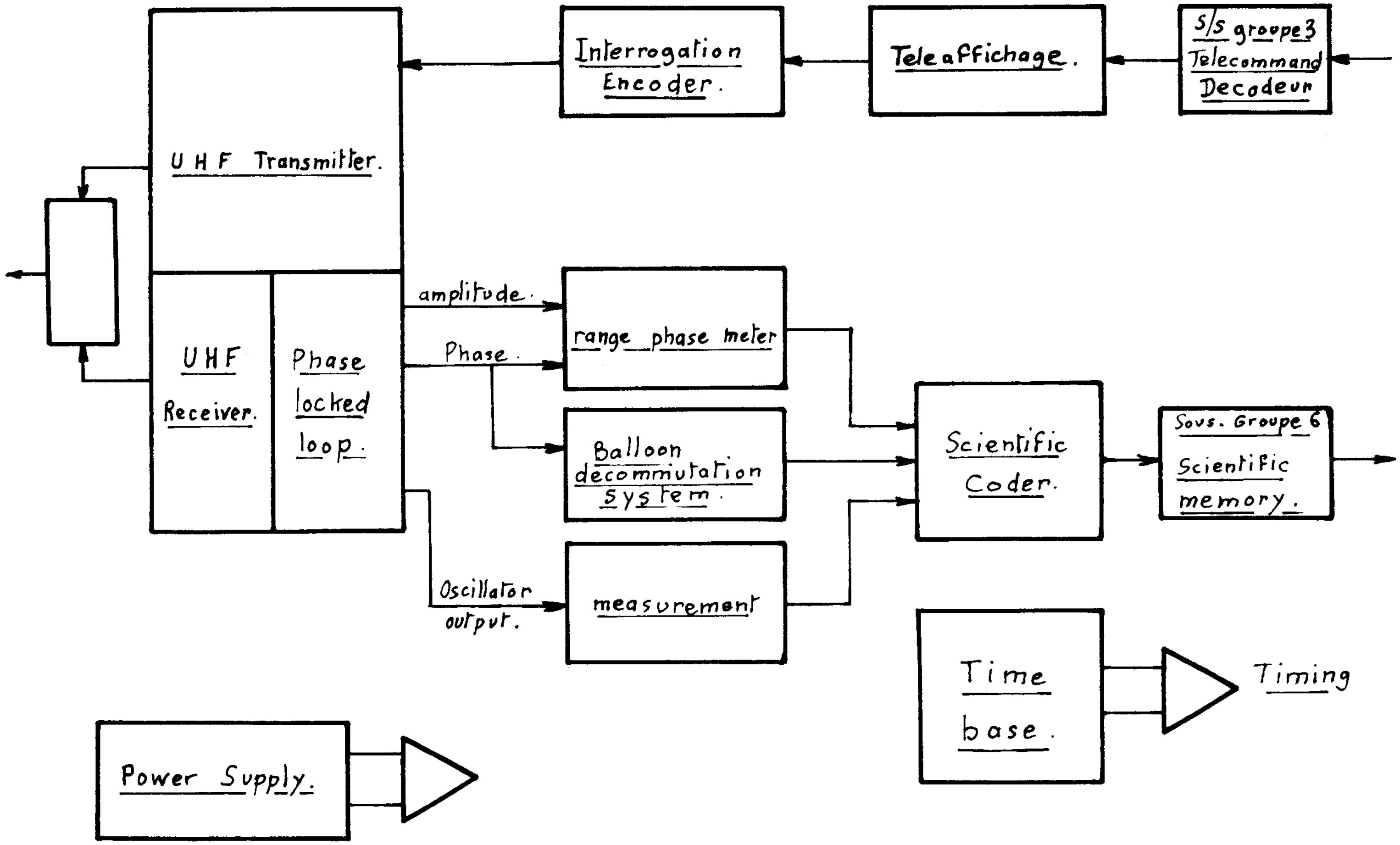


Fig 4

TIMING DIAGRAM



SATELLITE EQUIPEMENT Fig. 5

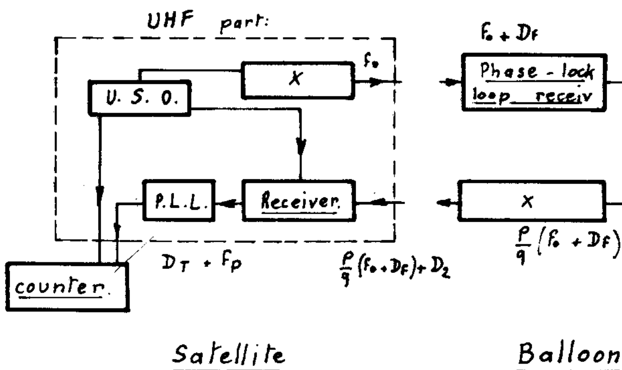


Fig. 6

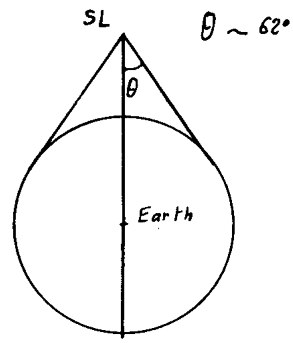
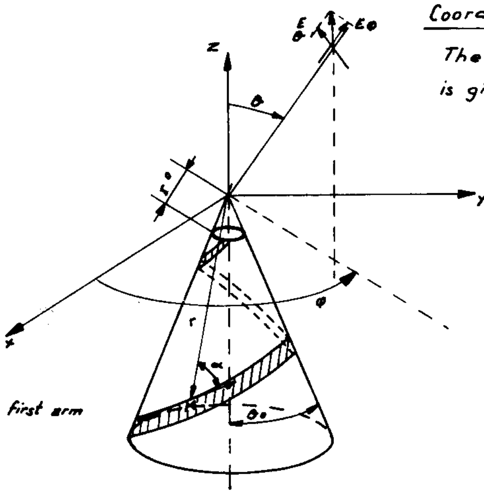


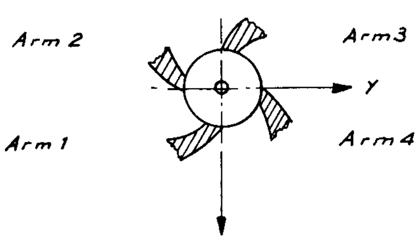
Fig. 7



Coordinates and parameters of the spiral

The radius vector to any point on the edge of the first arm is given by : $r = r_o \exp . \frac{\sin \theta_o}{Tg\ \alpha}$.

Fig. 8



The voltages impressed are :

$V_1 = V_o\ e^{J o}$

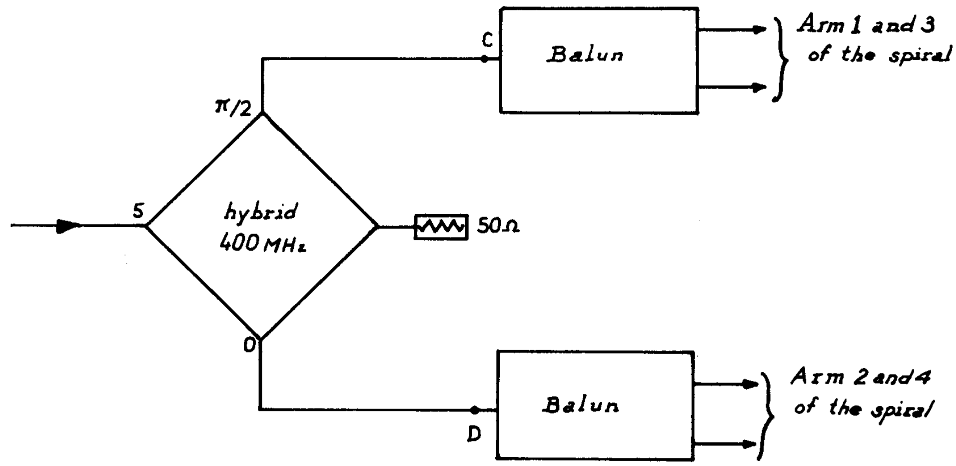
$V_2 = V_o\ e^{-J \pi/2}$

$V_3 = V_o\ e^{-J \pi}$

$V_4 = V_o\ e^{-J 3\pi/2}$

Top view of the spiral

Fig. 9



Feeding system of the UHF Conical antenna

Fig. 10

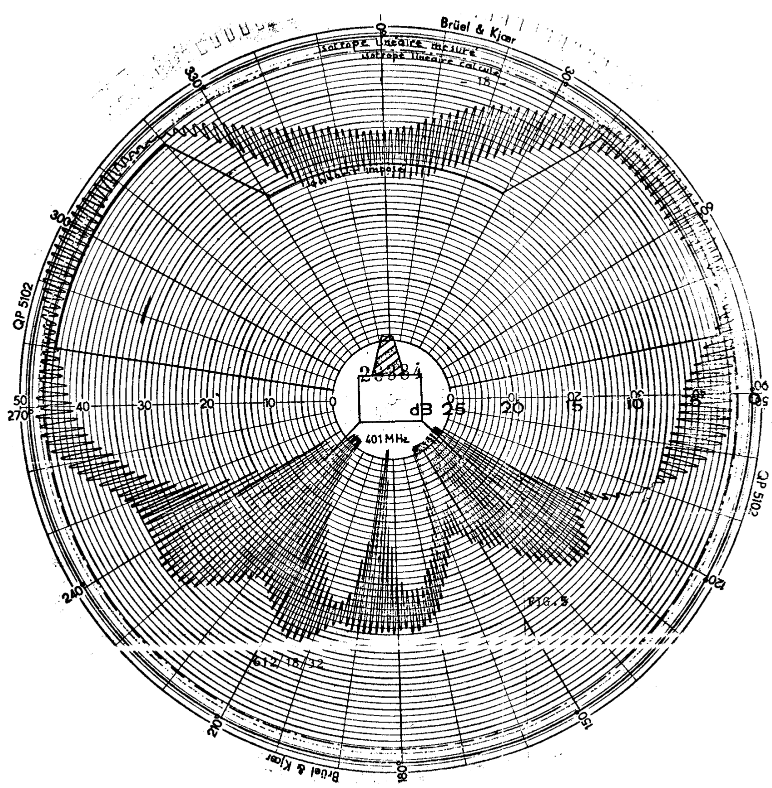


Figure 11

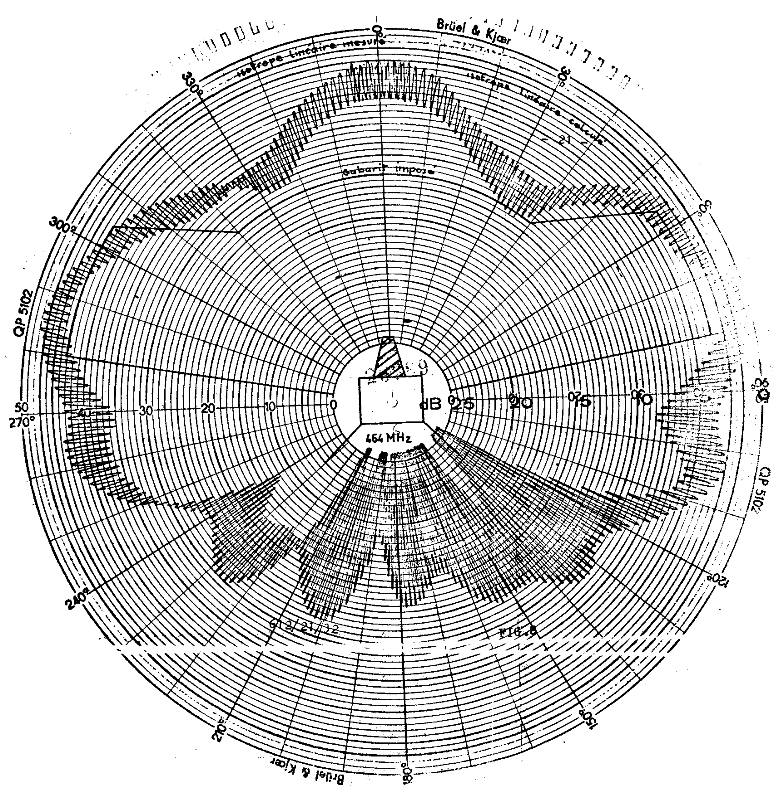
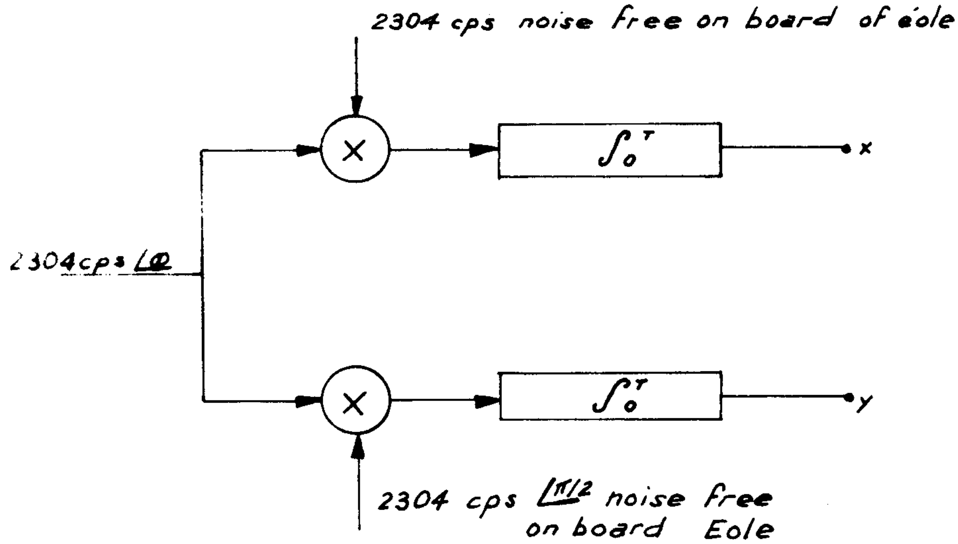


Figure 12



Phase meter on 2304 cps

Fig: 13