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THE ALOUETTE II TOPSIDE IONOSPHERIC SOUNDER (U)

by

C.A. FRANKLIN and M.A. MACLEAN

ELECTRONICS LABORATORY

OTTAWA CANADA

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FOREWORD

This report was first presented as an oral paper at the International Conference on Electronics and Space held in Paris, France, April 10–15, 1967.

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ABSTRACT

This report describes the swept-frequency pulsed sounder in the Alouette II satellite. Following a general description of the system design, attention is concentrated on some of the more difficult problems involved in its realization. Chief among these are the problems of obtaining enough transmitter power, of building a receiver with a large dynamic range, and of connecting transmitter and receiver to a common antenna. Also described are the techniques and practices used to achieve a very long life in orbit.

Introduction

The Alouette II spacecraft was launched on November 29, 1965, into a 500 x 3000 km elliptical orbit at an inclination of 80 degrees. The primary experiment is the ionospheric sounder, used to investigate the properties and behaviour of the ionosphere from the F-region maximum up to the height of the satellite.

The sounder is of the pulsed, swept-frequency type and the output is telemetered to the ground for the production of ionograms that display apparent range as a function of frequency.

Sounder Characteristics

A summary of the principal characteristics of the sounder is as follows:

Tuning range	0.12 - 14 MHz
Sweep rate	0.125 MHz/sec to 2 MHz 1 MHz/sec above 2 MHz
Sweep duration	32 sec
Transmitter power	300 watts (pulsed)
Transmitter bandwidth	0.2 - 8 MHz (-3 db) -8 db at 14 MHz
Pulse	100 μ sec at 30/sec
Antenna	crossed dipoles, 73 and 23 m
Receiver IF bandwidth	37 kHz
AGC range	50 db
Noise figure	14 db
Telemetry	direct FM at 136 MHz
Weight (excl. antenna and telemetry)	15.8 kg
Antenna system weight	11.2 kg
Power consumption (excl. telemetry)	25 watts.

System Design

In general design, the Alouette II sounder is similar to the one flown previously in Alouette I (1962)[1]. However, the frequency sweep is wider and the transmitter power has been increased by a factor of three to enable soundings to be made from a higher orbit. Experience with the earlier sounder showed that its broadband receiver was unduly susceptible to intermodulation between strong transmissions from the ground breaking through the ionosphere above the critical frequency. The Alouette II sounder receiver has therefore been given more front-end selectivity.

Figure 1 is a block diagram of the sounder. The frequency range of the swept oscillator is 19.12 - 33 MHz and this is heterodyned to the sounding range of 0.12 - 14 MHz. The 19 MHz signal used for this purpose is derived from a gated frequency-doubler which is switched off during reception to avoid interference with the receiver whose first IF is also 19 MHz. The mixer output drives either the 300-watt broadband power amplifier or a spare 100-watt amplifier. Power is distributed between the two crossed dipoles by a crossover network which directs most of the power to the 73-metre dipole below 4.7 MHz and to the shorter one above that frequency.

The receiver has two alternative preamplifiers, one with a broadband response from 1.5 - 11.5 MHz and the other with three switched bands covering 0.1 - 14 MHz. Each preamplifier is preceded by a solid-state TR switch since the receiver and transmitter share a common antenna. The receiver uses the 19.12 - 33 MHz swept signal as the local oscillator for its first mixer.

The swept frequency is calibrated by comparing it with a series of harmonics from three crystal oscillators. Each time the swept signal coincides with one of the harmonics, a marker pulse is generated. The sweep calibrator is driven by the output of a mixer using a local oscillator at 18.5 MHz to minimize interference with the receiver. As well as calibrating the sweep, the marker pulses at 2 and 7 MHz control the switched preamplifier and the pulse at 2 MHz initiates the change in sweep rate at that frequency.

Transmissions are timed by a 30 Hz oscillator which produces a 100 μsec pulse to turn on the drive to the transmitter, a 400 μsec pulse to short-circuit the preamplifier inputs, and a synchronizing pulse which is transmitted to the ground.

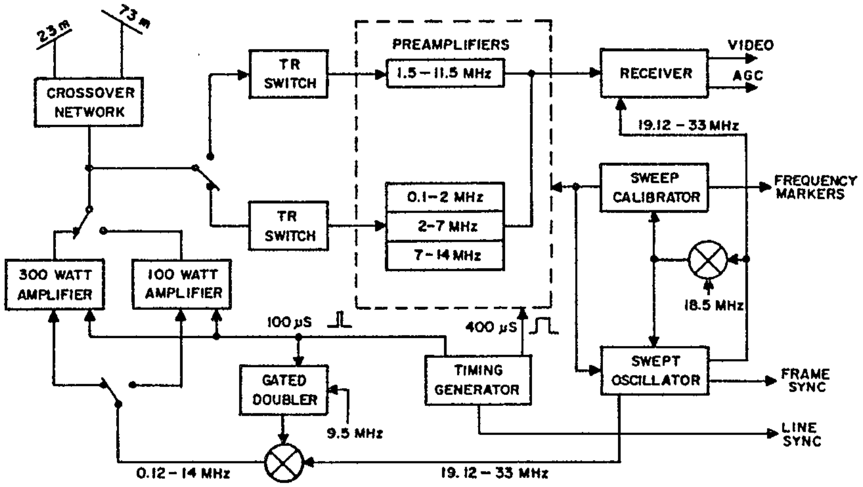

Fig. 1. Alouette II Sounder.

Transmitter Power Requirements

The largest factors determining the transmitter power requirements are the range from the satellite to the point of reflection, the cosmic noise background, and the antenna mismatch losses during transmission. It should be noted that the apparent range of the echoes will be greater than the physical range when ionospheric retardation effects are encountered, such as when sounding close to the penetration frequency. The cosmic noise background is large enough to dominate receiver front-end noise at all but the highest sounding frequencies (about 45 db above 300 °K thermal noise at 2 MHz) and it varies with frequency at about the same rate as the capture cross-section of the antenna (inversely with f^2). A rather high antenna mismatch loss is the penalty for covering a wide frequency range with a fixed coupling network.

Additional losses result from the splitting of the propagated energy into circularly-polarized 'ordinary' and 'extraordinary' components, and from unfavorable orientation of the antenna during parts of the satellite motion.

On the positive side, the ultimate presentation of the data in the form of an ionogram permits some visual integration of weak echoes received from adjacent pulses. Experiment has shown that the weakest signal detectable in this way has a power about equal to the noise at the receiver input.

Summarizing these effects we have:

Transmitter power (300 watts)	+ 25 dbw
Cosmic noise (f = 2 MHz, 37 kHz b/w)	- 113 dbw
	+ 138 db
Antenna mismatch loss on transmission	- 10 db
Antenna pattern fading	- 6
0 and X wave splitting	- 3
Polarization loss	- 3
	+ 116 db.

The maximum range for a unity signal-to-noise ratio would then be about 3,770 km. In comparing this to the physical range from the satellite, at apogee, to the F-region maximum (2,500 - 2,750 km), the ionospheric retardation effects should not be forgotten.

In practice, the power of 300 watts has been found more than adequate at the lower satellite heights. The performance at apogee is good except when a large amount of retardation is taking place.

The 300-Watt Transmitter

The development of this transmitter was one of the major electrical problems in the spacecraft. The high power requirements and the wide bandwidth made it necessary to take the greatest care in circuit design, transformer design, and physical layout. Because of the highly reactive and variable impedance of the antenna system across the frequency range, the transmitter had to be capable of operating without damage or instability into complex load impedances varying in magnitude from a few tens of ohms to about 5,000 ohms.

A block diagram of the transmitter is shown in Figure 2. It has ten transformer-coupled stages arranged in the following sequence: three single-ended class A common-base stages, one single-ended class A common-collector stage, four push-pull class B common-collector stages, and two push-pull class A common-base stages.

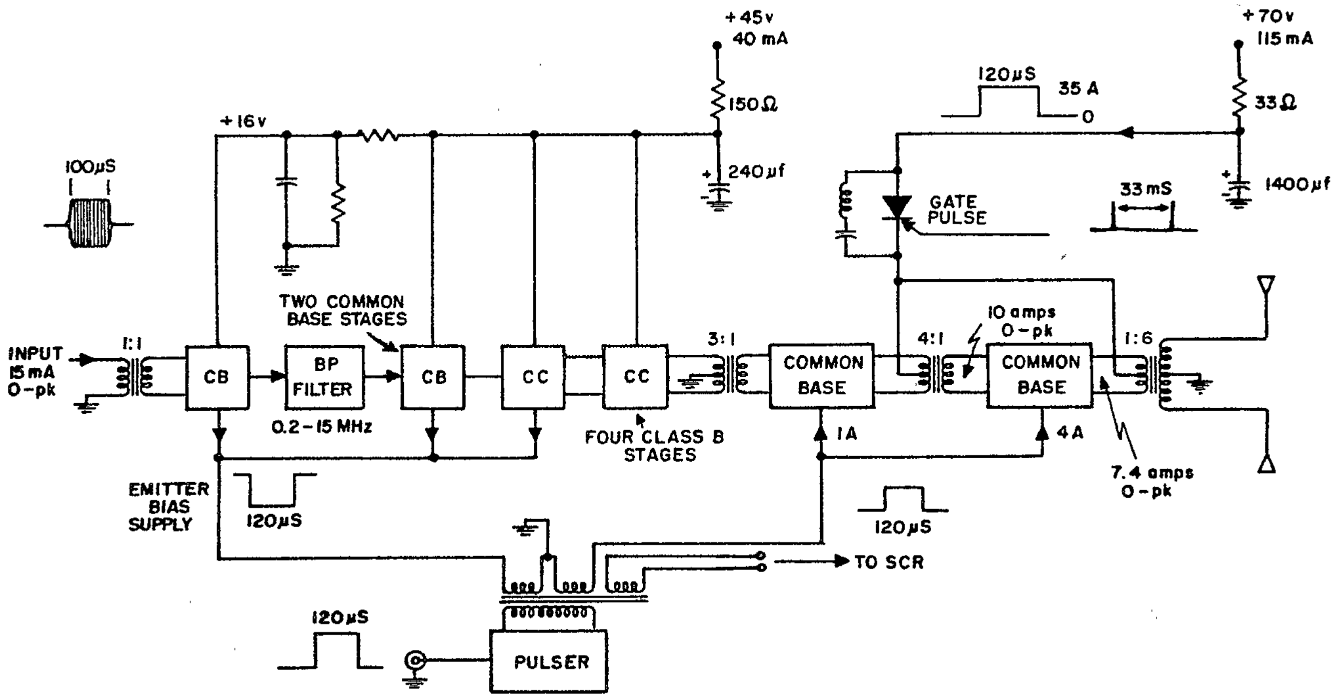

Fig. 2. 300-Watt Transmitter.

The transmitter is turned on by a transformer-coupled pulser driving the bases of the two final stages and the emitters of the three low-level class A stages. At the same time, the RF drive to the unit is pulsed on. The two final stages share a 70-volt collector supply with a large reservoir capacitor to supply the 35 ampere current surge that occurs when the transmitter is pulsed. To avoid excessive power drain caused by collector leakage in the output transistors an SCR switch, shunted by an LC turn-off circuit, is connected between the reservoir capacitor and the output stages.

Six 2N1900 transistors are used in the output stage, connected in push-pull parallel. These are triple-diffused, interdigitated, planar devices. Each is biassed to 3.3 amperes during the pulse. The maximum collector dissipation occurs with no RF drive present or with a short-circuited load and is about 290 watts for each transistor. However, the long thermal time-constant of the transistors compared to the pulse length prevents excessive temperature rise. Collector junction breakdown with high impedance loads is prevented by zener diodes connected between the collectors and ground which place an upper limit on any voltage transients appearing there. In addition, these prevent excessive voltages from being produced in the antenna system.

The penultimate stage uses two 2N1900 transistors which are transformer-coupled to the output stage, providing a drive of about 10 amperes peak.

The design of the coupling transformers is most critical. Great efforts were made to achieve low leakage inductance and stray capacitance in order to obtain the desired bandwidth. All the transformers use ferrite pot cores and, in some cases, copper tape was used for the windings instead of wire.

To prevent noise from the transmitter reaching the receiver during reception, silicon diodes are connected in series with each output lead. These diodes have a high impedance to low-level noise but introduce only a negligible loss during transmission.

The power output at mid-band is 300 watts and the response is 3 db down at 0.2 and 8 MHz and is 8 db down at 14 MHz. Power consumption is 10.3 watts, the power gain is 50 db, and negligible changes in performance occur over the temperature range of -50°C to +75°C. Dimensions of the transmitter are 20 x 18.5 x 6.5 cm and the weight is 3.5 kg.

The TR Switch

Figure 3 is a schematic of the TR switch. During reception, a small bias current of about 2 mA maintains in conduction the four diodes in series with each of the balanced antenna leads. During transmission, the high voltages on the antenna cause one of the diode pairs in each lead to become non-conducting. For example, if the upper antenna terminal goes negative, diodes D3 and D4 are cut off while if it goes positive, diodes D1 and D2 are cut off.

Charge-storage effects in the input diodes can cause a large leakage of energy into the receiver unless special precautions are taken. For instance, when D1 and D2 are turned off, their stored charge is driven out and will pass through D3 and D4 into the receiver unless absorbed elsewhere. The capacitor C connected to the junction of the 1 kilohm and 5.6 kilohm resistors accumulates a negative charge by rectification of the RF signal by D1 and D2. This keeps D3 and D4 cut off during the whole RF cycle. Now, when the stored charge is driven out of D1 and D2 during the positive half-cycle of the input voltage, it passes through D5 and D6 to C and thence to ground instead of into the receiver.

A further reduction of the leakage into the receiver is obtained by clamping the preamplifier inputs to ground with a pulse that starts slightly before the transmitted pulse and ends slightly after. Full sensitivity of the receiver is restored in about 250 μsec.

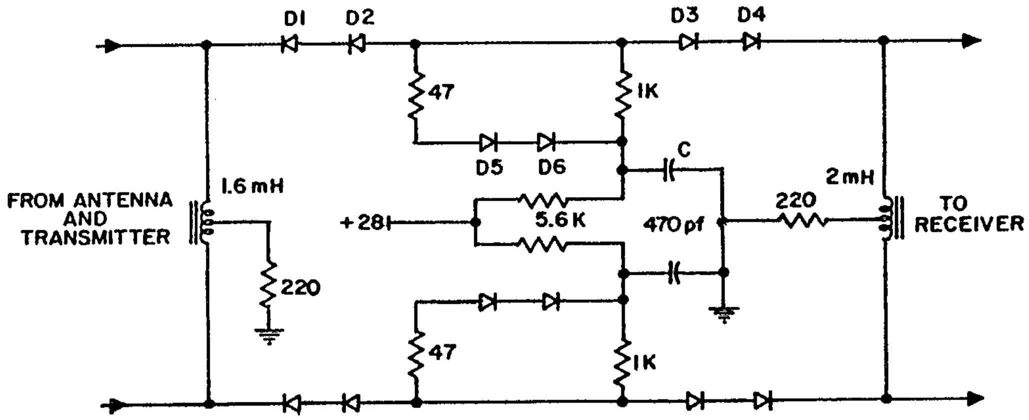

Fig. 3. Solid-State TR Switch.

The diodes in series with the signal path (D1 - D4) are diffused silicon types. They are packaged in pairs having a combined breakdown voltage of 1.2 kilovolts.

The Receiver

A major aim in the design of the receiver was to achieve a large dynamic range and minimize intermodulation between strong transmissions from the ground. To this end, the gain before the first IF filter was made as low as possible, consistent with a satisfactory noise figure, and switched band-pass filters were included in the preamplifier. The first gain-controlled stage is placed ahead of the mixer as a further precaution against intermodulation occurring in the mixer.

The preamplifier, Figure 4, has two cascaded stages with the selectivity being provided in the first stage. Either one or two alternative first stages can be selected by command from the ground. The prime system uses three switchable amplifier-filter modules covering the bands 0.1 - 2 MHz, 2 - 7 MHz and 7 - 14 MHz. The secondary system, intended for use if the switching mechanism fails, consists of a single amplifier-filter module tuned to 1.5 - 11.5 MHz.

Each module consists of a push-pull grounded-base amplifier which is transformer-coupled to a band-pass filter. The four outputs are connected to a summing node which is the emitter of the preamplifier second stage. The three modules comprising the prime system are switched electronically by controlling the voltage applied to the emitter bias resistors. In Figure 4, for example, a negative bias turns on the transistors (Q1) and the diodes in series with the signal path (D1). The shunt (D2) are turned off. When the bias is positive, on the other hand, D2 conducts and D1 and Q1 are turned off. This type of switch is capable of a very large attenuation when switched off since the leakage through the capacitance of D1 is shunted to ground by D2.

In practice, the tuned preamplifier has significantly improved the dynamic range. Intermodulation occurs chiefly in the stages between the band-pass filters and the IF filter and these are protected from out-of-band signals. Two large signals applied simultaneously must each be about 63 db above the threshold sensitivity of the receiver to cause perceptible intermodulation products when they are within the pass-band of the filter, while they must exceed 79 db if they are outside.

In Figure 5 is a sequence of recordings of the receiver AGC voltage as the satellite made a north-to-south pass over Western Europe in December 1965. In the top recording, the ionospheric penetration frequency is very low and the AGC is at full scale for most of the time between 1 and 14 MHz. As the

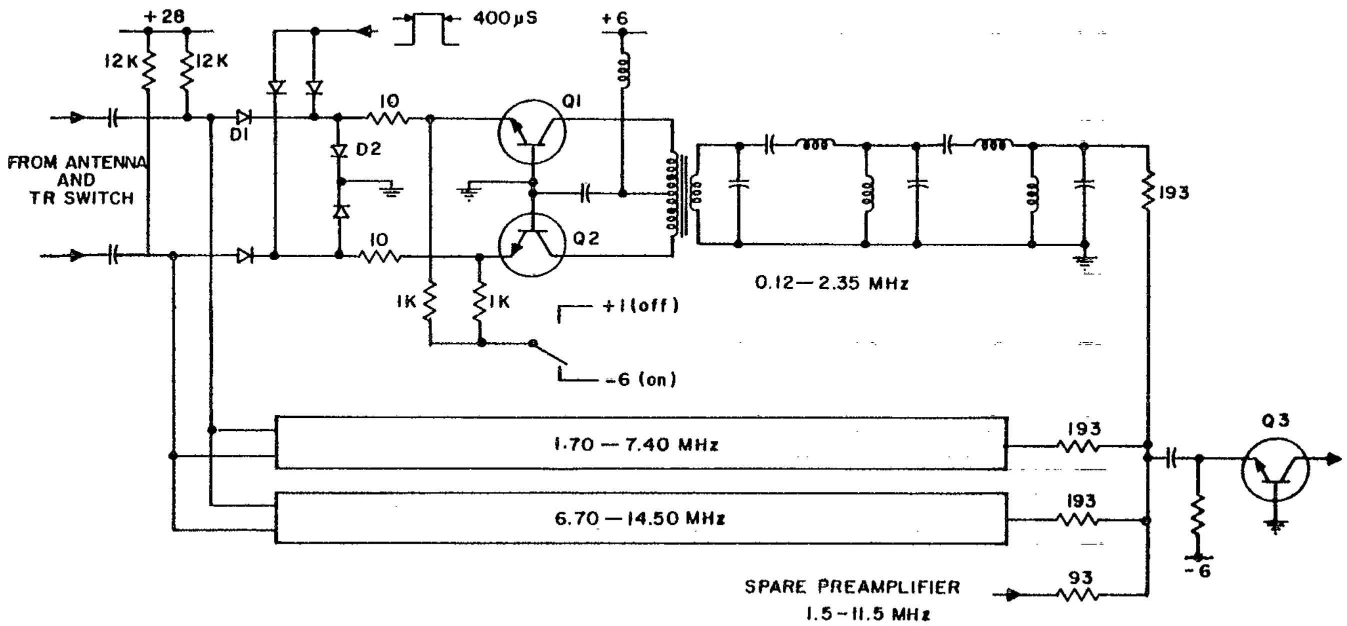

Fig. 4. Sounder Receiver Preamplifier.

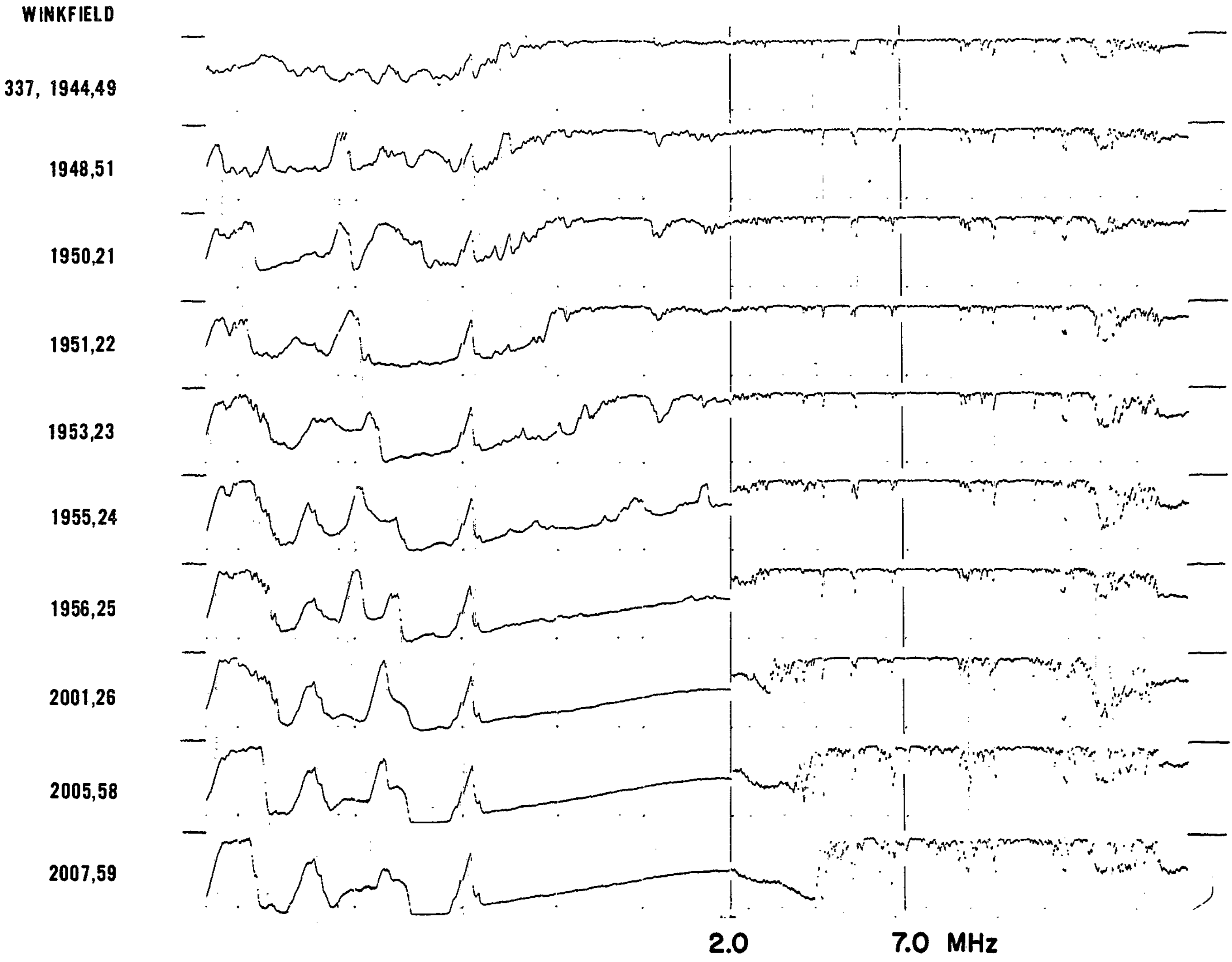

Fig. 5. AGC Records.

satellite moves south the penetration frequency rises until, in the bottom recording, the AGC voltage is characteristic of the natural cosmic noise background between about 1 and 4.5 MHz. In the 6th, 7th, 8th, and 9th records, one can see a distinct step in the AGC voltage as the preamplifier is switched at 2 MHz. This represents the amount of spurious energy generated at this frequency as intermodulation products of signals above 2 MHz which were previously excluded by the band-pass filter.

Figure 6 shows the remainder of the receiver. In the first mixer the signals are converted to 19 MHz and passed through a crystal filter with a bandwidth of 120 kHz. The good skirt selectivity of this filter, and the use of a carefully balanced diode ring mixer, allow the local oscillator to sweep within about 100 kHz of the IF without desensitizing the receiver. After some amplification at 19 MHz the signals are converted to 500 kHz. An LC filter here sets the overall bandwidth of the receiver to 37 kHz. In the 500 kHz amplifiers the amplitude response is controlled by limiting diodes to produce an output which is a linear function of the input for the first half of the output voltage range and approximately logarithmic for larger outputs.

Envelope detectors following the 500 kHz stages provide the video output and an AGC voltage to control one stage ahead of the first mixer and the first 19 MHz stage. The time constant of the AGC is varied according to the sweep rate. Up to 2 MHz it has an attack time of 500 msec and a decay time of 110 msec to improve the performance with the long plasma resonances that occur in this range. Above 2 MHz these times are modified to 60 and 12 msec respectively. The post-detection bandwidth of the receiver is 12 kHz.

Interference reduction was a major preoccupation in the design of the receiver and in the integration of the whole spacecraft system. Potential sources of interference are the various oscillators in the sounder system, the harmonic generators in the sweep calibrator, the dc-dc converters, and the telemetry transmitters.

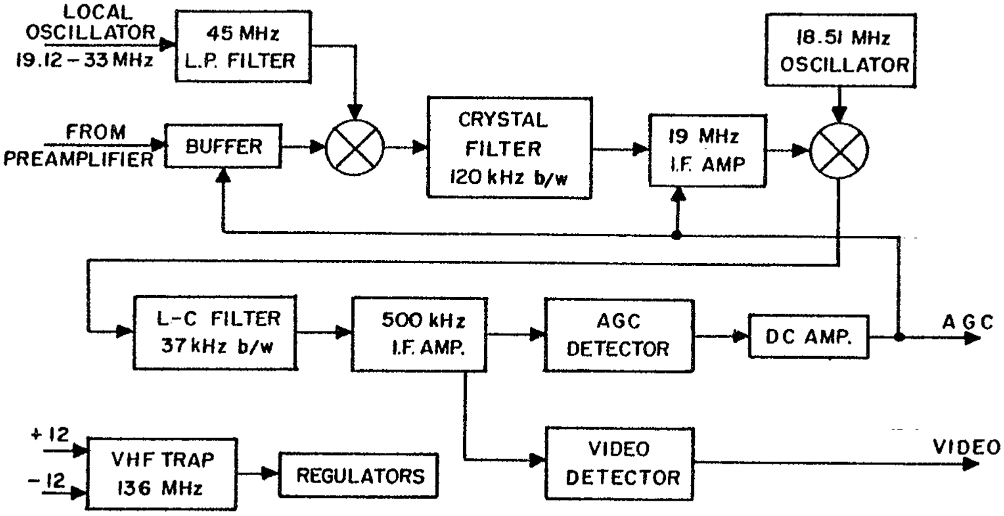

Fig. 6. Sounder Receiver.

The Swept-Frequency Generator

The sweep generator is a Miller integrator, Figure 7, with a variable current source providing the increase in rate above 2 MHz. The increase is initiated by a pulse from the sweep calibrator when this frequency is reached. At the high frequency end of the sweep, the output of the integrator is sensed and a current sink is switched on. This resets the integrator, a process which takes about 3½ seconds.

Because the lowest sounding frequency (0.12 MHz) is such a small fraction of the actual frequency of the oscillator (19.12 MHz), drift of the starting frequency with time could be a serious problem. To avoid this drift, the correct starting frequency is sensed during the flyback and the current sink is switched off at this point.

The swept oscillator is tuned with an inductor having a control winding to vary the permeability of the ferrite core. The control characteristic is somewhat non-linear but this has been partly corrected by a diode-resistor network. Extreme linearity of the sweep is not a requirement because of the automatic sweep calibration. The calibrator is designed to provide a distinctive pattern of markers, easy to identify on the ionogram and close enough to give the desired accuracy.

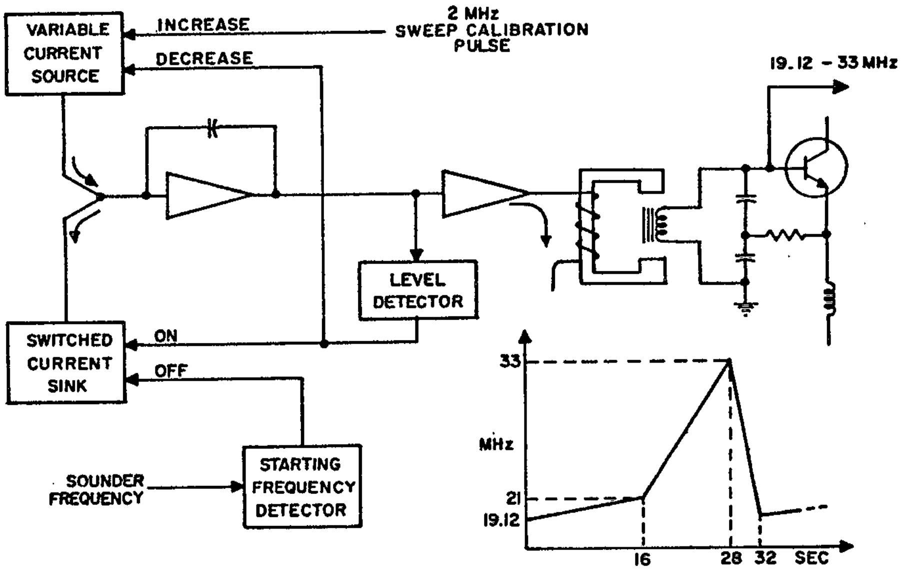

Fig. 7. Swept-Frequency Generator.

Telemetry

The video output from the sounder receiver is mixed with synchronizing pulses at the transmitter pulse rate and with pulses signalling the start of each sweep to form a composite similar to a television signal. This frequency-modulates a 136 MHz transmitter. The use of FM provides good low-frequency response but required the development of a crystal-controlled transmitter with good linearity over a deviation range of ± 50 kHz.

Data Presentation

The usual form of presentation is the ionogram, of which an example is shown in Figure 8. Echoes are displayed as a function of apparent range and frequency.

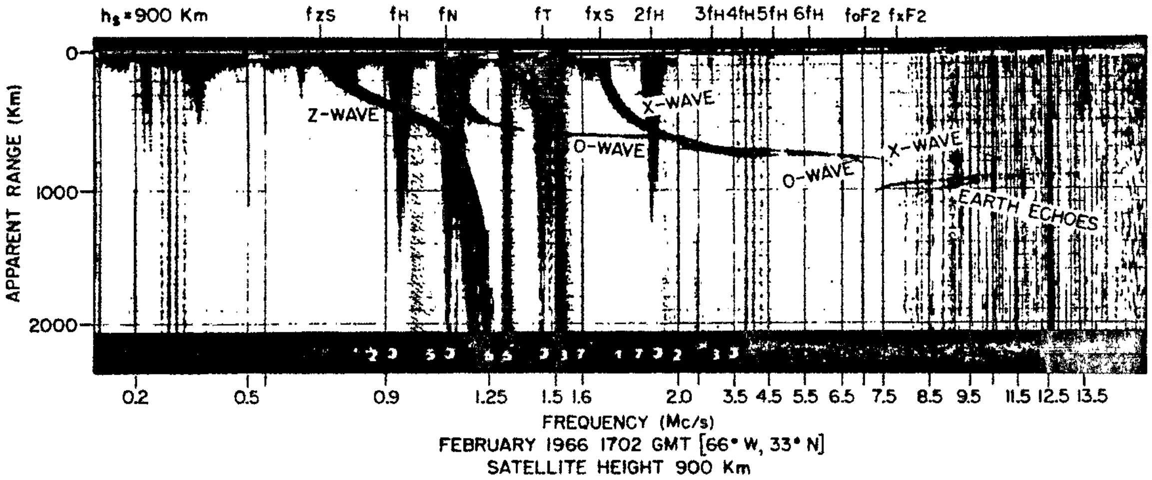

Fig. 8. Alouette II Ionogram.

Reliability

This spacecraft has operated without a single failure for over 16 months while its predecessor, Alouette I, is still providing data for 2½ hours per day after 4½ years in orbit. These results are attributed to an approach to design that emphasizes extremely large operating margins, to the use of extensive testing to uncover design weaknesses, and to the great care that was taken during assembly and inspection.

At the design stage, every effort was made to produce optimum circuit configurations in relation to expected modes of component failure or degradation. Systematic degradations, such as radiation effects on semiconductor components, were considered very carefully. Thus, the great majority of circuits were designed to tolerate transistors having current gains as low as 10 and leakage currents of several tens of microamperes. Much less reliance was placed on statistical reliability calculations than on the achievement of very wide operating margins based on a good physical understanding of device and circuit operation.

Circuits were designed to operate over the temperature range of -50° to $+75^\circ$C with supply voltages varied by ± 25%. On several occasions this testing uncovered weak design or faulty components. In a few cases some relaxation of these goals was allowed but only when the reason for failure to meet them was fully understood and carefully considered in relation to the operational requirements. The system test phase was used as an additional opportunity to verify the design and many changes were made quite late in the program to correct obvious weaknesses.

When appropriate, components were screened or burned-in before delivery to eliminate manufacturing defects. Despite these precautions, several components failed quite early during testing. It is felt that a fairly lengthy period of system testing was a significant factor contributing to the reliability of the spacecraft in orbit.

Acknowledgement

Alouette II was part of a cooperative space program between the United States and Canada. The Canadian Defence Research Telecommunications Establishment was responsible for the design and construction of the spacecraft and its instrumentation, and for the installation and operation of two ground stations. The National Aeronautics and Space Administration provided the launch vehicle, launch facilities, and a world-wide network of ground stations.

Reference

1. Franklin, C.A., Bibby, R.J., Sturrock, R.F., and D.F. Page. *Electronic and System Design of the Canadian Ionospheric Satellite.* IEEE International Convention Record, **Part V**, p 64, 1963.

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