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Technical Note

1970-3

**The Results of the LES-5 and LES-6
RFI Experiments**

W. W. Ward
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C. J. Zamites, Jr.

6 February 1970

Prepared under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

THE RESULTS OF THE LES-5 AND LES-6 RFI EXPERIMENTS

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LEXINGTON

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ABSTRACT

The RFI environment near synchronous orbital altitude in the band 255-280 MHz was measured by sub-synchronous Lincoln Experimental Satellite #5 (LES-5). Similar measurements covering the band 290-315 MHz have been made by station-kept LES-6. These experiments are a joint effort between the M.I.T. Lincoln Laboratory and the Aerospace Corporation.

Data from the RFI instruments (built by Aerospace) aboard the spacecraft are telemetered to Earth and subjected to several stages of processing before interpretation. Results obtained by computer and manual processing and a description of the equipment and calibration procedures are presented here. More than 250 valid RFI-measurement scans were collected from LES-5, covering a world-wide distribution of sub-satellite longitudes, before that experiment was interrupted eight months after launch by a circuit failure that repaired itself 16 months after launch. The LES-6 experiment has yielded a much greater volume of data, but limited to the geographic coverage from the station-kept position (near 90° west longitude).

Close quantitative correlations in frequency and average-power level between telemetry data from LES-5 and LES-6 and the nominal operating characteristics of several large transmitting stations in these segments of the military UHF band have been established. The outstanding signals come from the time-division-data-link (TDDL) sites in the air-defense system within the continental U. S. Many other signals have also been detected. Some portions of the bands scanned show little activity. The nominal sensitivity of the LES-5 RFI instrument (signal = noise) corresponds to Earth-surface transmitter EIRP of 50 to 100 w (RHCP) near 255 MHz. LES-5 sensitivity is 20 db poorer toward the high end of its band (280 MHz). The nominal sensitivity of the LES-6 RFI instrument corresponds to EIRP of 10 to 25 w (RHCP) across the band 290-315 MHz.

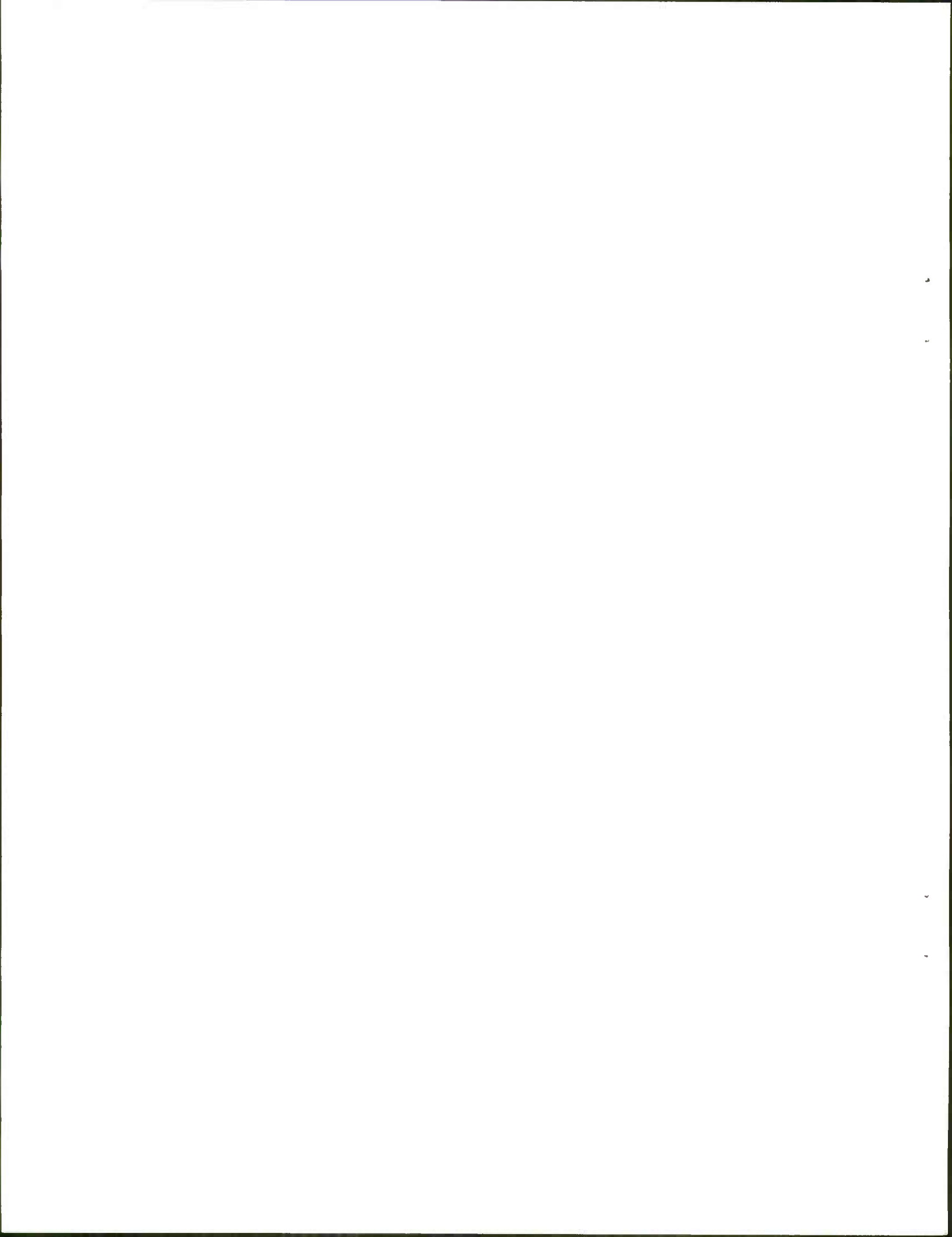
The success of the LES-5 and LES-6 RFI experiments shows that it is practical to monitor the level of activity in selected bands of the communication spectrum, throughout wide portions of the Earth, from synchronous orbit. This capability may be useful in the management of portions of the electromagnetic spectrum where frequency allocations are at a premium.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

"A certain young lady of Skye
Grew up most exceedingly shy.
When undressing at night,
She'd turn out the light
To escape the All-Seeing Eye."

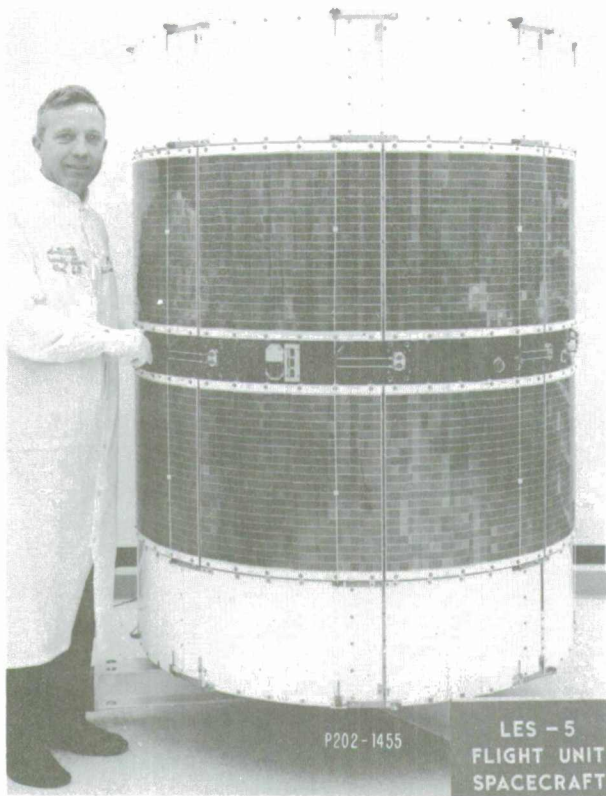
CONTENTS

Abstract	iii
Glossary of Acronyms and Abbreviations	vii
I. INTRODUCTION AND SUMMARY	1
II. DESCRIPTION OF THE RFI INSTRUMENT	5
III. DATA REDUCTION AND CALIBRATION	11
IV. BASELINE PERFORMANCE AND SINGULAR EFFECTS	13
V. NOMINAL SENSITIVITY AND ESTIMATION OF TERMINAL EIRP	19
VI. INTERPRETATION OF SOME SAMPLE DATA	20
VII. REGIONAL CHARACTERISTICS OF LES-5 RFI OBSERVATIONS	37
VIII. CONCLUSIONS	43
Acknowledgments	44
References	45



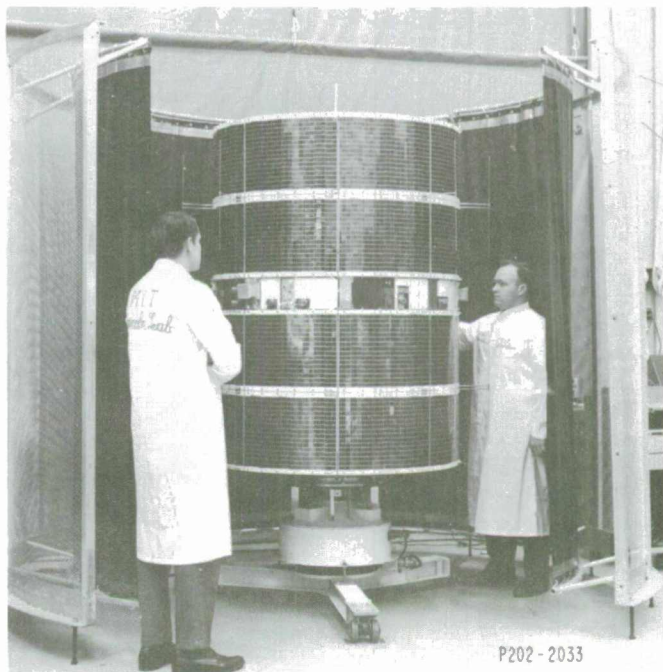
GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFS	Air Force Station
AGS	Automatic gain control
AI	Air Installation
ATS	Applications Technology Satellite (NASA)
CONUS	Continental United States (exclusive of Alaska)
dbI	Antenna gain in decibels with respect to a lossless isotropic radiator of specified polarization.
dbmw	Power level in decibels with respect to 1 milliwatt
ECAC	Electromagnetic Compatibility Analysis Center
EIRP	Effective isotropically radiated power
EST	Eastern Standard Time
GMT	Greenwich Mean Time
HF	High frequency
HPBW	Half-power beam width
IF	Intermediate frequency
LES	Lincoln Experimental Satellite
LHCP	Left-hand circularly polarized
LO	Local oscillator
LP	Linearly polarized
PIN	Semiconductor diode consisting of p+, intrinsic, and n+ regions
RF	Radio frequency
RFI	Radio-frequency interference
RHCP	Right-hand circularly polarized
TDDL	Time-division data link
UHF	Ultra-high frequency (225-400 MHz in military usage)
VCO	Voltage-controlled oscillator
VHF	Very-high frequency (includes lower end of military UHF band)



Lincoln Experimental Satellite -5 (LES-5)
launched 1 July 1967.

Lincoln Experimental Satellite -6 (LES-6)
launched 26 September 1968.



I. INTRODUCTION AND SUMMARY

The idea of making a survey of the electromagnetic (RFI) environment from an orbiting satellite (broadgathering) is so natural that it must have originated long before the first satellite was launched. Although little has been published on such matters, it is plausible to imagine that reconnaissance satellites, equipped with ferret receivers, have been carrying out specialized RFI-measurement experiments for some time.¹ The first attempt to survey the spectrum from 150 to 1000 MHz with a bank of 50-MHz-wide crystal-video receivers² was negated by launch failure. A second attempt was made as one of the experiments on the OV 1-18 spacecraft, launched into a nominal 350 nm x 250 nm polar orbit (99° inclination) on 17 March 1969. Failure of the satellite stabilization system and loss of prime power to the equipment have prevented any useful data collection from this experiment. The British satellite Ariel III [launched in a nearly circular polar orbit (80° inclination) at ~550-km altitude on 5 May 1967] carries a special receiver to make measurements of radio noise at 5, 10, and 15 MHz.^{3,4} A recently published report^{5,6} by Convair Division of General Dynamics outlines how an Orbiting Spectrum-Measurement Experiment at an altitude of 200 nm might be accommodated within NASA's Apollo Applications Program. RFI-measurement experiments directed to the problems of commercial satellite communication are under consideration for NASA's Applications Technology Satellites ATS-F and G.⁷

The importance of the synchronous corridor for space-borne communication systems and other activities has led to predictions and speculations about the electromagnetic environment there. Granted that the environment cannot be expected to remain static, there is virtue to actually measuring it at some given time. As Lord Kelvin said,

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind..."

The planned situation of Lincoln Experimental Satellite #5 (LES-5) in orbit was an appealing one for making an RFI-environment survey. The toroidal LES-5 antenna system sees a large fraction of the surface of the Earth at any given time.

(Fig. 1). The sub-synchronous LES-5 orbit altitude would cause the satellite to drift eastward, so the whole Earth (exclusive of the polar regions) could be scanned in eleven days. LES-6 was planned to be station-kept in longitude, so it did not afford a global-survey capability. However, it offered an opportunity to scan a different portion of the spectrum, with the greater sensitivity provided by the larger receiving cross-section of its electronically despun antenna beam. (Fig. 2). LES-5 was successfully inserted into a nearly circular, almost equatorial, quasi-synchronous orbit on 1 July 1967. LES-6 was successfully inserted into a nearly circular, almost equatorial, synchronous orbit on 26 September 1968 and was "anchored" near 90° west longitude (Fig. 3).

The primary purpose of LES-5 and LES-6 was to provide in orbit communications transponders in the military UHF band.⁸ As adjuncts to the comparatively narrow-band transponder receivers, wide-band, swept-frequency receivers (called RFI instruments) were designed and built for LES-5 and LES-6 by the Laboratories Division of the Aerospace Corporation. The LES-5 instrument covers the band 255-280 MHz. The LES-6 instrument covers the band 290-315 MHz. In these experiments, data from the RFI instruments are telemetered to Earth and subjected to several stages of processing before interpretation. This paper describes the equipment and the calibration procedures and presents results obtained by computer and manual processing of the output data.

Data from both RFI instruments are perturbed at times by the effects of troubles elsewhere in the spacecraft. It has proved possible to acquire an ample data base despite these difficulties. The LES-5 instrument will cease to function when the on-board timer shuts down the entire satellite (on 1 April 1972 \pm 15 days). LES-6 does not carry a timer, so that instrument should function for a long time, subject to proper operation of other spacecraft sub-systems.

It has been found possible to establish close quantitative correlations in frequency and average-power level between the data telemetered from the LES-5 and LES-6 RFI instruments in orbit and the nominal operating characteristics of several large transmitting stations that radiate in these segments of the military UHF band and are located within the continental U. S. (CONUS). Many other signals have been detected. The LES-5 and LES-6 RFI experiments are not quite the All-Seeing Eye of the well-known limerick, but they have brought forward some hard facts of observation regarding the electromagnetic environment near synchronous orbital altitude in the military UHF band.

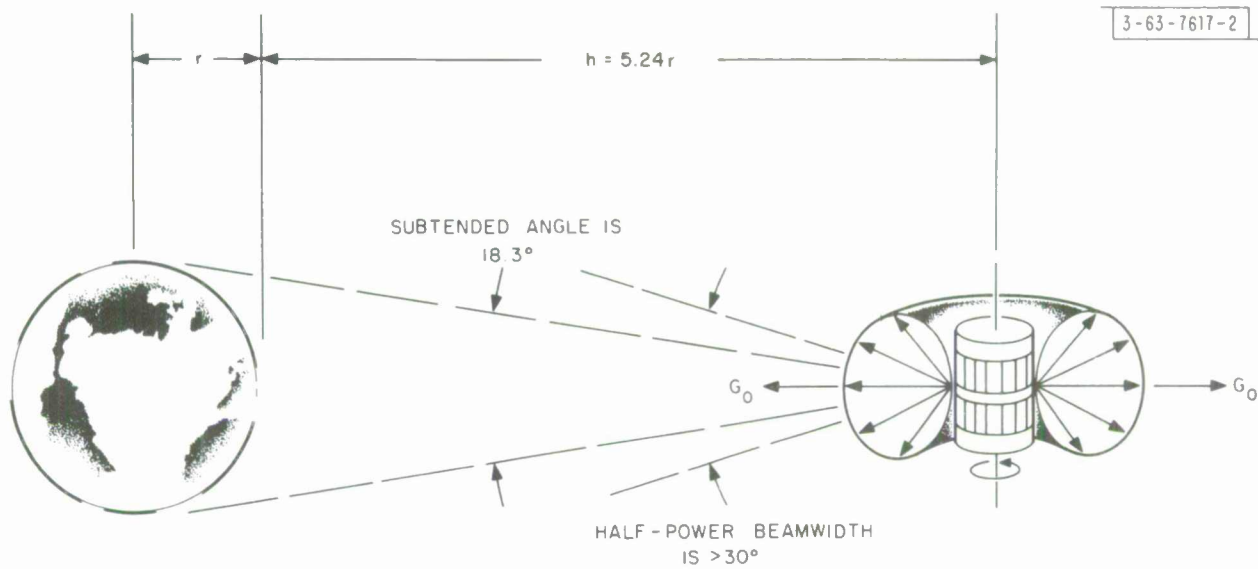


Fig. 1. Illumination of the Earth by the LES-5 antenna pattern.

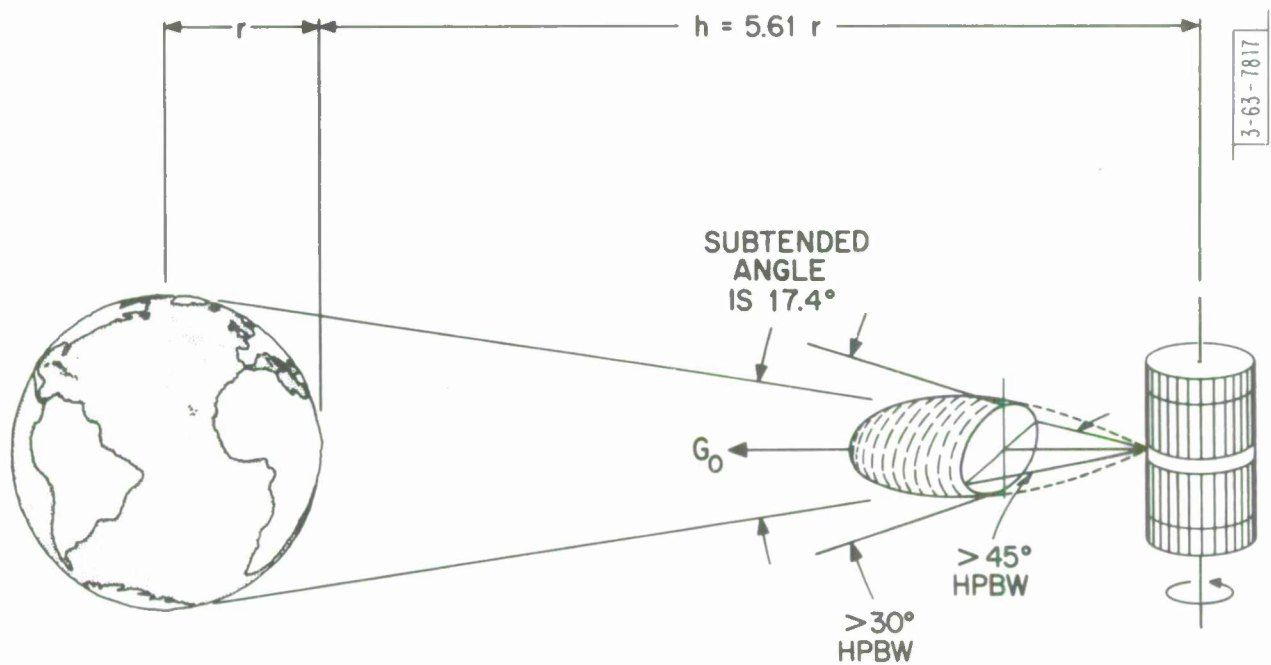


Fig. 2. Illumination of the Earth by the LES-6 antenna pattern.

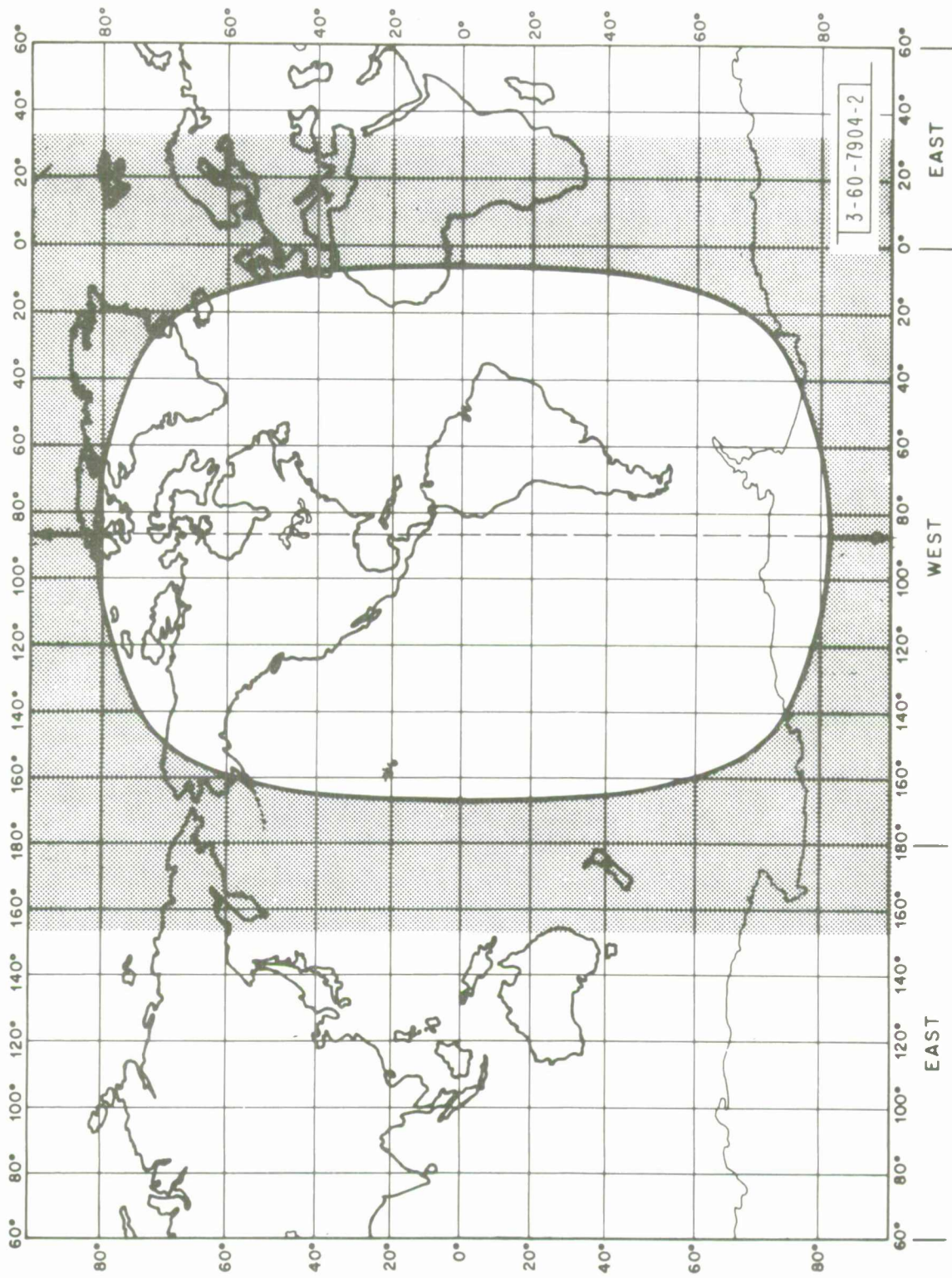


Fig. 3. 0°-elevation-angle contour for LES-6 at 90° west longitude.

II. DESCRIPTION OF THE RFI INSTRUMENT

A. General

The RFI instrument shares the spacecraft antenna,^{9,10,11} triplexer,^{12,13} and first RF amplifier with the communications transponder (Fig. 4). The local-oscillator and intermediate-frequency-amplifier frequencies of the RFI receiver were selected after a computer study of all spurious-frequency intermodulation products that might be formed on board the spacecraft. A modified version of the LES-5 RFI instrument (which is described below) was fabricated for LES-6.

The LES-5 RFI instrument is a double-conversion, swept-superheterodyne receiver. The receiver is designed to tune from 283 MHz to 253 MHz in 256 steps of approximately 120 kHz each, dwelling at each step for 2.56 sec. The time for a complete frequency scan is approximately 11 minutes. Fixed-frequency operation is available upon programmed control from the spacecraft timing system. In the fixed-frequency modes, the RFI instrument functions as a command receiver for the spacecraft.

With a system noise figure of 3 db (at 255 MHz) determined by the external preamplifier (first RF amplifier) and a receiver noise bandwidth of 120 kHz, the nominal receiver sensitivity is -120 dbmw. The receiver will measure the average RF power within its 120-kHz bandwidth with a dynamic range of 60 db. It will measure the peak (pulse) RF power with a dynamic range of 60 db above the average RF power level, but not exceeding 0 dbmw at the receiver input. Internally generated crystal-marker signals have been included for in-flight calibration of both frequency and amplitude characteristics. The RFI instrument is housed in a box 4 x 8 x 5 inches high. It weighs 3.3 lbs. and consumes less than 1 watt of DC power.

B. Circuit Description

The input signal to the RFI instrument is first band-pass filtered to attenuate out-of-band signals. The preselector filter and the crystal-marker filter are three-pole, 0.1 -db-ripple Chebycheff filters with 0.5 -db passbands from 250 MHz to 285 MHz. Following the preselector filter, the signal is combined with the crystal-marker spectrum in a 3 -db hybrid coupler.

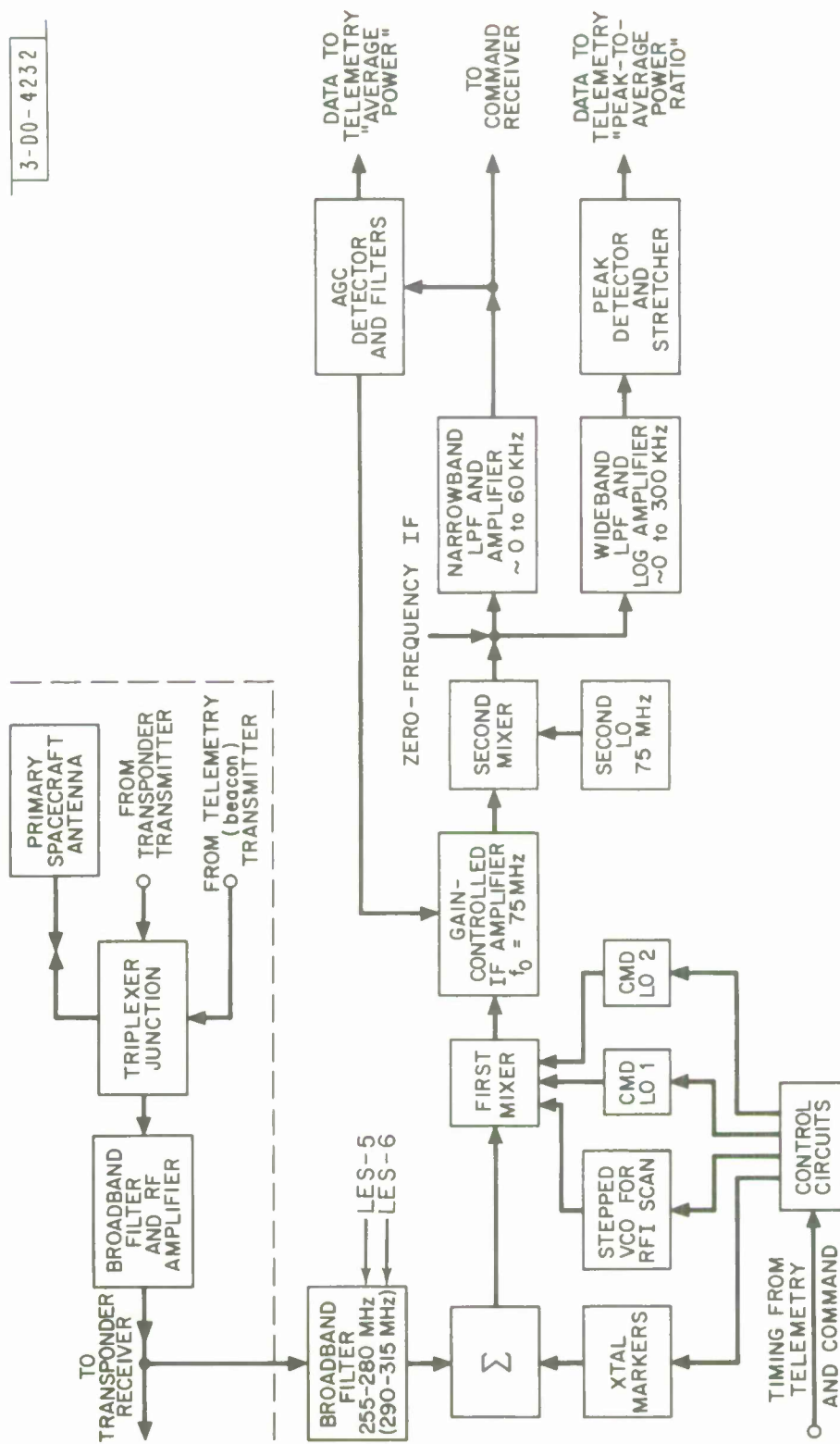


Fig. 4. RFI instrument LES-5, -6.

The crystal markers are used for frequency and amplitude calibration of the receiver. The markers are programmed to appear during every fourth sweep of the receiver (Fig. 5). The marker spectrum and the approximate equivalent input power levels are shown in Fig. 6. During each marker-mode interval, the receiver scans from approximately 283 MHz to 253 MHz, displaying six or seven principal triplets of markers (depending on temperature) and several low-level subordinates. RFI data taken during the marker-mode intervals must generally be discarded because of possible confusion between markers and received signals.

The signal plus markers are combined with the first local oscillator in the first mixer to form a 75-MHz difference frequency. During alternate 11-minute periods, the first local oscillator is alternately the swept voltage-controlled oscillator (VCO) or one of two crystal command-frequency oscillators. The frequency of the VCO is stepped from 358 MHz to 328 MHz by an analog staircase voltage. The staircase voltage is generated by an eight-bit shift register and a digital-to-analog converter in the LES-5 command-logic unit. The staircase voltage is shaped in the translator to compensate for the non-linearity in the varicap-controlled oscillator.

The gain of the 75-MHz first IF amplifier is controlled by means of PIN-diode attenuators. The automatic gain control (AGC) voltage, derived from the second-IF output, controls the first-IF gain to maintain the second-IF output signal (or noise) at 1.4 v rms. The output power from the gain-controlled first IF amplifier is approximately -88 dbmw.

The second-local-oscillator frequency is 75 MHz, the same as the center frequency of the first IF amplifier. This design choice results in a zero-frequency second IF*. The bandpass of the second IF amplifier is 50 Hz to 60 kHz. Since there is no image rejection at the second mixer, the spectrum is folded, and the RF bandwidth is 120 kHz with a 100-Hz hole in the center. For power measurements, the spectrum folding and the small hole in the center of the passband are not considered to be detrimental. The output signal from the second IF amplifier is detected and low-pass-filtered to develop the receiver AGC voltage. ** The AGC voltage is a measure of the average RF signal level at the input to the receiver in the 120-kHz passband. The AGC response is logarithmic.

* It is interesting that the designers of the HF receivers^{3,14} on Ariel III also selected zero-frequency IF's, using the homodyne configuration.

** The AGC transient is over within a few tenths of a second.

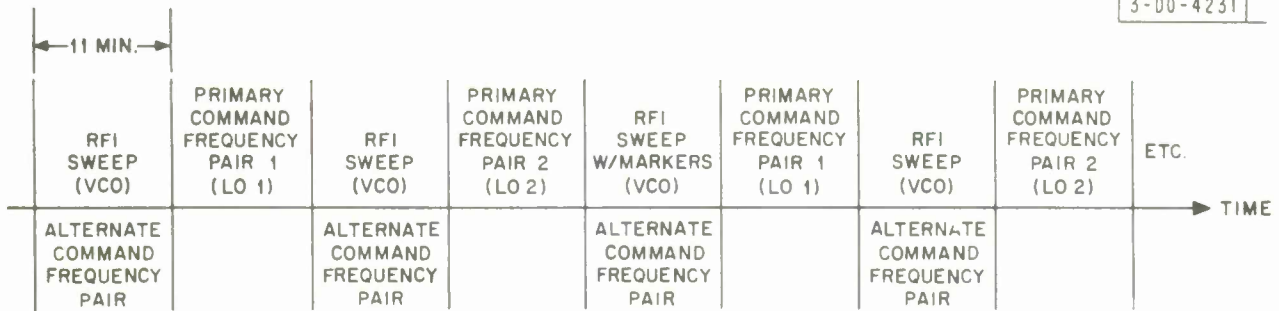


Fig. 5. RFI instrument and command-system timing sequence, LES-5, -6.

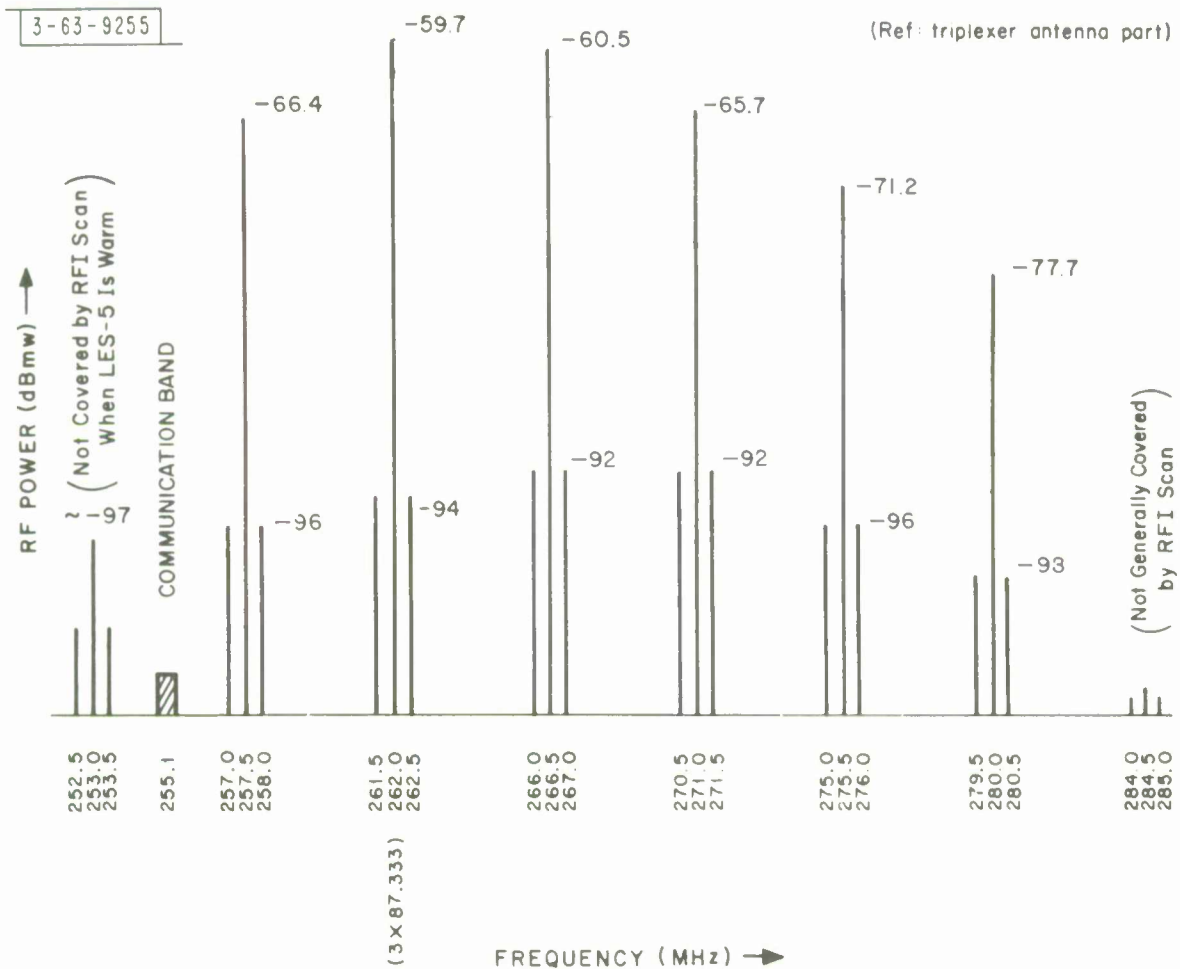


Fig. 6. LES-5 crystal markers.

Another output from the second mixer is filtered by a 300-kHz low-pass filter and then amplified in a logarithmic amplifier. The amplifier has a dynamic range of 60 db. The log output is peak-detected and pulse-stretched. Since the AGC action takes place ahead of the second mixer, the log output to the telemetry system is a measure of the ratio of peak RF power in a 600-kHz bandwidth to average RF power in a 120-kHz bandwidth.

C. Principal Data Outputs

The principal data outputs from the RFI instrument are the average-power and the peak-to-average-power-ratio measurements.

- 1) "Average power" is the measured average power (derived from the AGC voltage) in a ~ 120 -kHz-wide window centered on the frequency step occupied by the RFI instrument at any given time. The power levels (in units dbmw) are referred to the antenna port of the triplexer (which is also the reference plane for antenna gain).
- 2) "Peak-to-average power ratio" is the ratio of (1) the peak power* in the ~ 600 -kHz-wide frequency window centered on the particular frequency step occupied by the RFI instrument at any given time to (2) the average power in the corresponding ~ 120 -kHz-wide window [see paragraph (1) above.] This power ratio (always ≥ 1 , measured in $\text{db} \geq 0$) has the following qualitative interpretation:
 - (i) Low db (down to 0) -- implies a strong CW signal lying in both narrow and wide frequency windows.
 - (ii) Intermediate db (about 15) -- implies noise in both frequency windows.
 - (iii) High db (perhaps 40 or more) -- implies a peak signal power in the "peak" channel that is much larger than the average power in the "average" channel. This larger signal might be a strong pulsed signal, or (more often) a strong CW signal lying within the wide frequency window but outside the narrow one. In either case, the peak strength of the strong signal (in dbmw) is the sum of the "peak" reading (in db) and the "average" reading (in dbmw).

*Not the instantaneous peak power but rather the peak value of the short-term average power (averaged over a few complete cycles).

Up to the present, little effort has been devoted to reduction of the output of the "peak" data channel. It is therefore labeled "questionable" throughout the data plots. Even in this form, it has considerable usefulness for qualitative identification of possible signals seen in the "average" data plots (for example, the characteristic M-shaped signature as the RFI instrument scans past a strong CW signal).

III. DATA REDUCTION AND CALIBRATION

Figure 7 gives an overview of information flow within the entire LES-5 RFI experiment. The information-flow diagram for the LES-6 experiment is similar. The transfer characteristics of both the RFI instrument and the telemetry system were measured separately and in combination before launch. The combined characteristics can be measured in orbit by sending suitable transmissions from a ground station of known EIRP. That is, these transmissions span the RFI-scan band and present known power-flux densities at the spacecraft. In the case of LES-6, signals radiated from Lexington at known (± 0.5 db) RHCP EIRP and frequency (within a few Hz) were received by the RFI instrument and telemetered to the ground for subsequent data-processing. The processed results indicate an over-all uncertainty of ± 1.5 db in power level and ± 100 kHz in frequency for the complete system.

The data in final form will be most useful if they are independent of the characteristics of LES-5 or LES-6, however. A desirable reference format for presentation of the data is the power received by a lossless isotropic RHCP antenna system at the satellite's position in space.

It has been assumed that the calibration process can be separated into two distinct factors; counts-to-raw-power at a given frequency (in the vicinity of the transponder up-link signal band), and raw-power-to-equalized-power across the RFI-scan band.

The computer-processed output of the RFI instrument gives an approximate measurement of the total average power found in each ~ 120 -kHz-wide frequency window during the time interval (~ 2.5 sec) spent at each step of the spectrum-analysis sweep. If the signal power received is large compared to receiver noise, the data are effectively representative of signal power only. If the received signal power is not large by comparison with receiver noise, a compensating correction must be made to extract the true value from the data.

The ~ 2.5 -sec integration time of the RFI instrument for each of its scanned frequency windows can be counted on to average out the random fluctuations of receiver noise. The fact remains that the recovery of signal power from the measured signal-plus-noise power is less accurate at low signal-to-noise ratios than at high. Level-quantization noise in the telemetry system becomes predominant, and its effects on the recovered data become increasingly significant. The effects of the temperature sensitivity of the LES-5 telemetry system are also more pronounced at low signal-to-noise ratios.

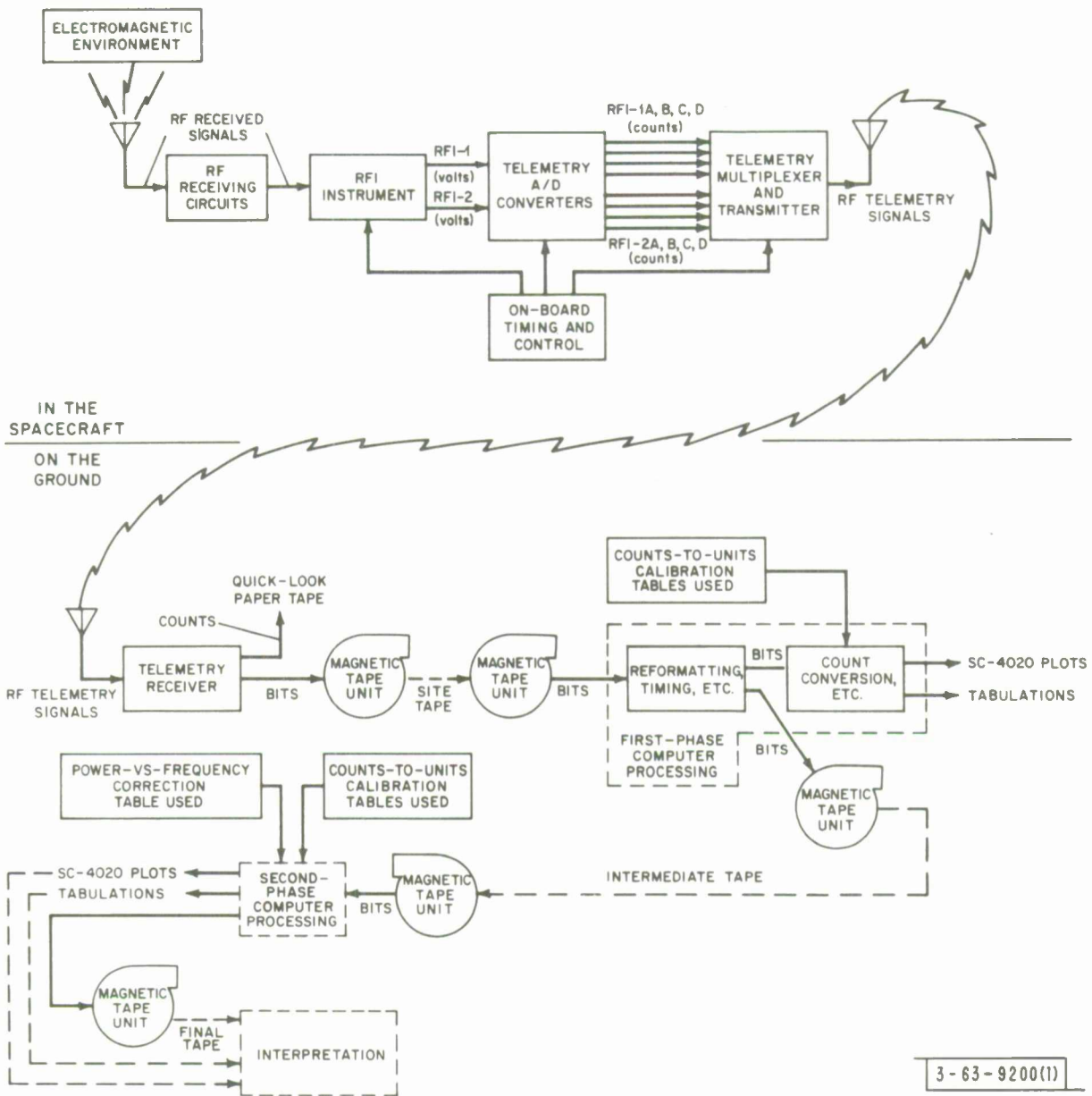


Fig. 7. Information flow in the LES-5 RFI experiment.

IV. BASELINE PERFORMANCE AND SINGULAR EFFECTS

A. Pre-Launch Testing

The baseline performance of the RFI instruments was established during pre-launch system testing at Lexington and at Cape Kennedy. After the satellites were inserted into orbit, there were always some received signals in view. Such signals are detected by their departures from the pre-launch baseline.

Figure 8 shows the performance of the LES-5 RFI instrument during electrical checks of the complete spacecraft at Cape Kennedy.* This particular frequency scan was taken in the small hours of 3 June 1967 (Saturday). It is the "quietest" such plot yet discovered. There are a few little wiggles in the average-power curve, corresponding to quantizing noise and to actual signals received by LES-5 through its antenna system, inside the Salisbury-screen shielding enclosure. The broad ripples in the baseline noise level are caused by interactions between the triplexer and antenna system and the input circuitry of RF amplifier #1 in the transponder, which feeds signals to the RFI instrument (Fig. 4). The lowest points in Fig. 8 correspond to minimum noise, where the intrinsic noise figure of RF amplifier #1 governs. The upward departures from these points correspond to increased noise levels, where input-impedance mismatch degrades the effective noise figure of RF amplifier #1. These broad ripples can be correlated fairly well with the passband characteristics of the LES-5 triplexer and antenna system. The apparent rise in the baseline noise level with frequency is introduced by the calibration procedure, in which compensation is made for the decreasing effectiveness of the LES-5 antenna system at higher frequencies in the RFI-scan band.

The baseline performance of the LES-6 RFI instrument is similar.

B. Principal Singular Effects for LES-5

It was found after launch that the LES-5 RFI instrument stepped across its frequency range about twice as fast as it should. Experience has shown that this asynchronism, with the associated degradations of telemetry data, holds sway for about 17 hours of each 22-hour orbit (Fig. 9). The predictability with which the intervals of regular timing occur with respect to the orbit of LES-5 suggests that there is some on-board interaction between the command-logic unit on the one hand and the Earth and Sun sensors and their associated electronics on the other. Perhaps a train of extraneous pulses leaks into the VCO staircase generator during intervals

*The notations "Mark 4 Mod A" and "Mark 4 Mod B" on the LES-5 data plots tell which sets of calibration and correction tables were used in the computer data-processing.

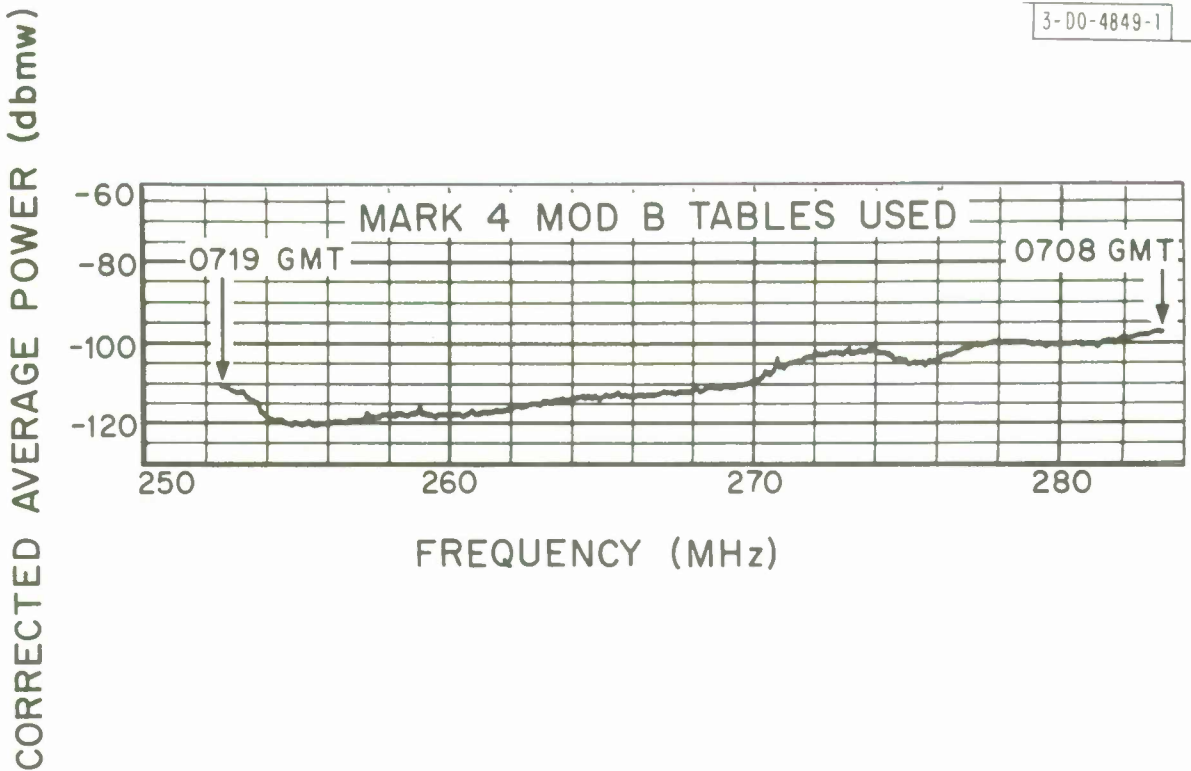


Fig. 8. LES-5 RFI scan, 3 June 1967. Baseline performance at Cape Kennedy before launch.

(Earth's polar axis is perpendicular to page)

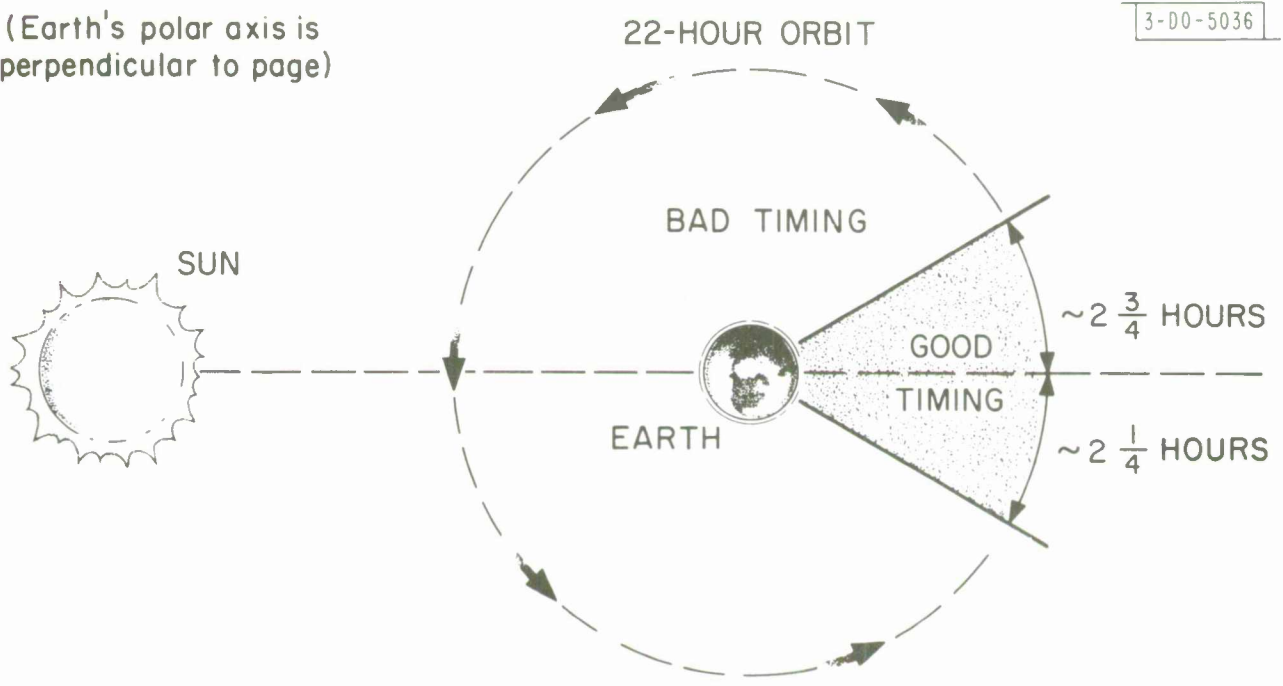


Fig. 9. LES-5 stepper timing.

of double-rate timing and, in combination with the proper pulse train, sends the stepper up the staircase faster than it should go. It can be seen by hindsight that the system testing of LES-5 before launch may not have been sufficiently extensive to uncover all such possible interactions.

There is a significant implication of this effect for the validity of LES-5 RFI data. We have limited our attention to single-rate data, for the double-rate data are incomplete and inaccurate. It is consequently not possible to examine for any particular section of the synchronous corridor the diurnal cycle of electromagnetic activity in the RFI-scan band. LES-5 stepper timing is good only in an ~5-hour-long interval roughly centered on the time when it is midnight along the sub-satellite meridian. The electromagnetic environment measured, therefore, is that of the late evening and early morning hours, rather than of daytime. Transmitting stations that operate only during daylight and early evening hours will generally not appear in LES-5 RFI data.

An intermittent circuit failure in the transponder drastically affects the effective sensitivity of the LES-5 RFI instrument. The sensitivity was reduced by 17 db (near 255 MHz) during the interval 18 March - 14 November 1968. There followed several months of full-sensitivity operation, another such degradation occurring some time between 3 and 13 March 1969. It is expected that this cycle of performance states, probably associated with the seasonal variation of sun angle and on-board temperatures, will recur during the useful life of the spacecraft.*

C. Special Characteristics of LES-6

The LES-5 antenna system generates a simple toroidal beam (Fig. 1) which has about ± 0.5 db equatorial ripple on 2.2 dbI (RHCP) gain (at 255 MHz). The LES-6 antenna system is more complex; it is useful to understand its operation in order to interpret the results of measurements made with the LES-6 RFI instrument.

LES-6 has an electronically despun (switched-beam) antenna system (Fig. 2). There are 16 beams formed in a plane normal to the spin axis of the satellite. These beams are directed radially outward, the peaks of the beams being $22\text{-}1/2^\circ$ apart. Only one beam is on at any given time. The individual beams have approximately 10 dbI of peak RHCP gain and half-power beam widths of 34° and 54° in the vertical and horizontal planes respectively. The beams and beam-switching (despinning) are shown in Fig. 10. The spacecraft spins at approximately 8.5 rpm, and each beam is on for approximately 0.44 seconds. During one RFI sample (2.56 seconds) approximately

*Note added in proof - It was noted on 2 December 1969 that the LES-5 transponder receiver had once again regained its full sensitivity.

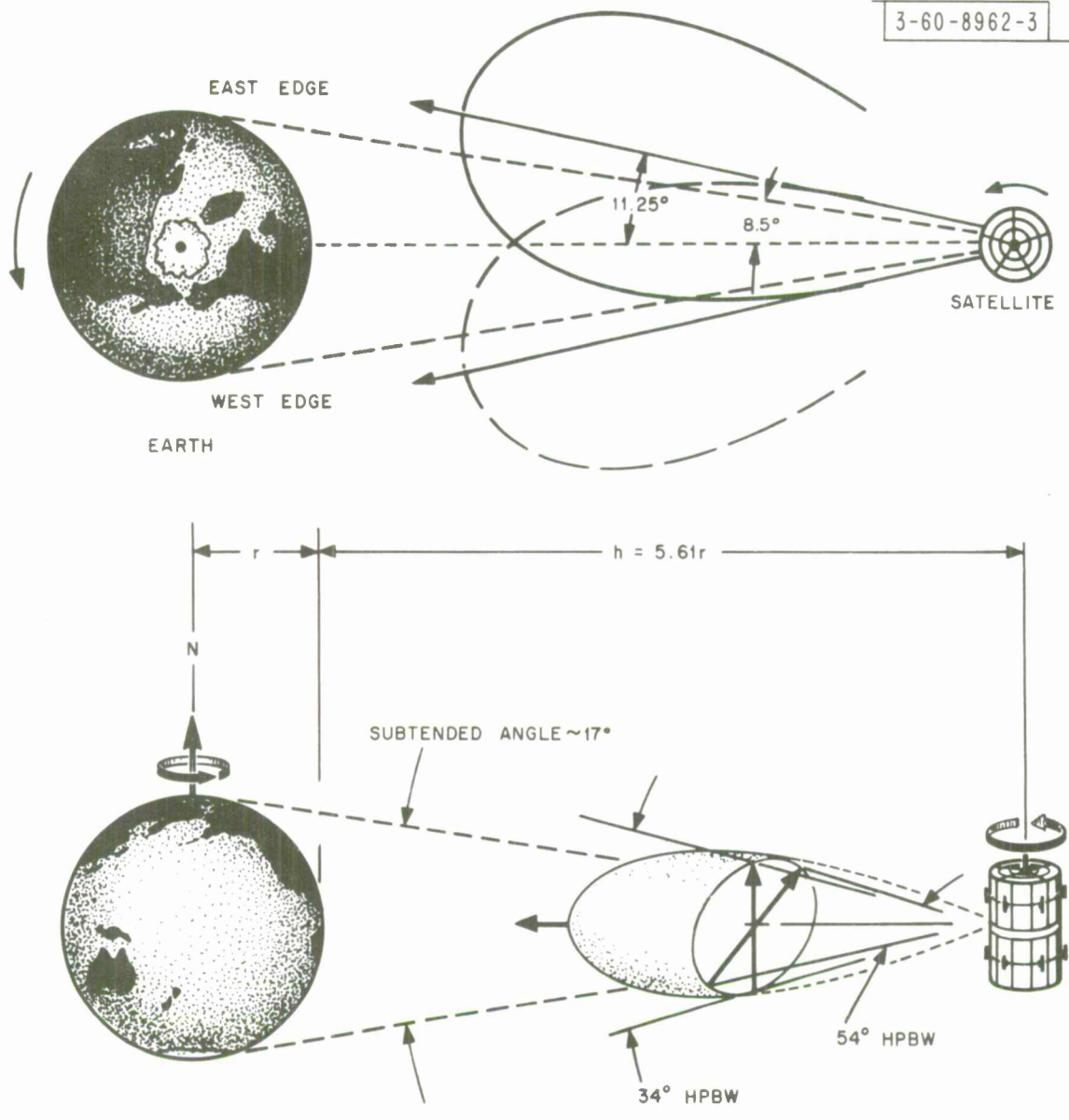


Fig. 10. LES-6 antenna-switching system.

5.8 beams are scanned. LES-6 will impose approximately 1 db (peak-to-peak) ripple on the signal received from a station on the plane formed by the earth's poles and the satellite-to-earth-center line and a 2 db ripple on the signals emanating from stations on the east and west edges of the viewing area. Gain variations from beam to beam at the peak are less than 1 db.

Each beam is RHCP with an axial ratio and gain optimized for the primary operating frequencies of the spacecraft transponder. The gain for each of the two receive linear polarizations varies independently over the RFI band, and the RHCP gain varies accordingly. Prelaunch measurements on the antenna system are plotted in Figs. 11 and 12. The median value of RHCP gain is incorporated in the second-stage data-reduction programs to reference RFI power levels to a lossless, isotropic, RHCP receiving antenna.

The LES-6 instrument is subject to corruption from time to time at the low end of the band due to on-board-generated interference. PIN-diode beam-switching transients produce high peak-to-average-power-ratio interference which corrupts the peak-to-average-power-ratio channel. The switching noise rolls off by approximately 10 db from the low to the high end of the RFI band. The duty ratio of the switching noise pulses is so small that they do not perturb the average-power channel. The average-power channel is also plagued from time to time by intermodulation products, developed between the LES-6 beacon and down-link communications signals, which fall in the RFI band. The intermodulation-product effects arise from nonlinear contacts on the cavity-backed slot antennas aboard LES-6.

The intermodulation-products in LES-6 appear to be much less severe in orbit than they were on the ground. LES-5 was also troubled by similar intermodulation effects, but RFI-scan data taken after a year in orbit show that they have gone away.

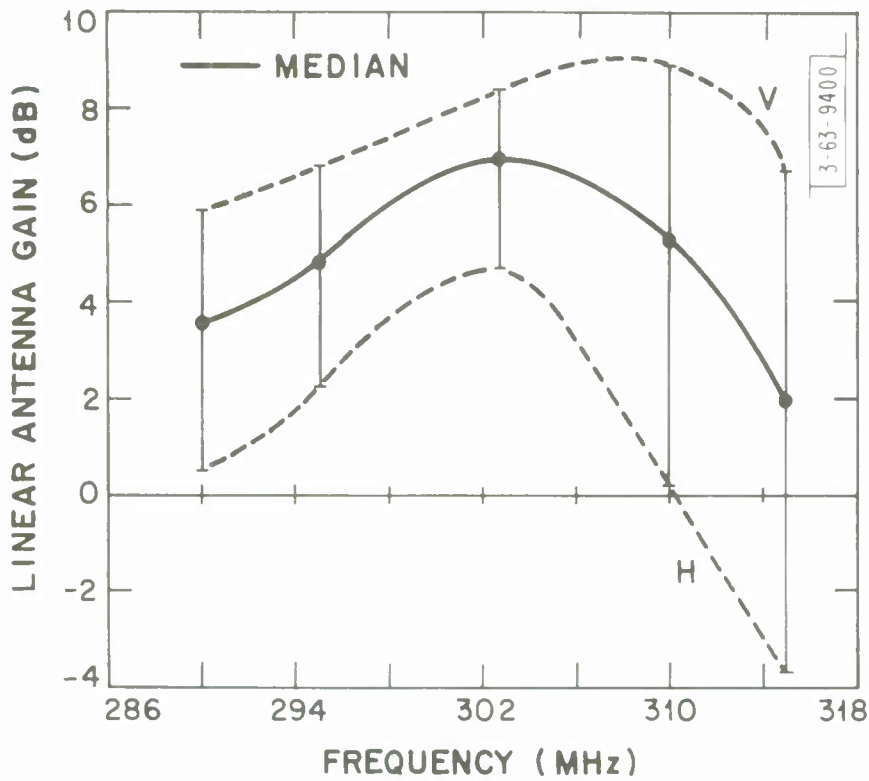


Fig. 11. LES-6 linear antenna gain vs frequency. (Ref.: Triplexer antenna port.)

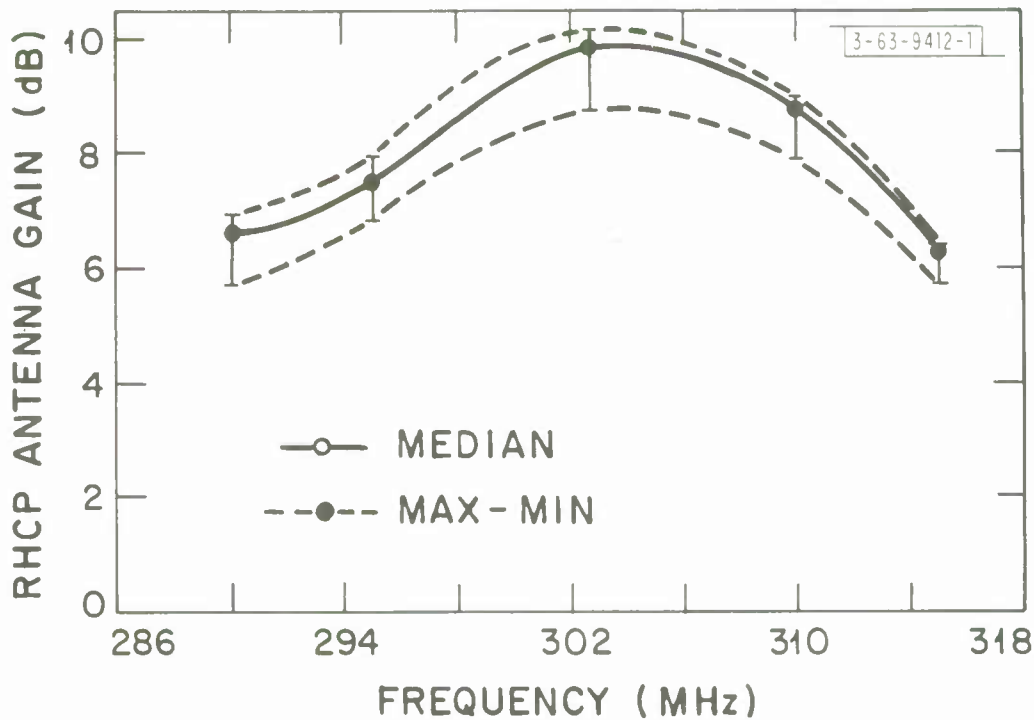


Fig. 12. LES-6 RHCP antenna gain vs frequency. (Ref.: Triplexer antenna port.)

V. NOMINAL SENSITIVITY AND ESTIMATION OF TERMINAL EIRP

As noted in Section II, the nominal average noise-power level for the RFI instrument near the transponder up-link frequency (255.1 MHz for LES-5, 302.7 MHz for LES-6) is -120 dbmw. Define the nominal sensitivity of the RFI instrument to be signal = noise. Then, knowing antenna gains and path losses, we can calculate the corresponding terminal EIRP on the surface of the Earth.

Characteristic	LES-5	LES-6
Received-signal level	-120 dbmw	-120 dbmw
Subtract nominal antenna gain	-2 dbI (RHCP)	-10 dbI (RHCP)
Add representative path loss	+172 db	+174 db

Terminal EIRP	+50 dbmw (RHCP) (100 w)	+44 dbmw (RHCP) (25 w)

In practice, signals can be detected in the RFI data at lower signal-to-noise ratios, so these terminal EIRP's are not limiting.

The gain of the LES-6 antenna system varies by a few db over its RFI-scan band (Fig. 12). The gain of the LES-5 antenna system falls off rapidly toward the high end of its RFI-scan band; RFI measurements are 20 db less sensitive at 280 MHz than at 255 MHz.

Note that these EIRP calculations are for RHCP transmitting stations. If a station is linearly polarized (LP), the RFI instrument will read it out 3 db low. If a station is LHCP, the RFI-instrument reading on it is very unreliable.

VI. INTERPRETATION OF SOME SAMPLE DATA

A. Overview

No attempt is made in this paper to supply a thorough commentary on the signals noted in the LES-5 and LES-6 RFI data. We present in this section a case history of plausible signal identification. A convincing association is made between the measured data telemetered from the LES-5 RFI instrument and what would be predicted for nominal operation of several large communication transmitters in CONUS. The gratifyingly close agreements in frequency and in average-power level between observed and predicted results give confidence that these RFI experiments are quantitative as well as qualitative successes.

The results of some further analysis of the LES-5 RFI data base are presented in Section VII.

B. TDDL's

The AN/FRT-49 time-division-data-link (TDDL) transmitters¹⁵ are significant benchmarks for the LES-5 and LES-6 RFI experiments. These communication stations in the CONUS air-defense system have high EIRP. The transmissions are narrow-band. We assume that each TDDL was operating at its nominal EIRP level when the observation was made. A more thorough investigation would include verification that a given station was indeed radiating at the time, together with measured data on transmitter output power and the antenna characteristics for the particular site concerned. People from Aerospace visited one TDDL site (Laguna Mountain Air Force Station).

$$\begin{aligned} P_{\text{TDDL}} &= 20 \text{ Kw} \rightarrow +73 \text{ dbmw} \\ G_{\text{TDDL}} &= \quad \quad + 6 \text{ dbI} \quad (\text{linear polarization, omni pattern}) \\ \hline (\text{EIRP})_{\text{LP}} &= +79 \text{ dbmw} \\ (\text{EIRP})_{\text{RHCP}} &= +76 \text{ dbmw} \end{aligned}$$

The average distance from LES-5 to a visible point on the surface of the Earth is approximately $R = 3.6 \times 10^7$ meter. The path loss near the middle of the LES-5 RFI-scan band is 172 db. The average power received at LES-5's position in space by a hypothetical lossless isotropic RHCP antenna is $+76 - 172 = -96$ dbmw. This level might vary as much as ± 1 db with frequency and distance. This uncertainty is a good deal

smaller than that introduced by the measurement accuracy of the RFI instrument, the data-reduction procedures used, and the other assumptions and approximations made in the course of this study. For example, the axial ratio of the LES-5 antenna system increases markedly toward the upper end of the RFI-scan band. The assumption of a constant 3 -db polarization-mismatch loss there is not exactly correct.

LES-5 and a given TDDL are mutually visible so long as their respective longitudes (sub-satellite* and geographical, respectively) do not differ by more than about 80° . This result is derived on a purely geometrical basis, without any consideration of atmospheric refraction or other effects that might extend (or shorten) the maximum longitude difference for mutual visibility. A list of TDDL stations at frequencies within the LES-5 and LES-6 RFI-scan bands (according to the file summary of 20 May 1968 from the Electromagnetic Compatibility Analysis Center [ECAC]) is given in Table I.

C. Specific Data

We present in this section data from 12 scans by the LES-5 RFI instrument. Eleven of them show signals that can be correlated with TDDL's. One does not. In their final form, the data represent the average power that would be received by a hypothetical lossless RHCP isotropic antenna at LES-5's position in space. We found in Section B above that the corresponding number for nominal TDDL operation (subject to several broad assumptions) was -96 dbmw. A sample calculation (for one of the signals in Fig. 13) shows -99.8 dbmw. This number is within 4 db of the nominal TDDL number.

Correlating this result with the TDDL listing in Table I, we find that the longitude difference between the sub-satellite point at the time of observation and the two stations at 261.6 MHz is approximately 70° . This is within the 80° geometrical limit. The two stations are comparatively close together, so there is no way to tell from LES-5 whether one, or the other, or both were operating.

Other significant signals seen and identified in Fig. 13 include that at 255 MHz (perhaps up-link working of the LES-5 transponder during the first few days after launch) and two more TDDL-identifiable ones at 276.7 and 278.6 MHz. Perhaps as many as 8 other signals can be seen in this RFI-measurement scan. They are 10 db or more below the TDDL signals. They have not been identified.

*Consider a straight line from the satellite to the center of the Earth. The intersection of this line with the Earth's surface determines a point lying "under" the satellite. The surface coordinates of this point are by definition the sub-satellite latitude and longitude.

Table I

AN/FRT-49 (TDDL) Ground-to-Air Transmitters Operating at Frequencies within the LES-5 and LES-6 RFI-Scan Bands (data from ECAC file summary dated 20 May 1968)

<u>Frequency (MHz)</u>	<u>City or Site</u>	<u>State</u>	<u>East Longitude</u>
254.4	Oakdale AI	Pa.	} 280 ⁰ ,
254.4	Vandenberg AFB	Calif.	
261.2	Makah AFS	Wash.	} 235 ⁰
261.4	Luke Range	Ariz.	
261.4	N. Truro AFS	Mass.	} 247 ⁰ ,
261.4	Montauk AFS	N. Y.	
261.4	Palermo AFS	N. J.	} 285 ⁰
261.6	N. Truro AFS	Mass.	
261.6	St. Albans AFS	Vt.	} to 290 ⁰
276.4	Calumet AFS	Mich.	
276.7	Bucks Harbor AFS	Me.	} 272 ⁰
278.6	Cape Charles AFS	Va.	
278.6	Ft. Fisher AFS	N. C.	} to
278.6	No. Charleston AFS	S. C.	
288.2	Luke Range	Ariz.	} 280 ⁰
288.2	Mt. Laguna AFS	Calif.	
288.2	Vandenberg AFB	Calif.	} to 247 ⁰
288.2	Makah AFS	Wash.	
293.3	Almaden AFS	Calif.	} 235 ⁰
293.3	Pt. Arena AFS	Calif.	
293.3	Klamath AFS	Calif.	} to 238 ⁰
293.3	N. Bend AFS	Oregon	
298.1	Montauk AFS	N. Y.	} 269 ⁰
298.1	Antigo AFS	Wis.	
298.1	Finland AFS	Minn.	} to 288 ⁰
298.5	Havre AFS	Mont.	
298.5	Fortuna AFS	N. Dak.	} 250 ⁰ to
299.0	Selfridge AFB	Mich.	
299.0	Lockport AFS	N. Y.	} 256 ⁰ to 277 ⁰ to 281 ⁰

FIG 13 3-4 JULY 1967 0833 LT 0833-0844 GMT 041 8908
 CORRECTED AVERAGE POWER (dbm) VS. FREQUENCY (MHz)

-67-8914-2

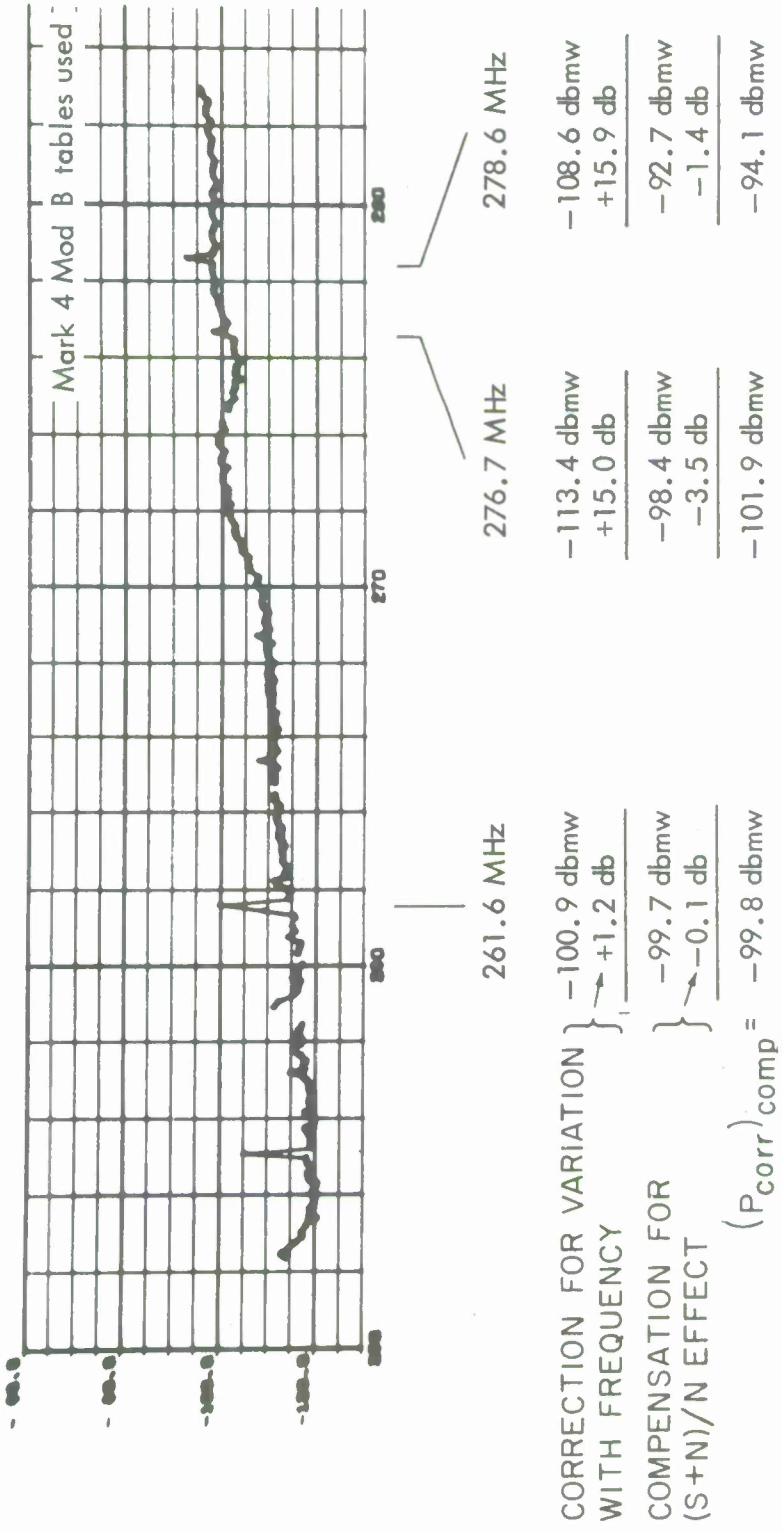


Fig. 13. LES-5 RFI scan, 4 July 1967, 0833-0844 GMT, ~357° east longitude.

There is much information in Figs. 13 through 23. It will be left to each reader to examine these Figures in the light of his own special interests. A few things are worth calling attention to, however:

- Figure 14 Why is there no detection of TDDL's at 276.4/276.7 MHz? The former (at 272° east longitude) was within view of LES-5.
- Figure 15 A strong signal at ~ 256.7 MHz. Who is it?
- Figure 16 A TDDL near 254.5 MHz is heard from.
- Figure 17 Two TDDL's near 261.3/261.6 MHz on and in view simultaneously.
- Figure 19 LES-5 was 19° west of the International Date Line, so that many TDDL's were not visible. There is marked activity - extending over several frequency bins - near 268.7 MHz.
- Figure 20 Why is the TDDL at 278.6 MHz received so poorly? Perhaps because the longitude difference is only 26° to 30°, so that the satellite is within a low-gain "cone of silence" extending above the omni antenna at each of these stations. The TDDL at 276.7 MHz is also received poorly. On the other hand, that at 261.4 MHz comes in loud and clear, perhaps because it is one of the ones in the western part of CONUS.
- Figure 23 The observed values of (presumed) TDDL signals do not always agree closely with the nominal number (-96 dbmw). For example, that at 261.1 MHz comes out -110.1 dbmw.

Figure 24 shows data from an RFI scan obtained when LES-5 was generally viewing the Europe-Africa-Asia land mass. The reduced data show (as would be expected) no signals corresponding to TDDL's. For interest, the corrected and compensated power measurements for the TDDL('s?) at 278.6 MHz are plotted in Fig. 25. The nine measurements obtained from this sub-set of the complete data file show a satisfying consistency. Averaging them in db, we get -100.1 dbmw. It will be recalled that the nominal TDDL performance number (based on several broad assumptions) was -96 dbmw.

D. LES-5 Evaluation

Data collected in orbit during the LES-5 RFI experiment show the expected distribution of TDDL transmitting stations in frequency. There is rough correlation of signal observation with mutual visibility of the satellite and the various stations. The agreement between nominal and measured power levels is surprisingly close, considering the coarseness of the assumptions that were made.

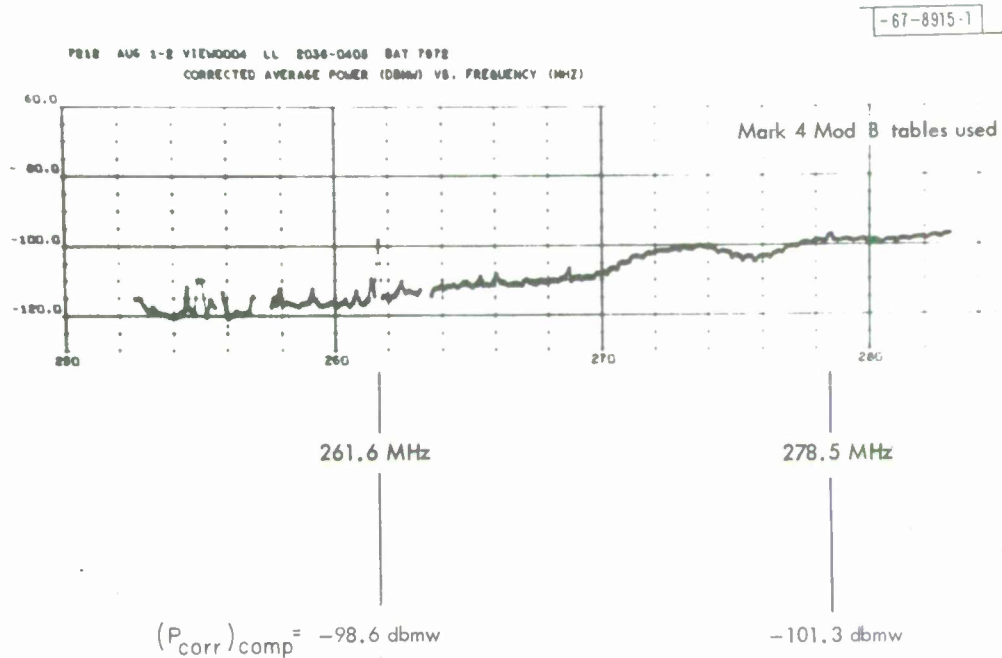


Fig. 14. LES-5 RFI scan, 1 Aug. 1967, 2052-2103 GMT, $\sim 216^{\circ}$ east longitude.

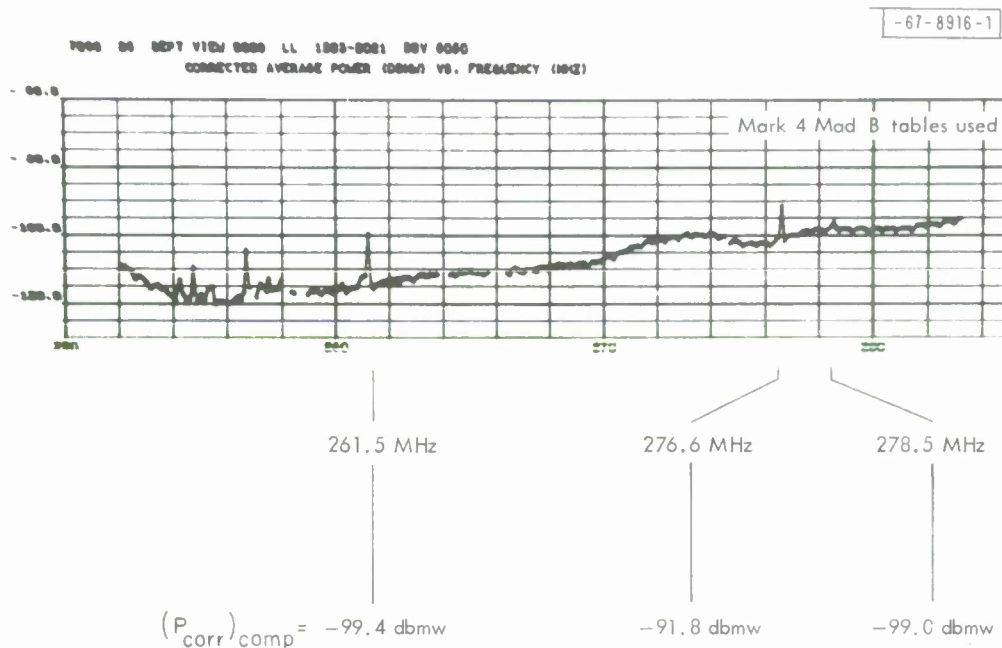


Fig. 15. LES-5 RFI scan, 25 Sept. 1967, 1357-1408 GMT, $\sim 218^{\circ}$ east longitude.

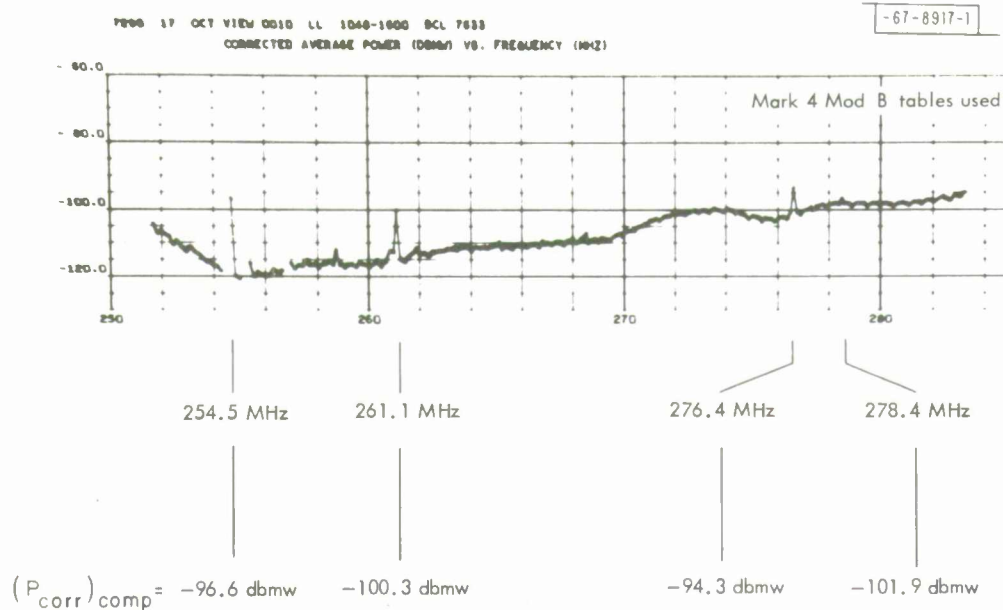


Fig. 16. LES-5 RFI scan, 17 Oct. 1967, 1115-1126 GMT, $\sim 219^{\circ}$ east longitude.

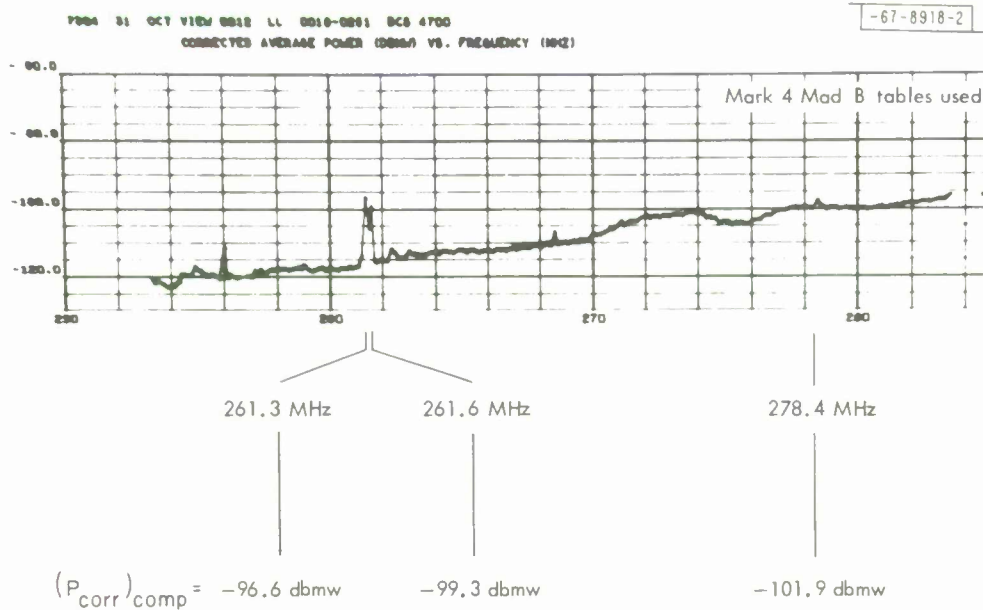


Fig. 17. LES-5 RFI scan, 31 Oct. 1967, 0136-0147 GMT, $\sim 307^{\circ}$ east longitude.

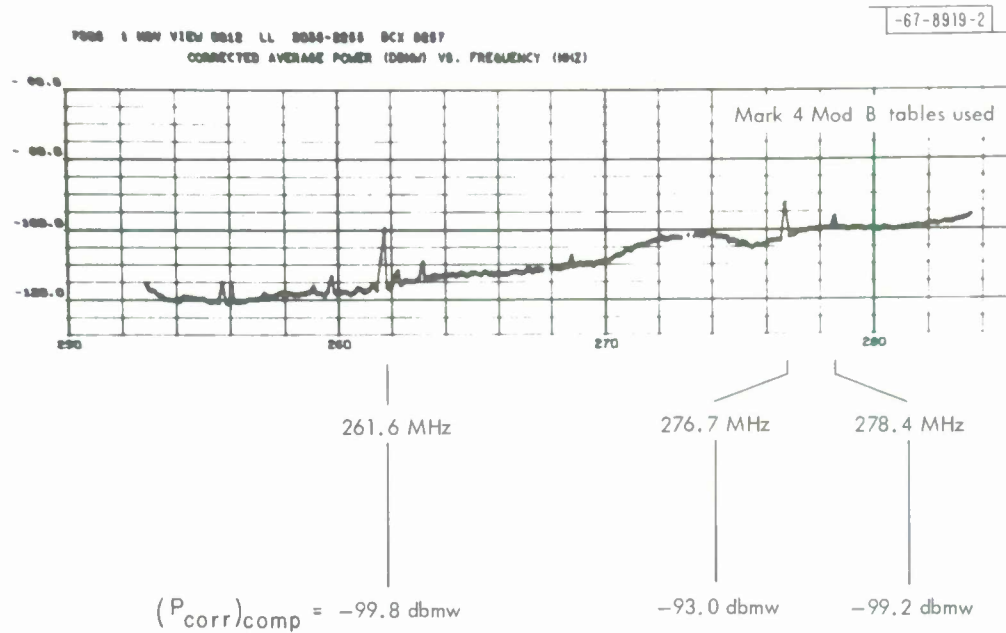


Fig. 18. LES-5 RFI scan, 1 Nov. 1967, 2048-2059 GMT, $\sim 006^{\circ}$ east longitude.

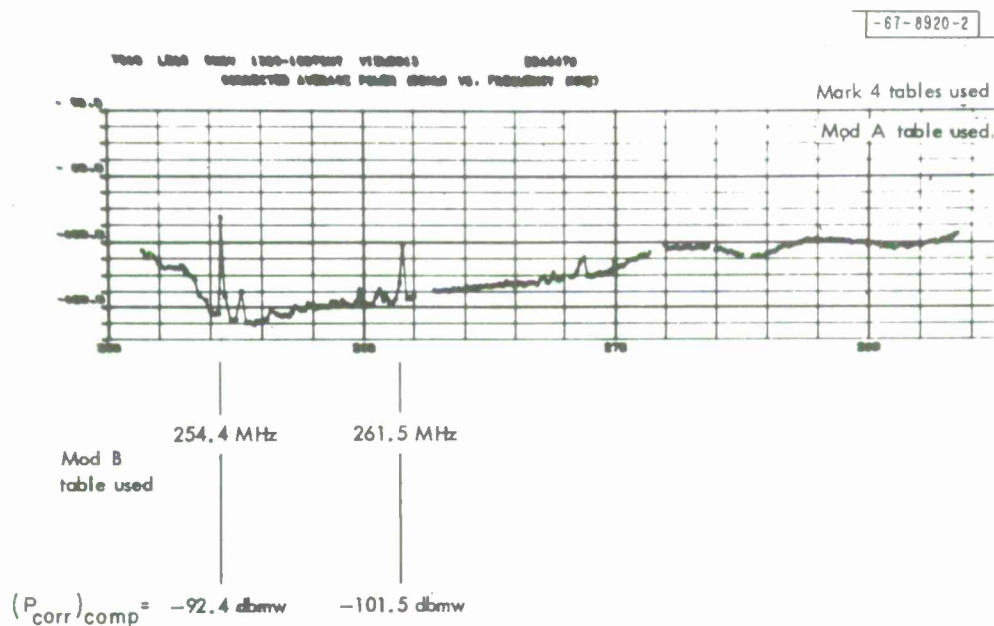


Fig. 19. LES-5 RFI scan, 6 Nov. 1967, 1356-1407 GMT, $\sim 161^{\circ}$ east longitude.

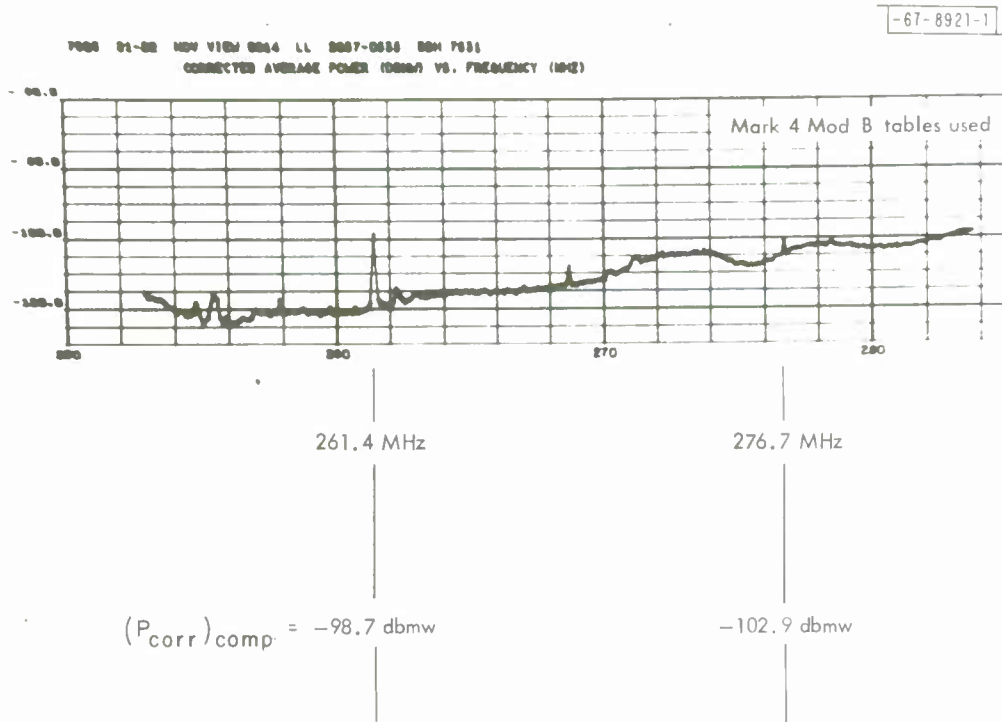


Fig. 20. LES-5 RFI scan, 22 Nov. 1967, 0118-0129 GMT, ~310° east longitude.

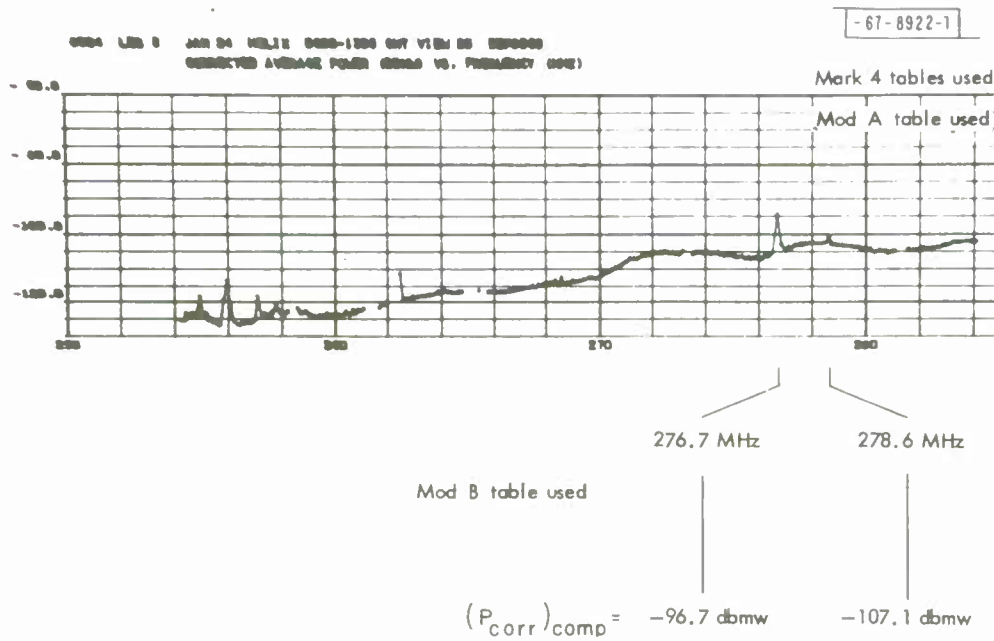


Fig. 21. LES-5 RFI scan, 24 Jan. 1968, 0724-0735 GMT, ~233° east longitude.

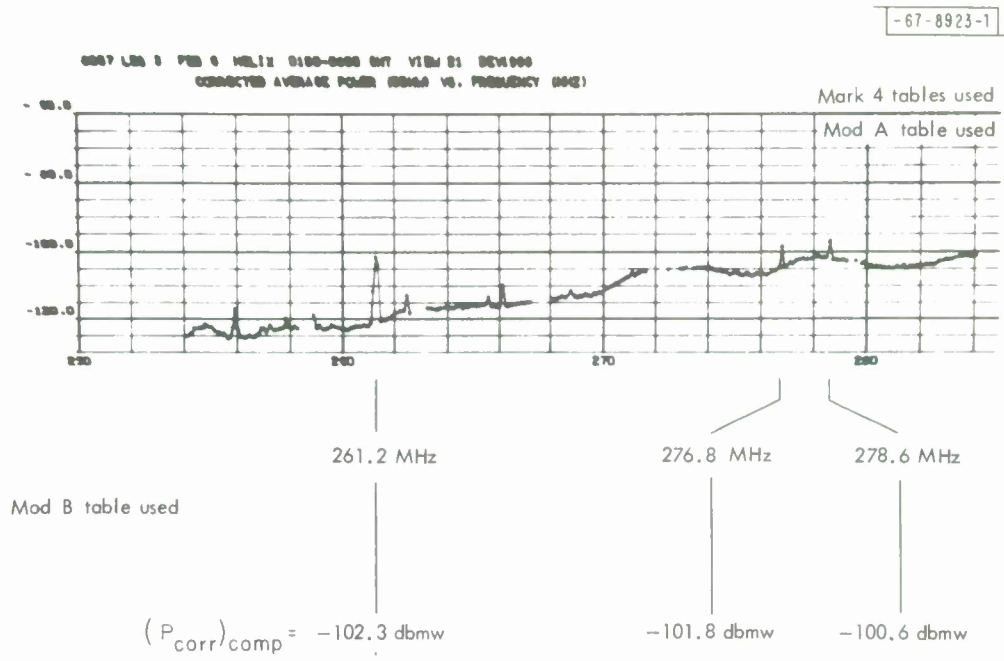


Fig. 22. LES-5 RFI scan, 6 Feb. 1968, 0529-0540 GMT, $\sim 298^\circ$ east longitude.

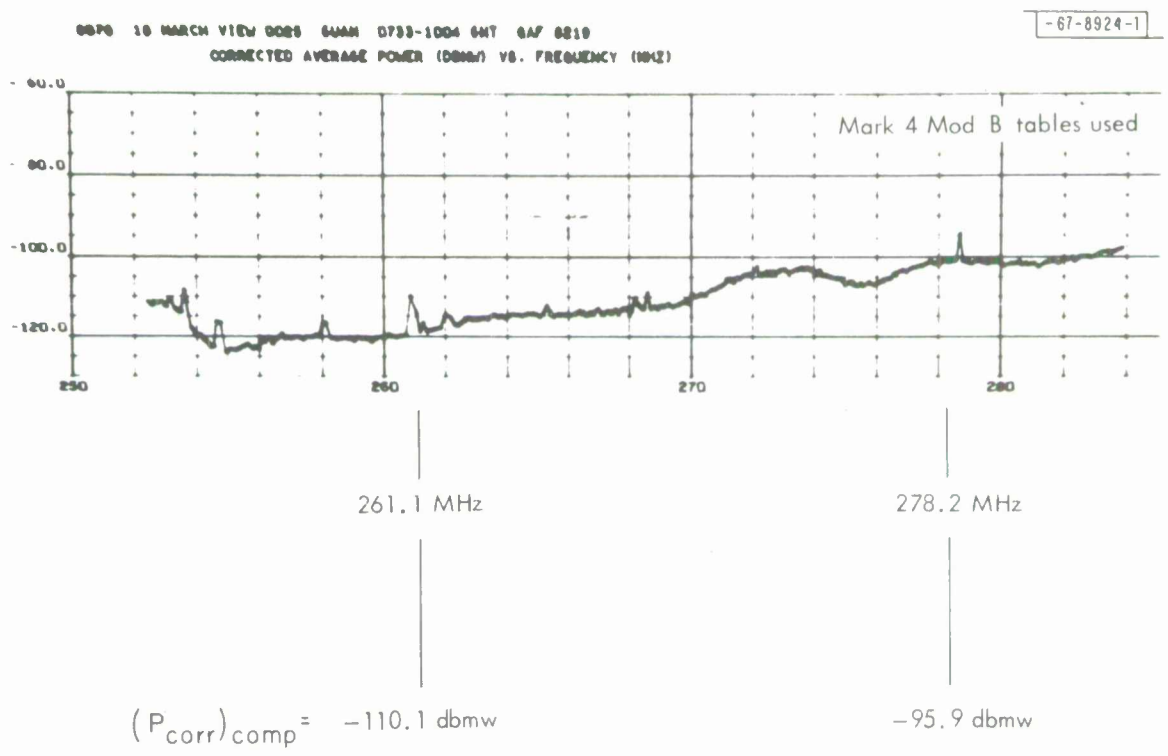


Fig. 23. LES-5 RFI scan, 18 March 1968, 0832-0843 GMT, $\sim 213^\circ$ east longitude.

ORRECTED AVERAGE POWER (dbmw)

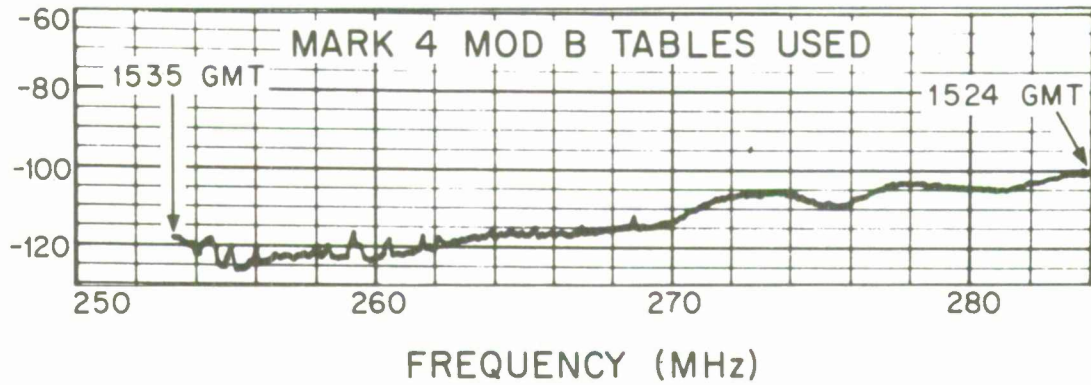


Fig. 24. LES-5 RFI scan, 12 Feb. 1968, ~150° east longitude.

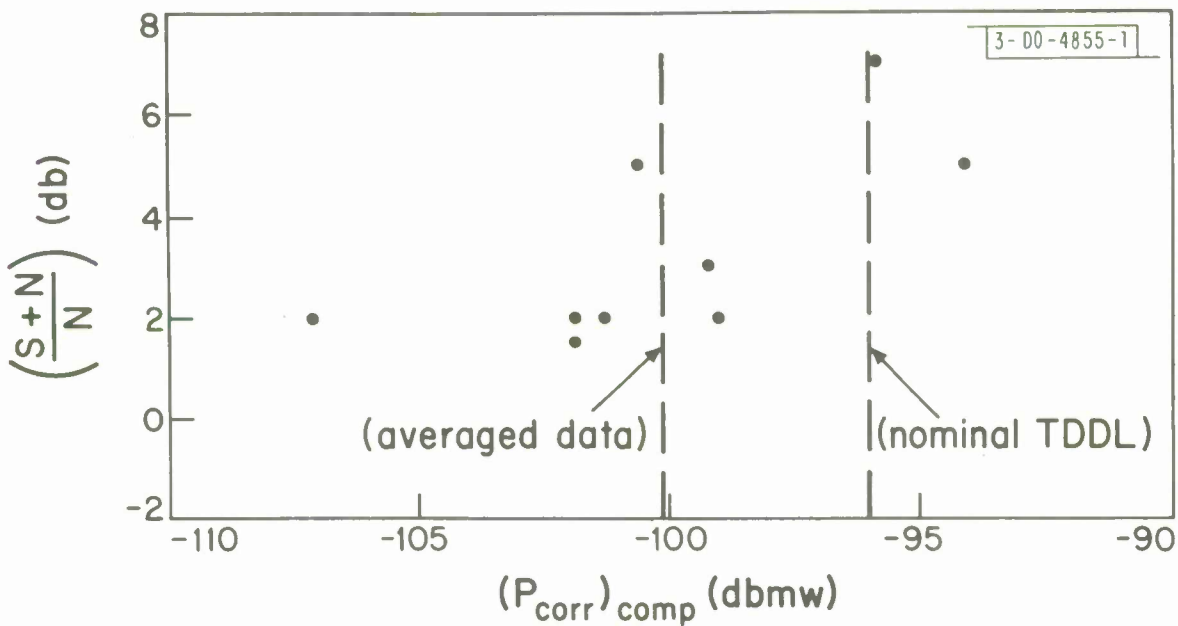


Fig. 25. Observation of TDDL's near 278.6 MHz by LES-5.

E. LES-6 Data

Other TDDL's are similarly useful as independent, externally supplied "markers" for the LES-6 RFI instrument. The nominal received power level for these signals is -98 dbmw (because of the higher frequency of the LES-6 RFI-scan band). Signals have been observed at those frequencies at average-power levels of up to -105 dbmw and peak-to-average ratios of 30 db. The 7 db loss could be due to the fact that LES-6 has been located toward the "hole" of the TDDL antenna patterns (Fig. 3).

Figure 26 shows two LES-6 RFI scans, taken about 6 hours apart.* It is seen that the general level of activity in the area seen is considerably reduced for the late-evening scan by contrast with the late-afternoon one. Some around-the-clock transmitters (TDDL's and others) continue to operate, however. To develop this point more fully, 24-hour data-taking runs were made with LES-6 occasionally. Figures 27, 28, 29, and 30 show sample RFI scans for equivalent times of day at different times of year. In general, the entire LES-6 RFI-scan band (290-315 MHz) appears noticeably more popular around the hours of 4 to 6 PM EST (2100-2300 GMT) as compared with 3 to 5 AM EST (0800-1000 GMT). Considering the tempo of life in North America, this is not surprising. For the observations made thus far, seasonal variations do not appear to be significant.

The LES-6 spacecraft has recently been moved to a new station near 38° west longitude. It will be interesting to see what the RFI environment is from that vantage point.

*The LES-5 RFI scans in this report show (signal plus noise) vs. frequency. For the LES-6 RFI scans, a constant noise component has been subtracted out. The LES-6 plots (signal vs. frequency) are generally more spikey than the LES-5 plots for this reason.

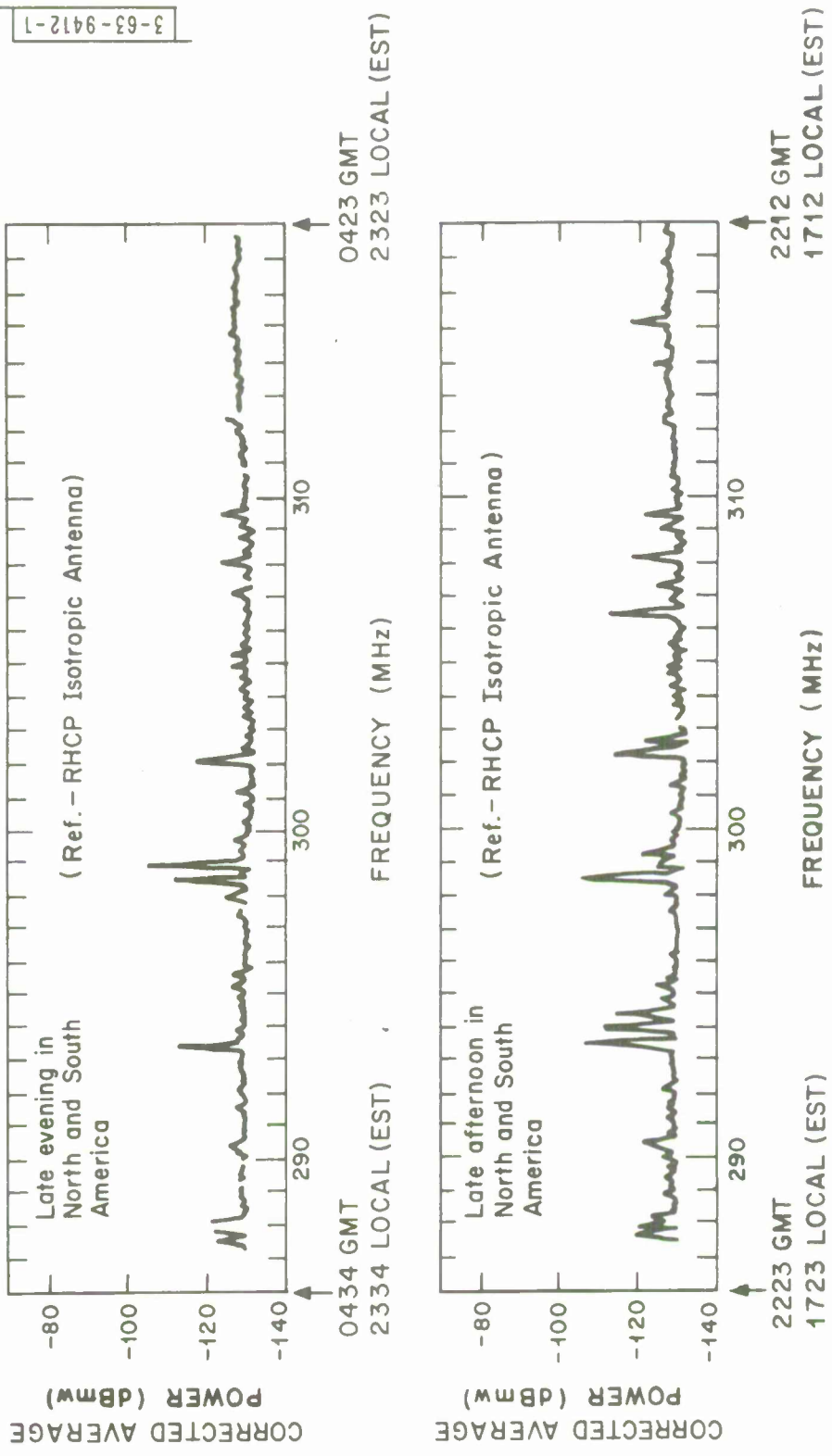


Fig. 26. LES-6 RFI scans, 4-5 Nov. 1968 (GMT), ~272° east longitude.

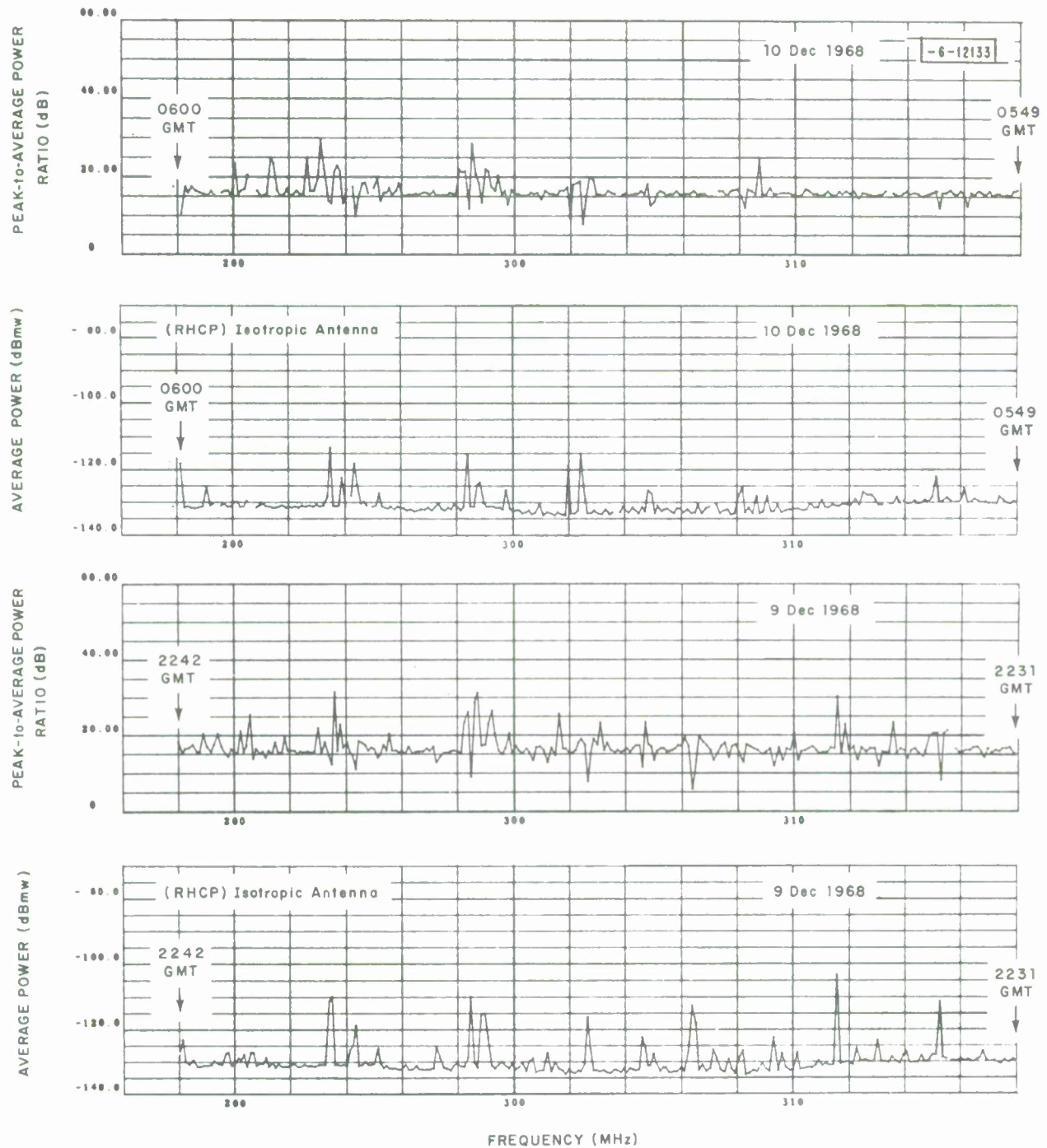


Fig. 27. LES-6 RFI scans, 9-10 Dec. 1968, $\sim 272^{\circ}$ east longitude.

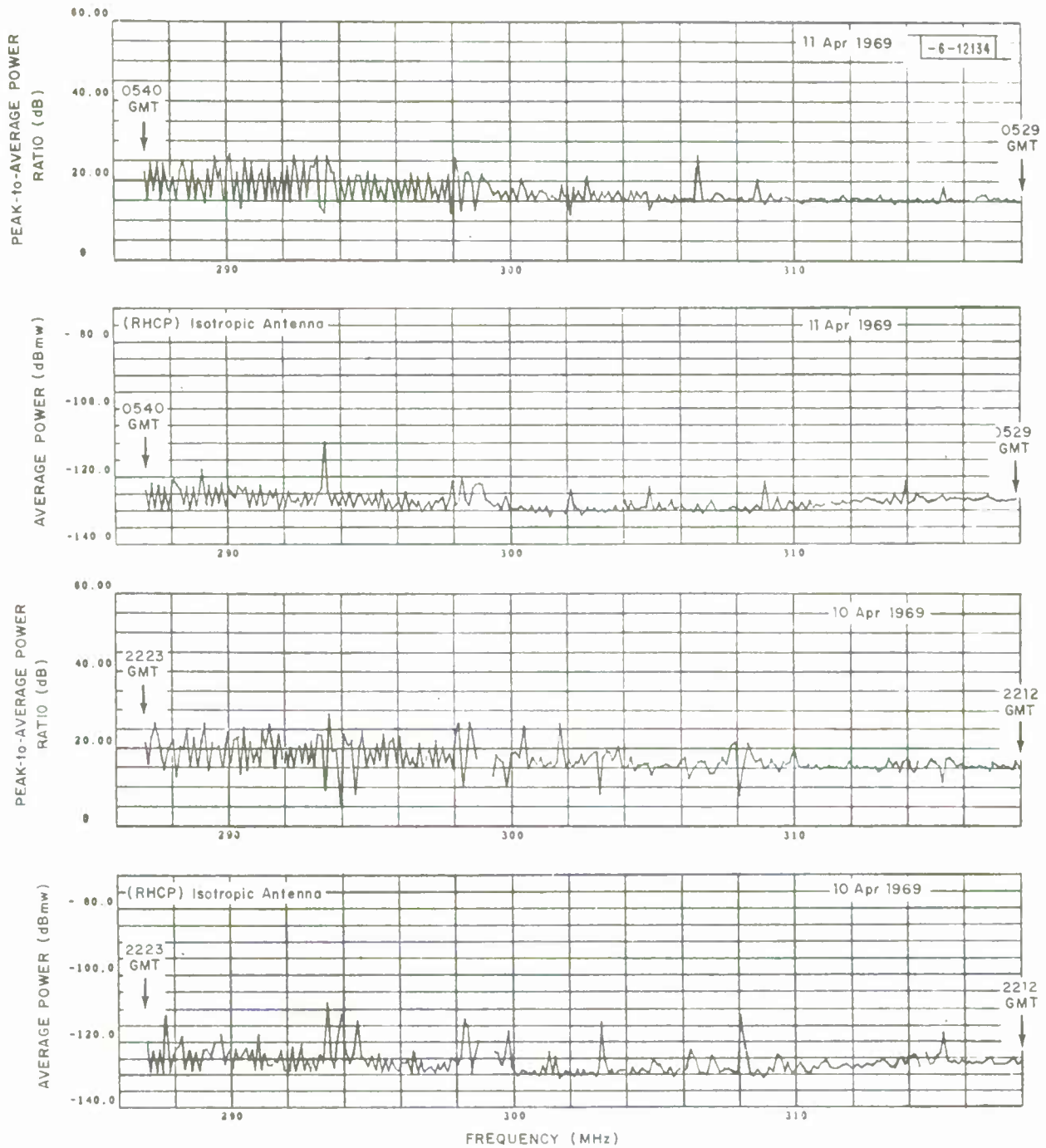


Fig. 28. LES-6 RFI scans, 10-11 April 1969, $\sim 272^\circ$ east longitude.

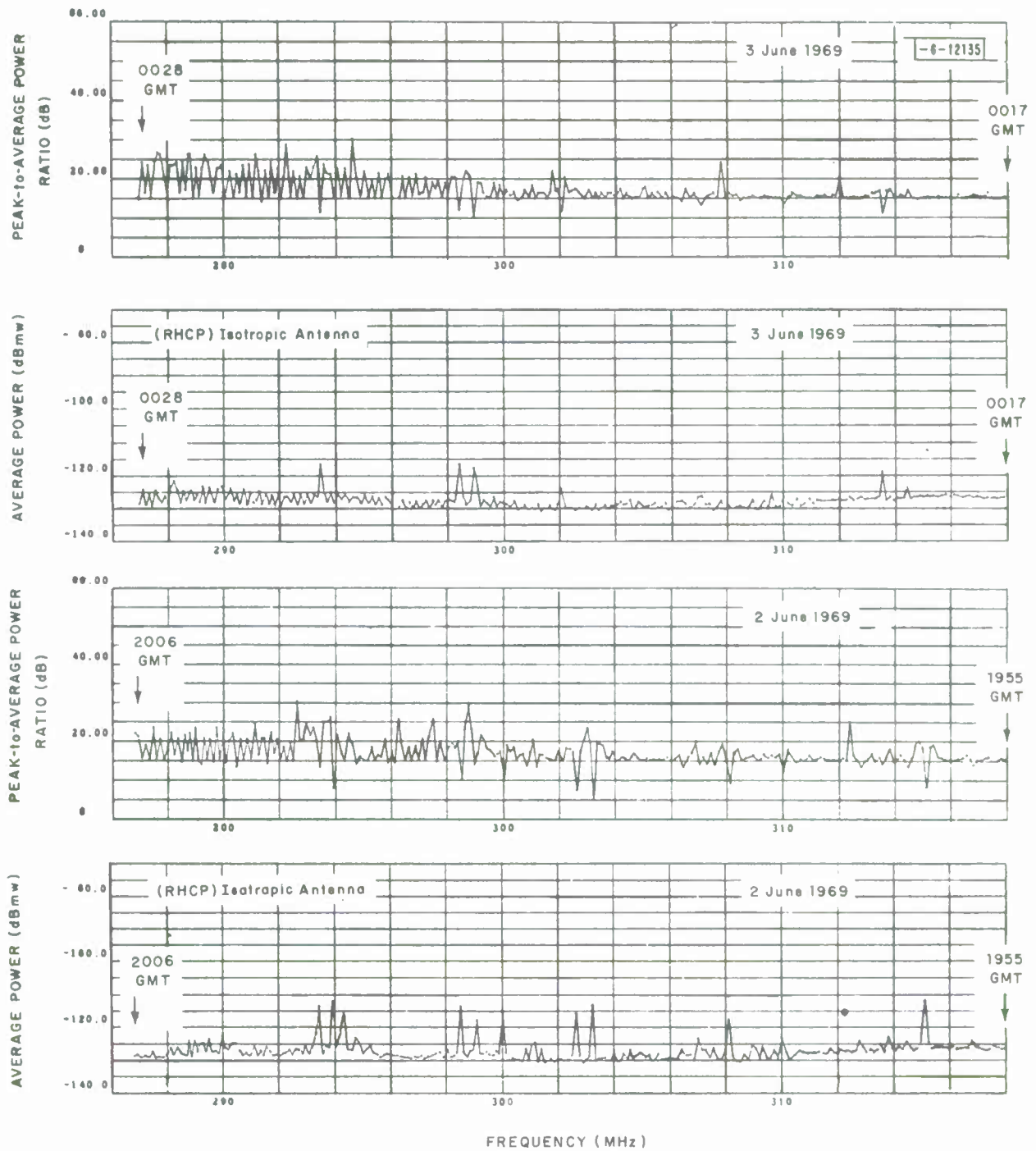


Fig. 29. LES-6 RFI scans, 2-3 June 1969, $\sim 272^{\circ}$ east longitude.

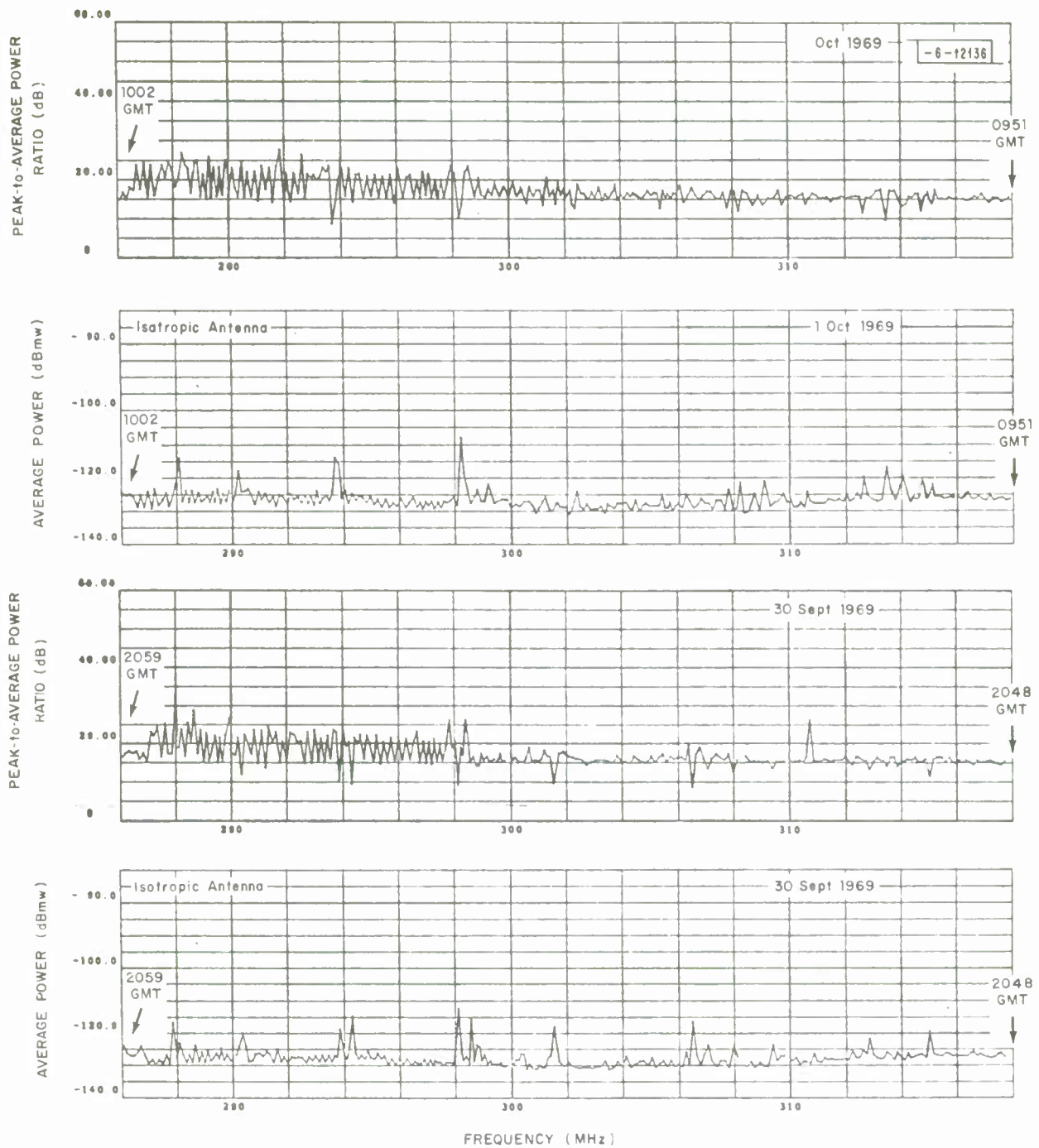


Fig. 30. LES-6 RFI scans, 30 Sept. - 1 Oct. 1969, $\sim 297^{\circ}$ east longitude.

VII. REGIONAL CHARACTERISTICS OF LES-5 RFI OBSERVATIONS

A. Data-Grouping Procedure

The LES-5 RFI data were reduced and normalized on a scan-by-scan basis by Lincoln Laboratory. As a further reduction, all the data were merged by Aerospace in groups as a function of geographical area. For merging of data, the Earth was divided into four zones as shown on Fig. 31. The data zones are identified as:

Zone I	North and Central America
Zone II	Europe, South America, and the North Eastern United States
Zone III	Asia and Australia
Zone IV	Pacific Ocean

All data collected while the sub-spacecraft longitude was within each zone have been merged as a data group. Data groups I through IV consist of data collected in zones I through IV respectively. The data in groups I through IV were collected between July 1967 and March 1968. The group V data were collected approximately one year later, during November 1968. The group V data were collected when the spacecraft was in the western portion of zone II, viewing North, Central, and South America. Because of the more-than-earth-coverage antenna pattern of LES-5, the data are representative of larger areas with overlay between data zones. Figure 32 shows the area of coverage when the spacecraft was centered in zone I.

B. Comments on Grouped Data

Figure 33 is a composite plot of all signals seen by the RFI instrument while the satellite was traversing the region from 150° west longitude to 80° west longitude. This region has been referred to as zone I in this report. The region covers all but the easternmost portion of the U. S. and Canada.

The upper curve of the figure is a plot of the strongest signals detected by the satellite during the several passes made over the zone. The lower curve is a plot of the average signal level at each of the frequency steps of the receiver during the recording period.

Several of the signals seen on these plots have been identified. At 254.4 MHz, a TDDL (AN/FRT-49 ground-to-air data-link transmitter, see Table I)

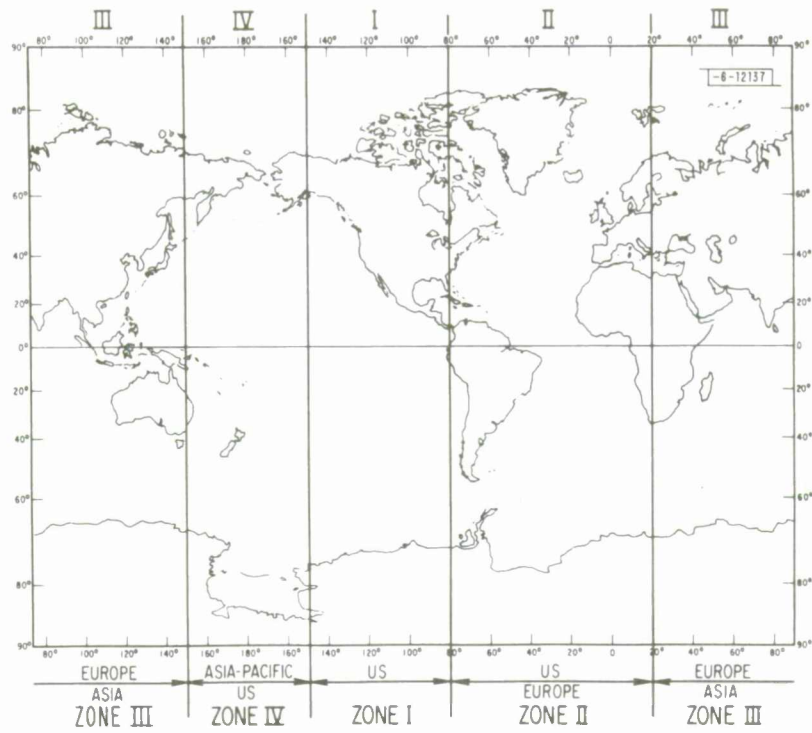


Fig. 31. LES-5 data-collection zones.

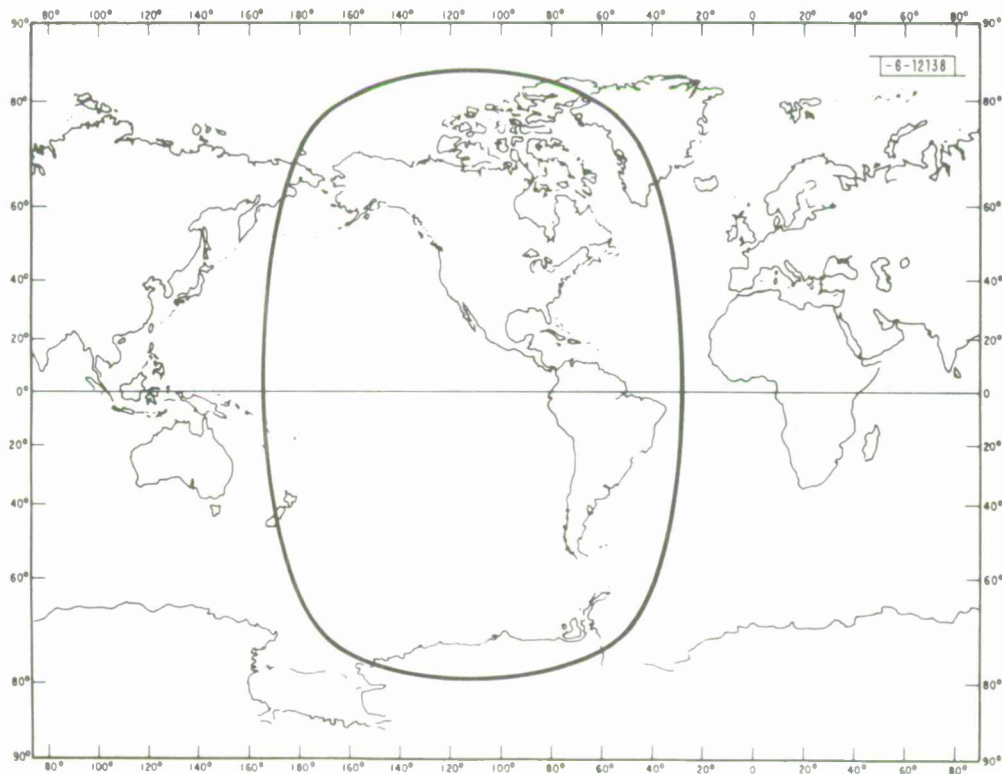


Fig. 32. LES-5 antenna coverage (center of zone I).

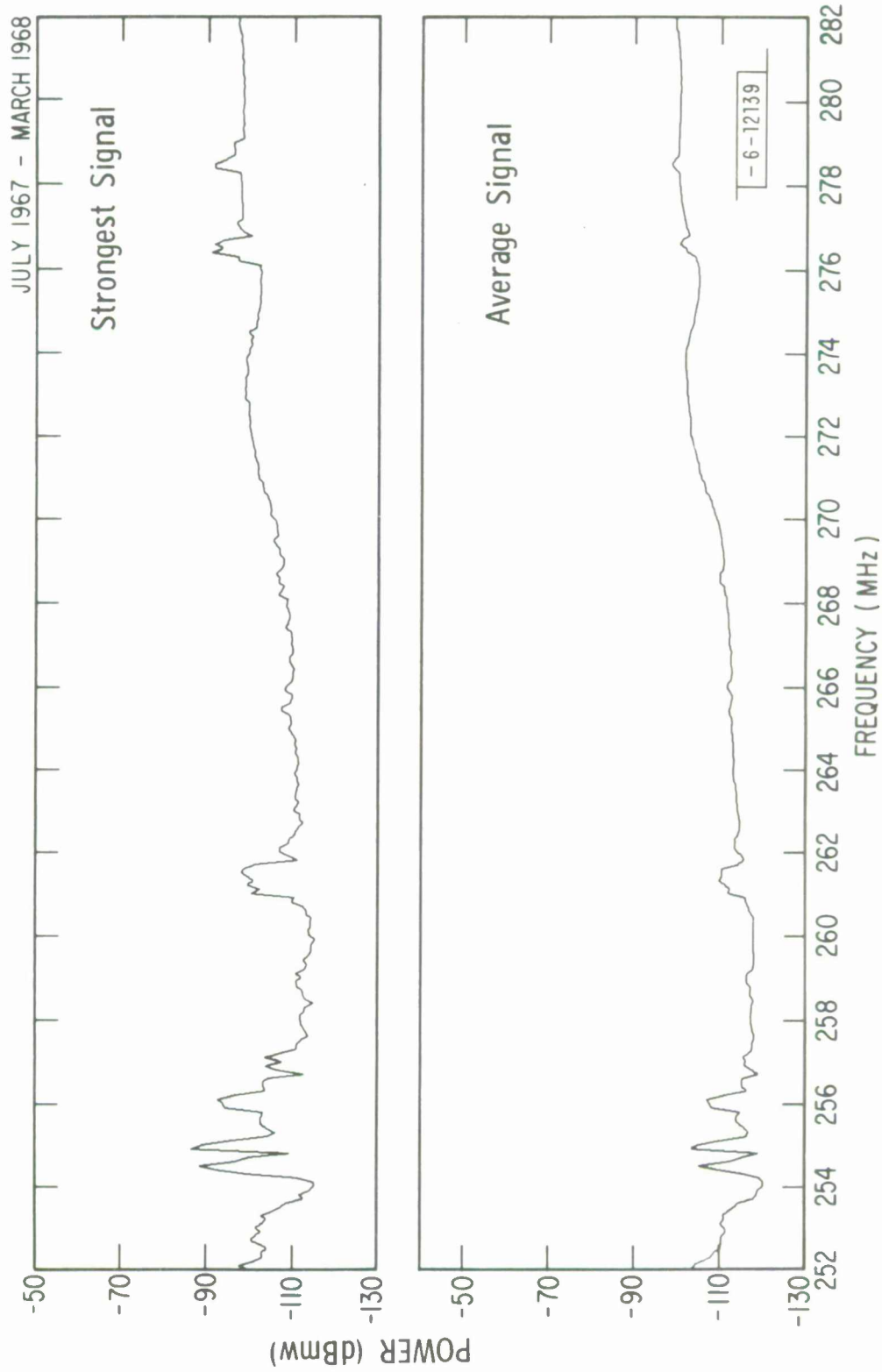


Fig. 33. RFI average power group I (71 scans).

located in Pennsylvania (one also located in California on the same frequency) can be seen. In this case the emitter located in California would contribute less signal since the radiation pattern of the TDDL contains a null in the region of the spacecraft. In the region of 261.1 to 261.6 MHz, some TDDL's located on the east coast of the U.S. can be seen. Again at 276.7 and 278.6 MHz, TDDL emissions from sets located on the east coast can be seen. Comparing the average signal levels on the bottom curve with the maximum signal levels on the top curve would indicate that the signals were detected at the spacecraft for from 1 to 10% of the time. In addition to the TDDL, many unidentified signals of amplitudes sufficient to cause concern are seen.

Figure 34 is the composite plot of all signals received while the satellite was in zone II. As would be expected, some signals seen from zone I are also visible from zone II locations. The average strength of these signals is less in zone II because, when the satellite is at the extreme eastward end of zone II, it is below the radio horizon of the TDDL's. The data collected by the satellite from zone III (Fig. 35) shows an absence of the TDDL signals seen in all other zones. This is as it should be since region III is out of sight of all emitters in the U. S. A number of emitters in the range of -120 to -110 dbmw are evident however. None of these signals has been identified, nor is any effort planned to attempt to identify them.

Satellite zone IV (Fig. 36) again places the RFI receiver within view of the U.S. and as expected, the TDDL's are very evident. It is of interest to note that the emitters at 276.7 and 278.6 located on the east coast have been detected in this zone.

The group V data shown in Fig. 37 are of particular interest since these data were collected a year later than the group II data. In general, the environment appears much the same as it did a year earlier. Note that the TDDL at 254.4 MHz was not detected in this data group.

C. Overview

The data presented in this report are the first known long-term RFI data collected by a receiver at synchronous altitude. The data show that strong signals radiated by ground-based emitters could cause serious interference with communication systems operating at certain frequencies in the military UHF band at orbital altitudes. There is little difficulty in correlating the TDDL parameters with the measured interference levels. Earlier analytical studies have not shown levels of interference as high as those measured in these tests.

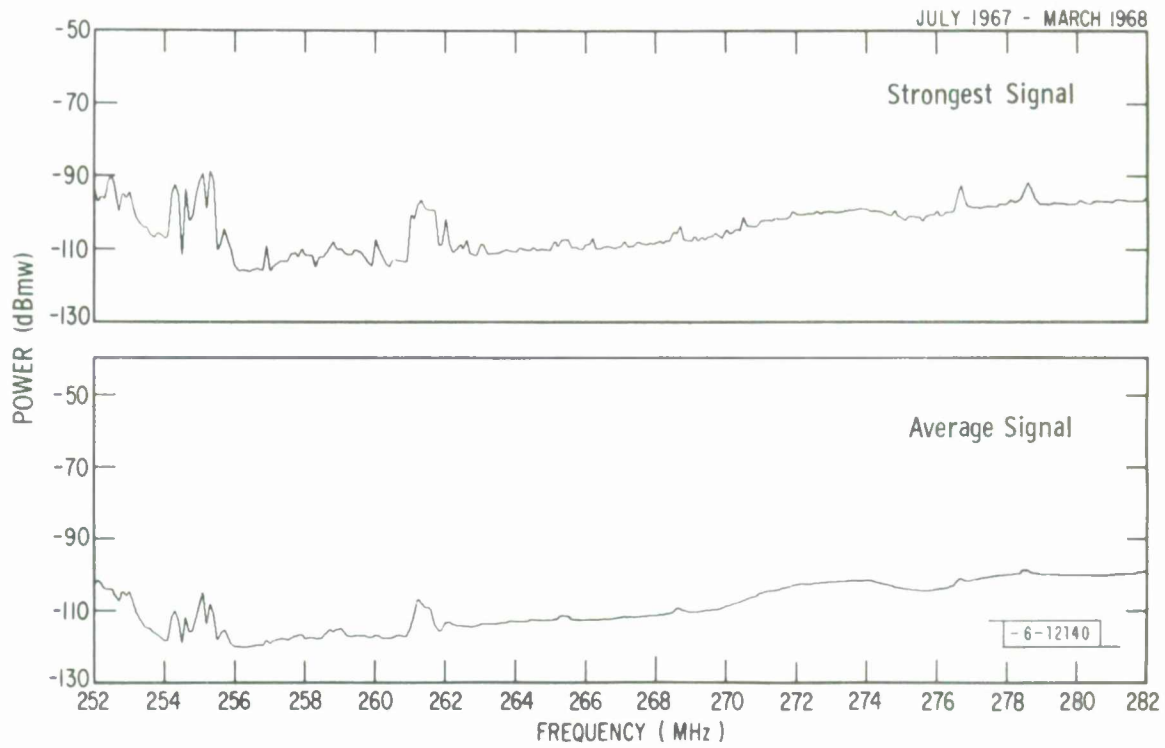


Fig. 34. RFI average power group II (109 scans).

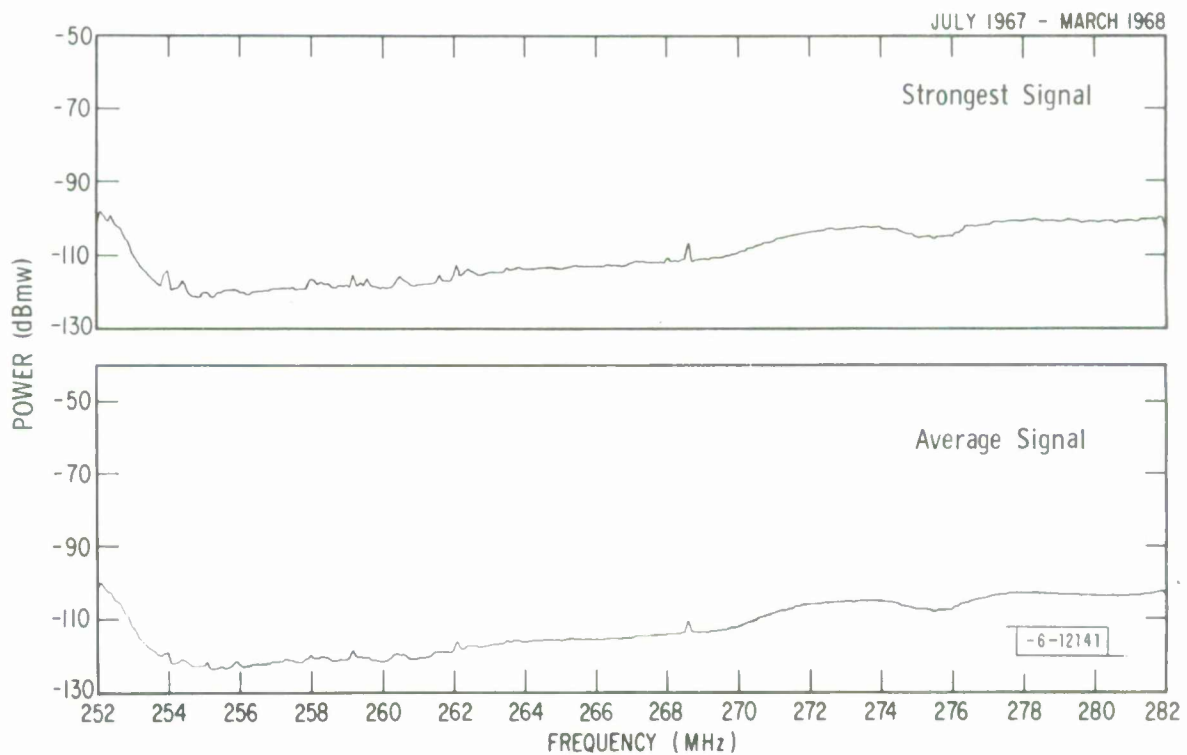


Fig. 35. RFI average power group III (12 scans).

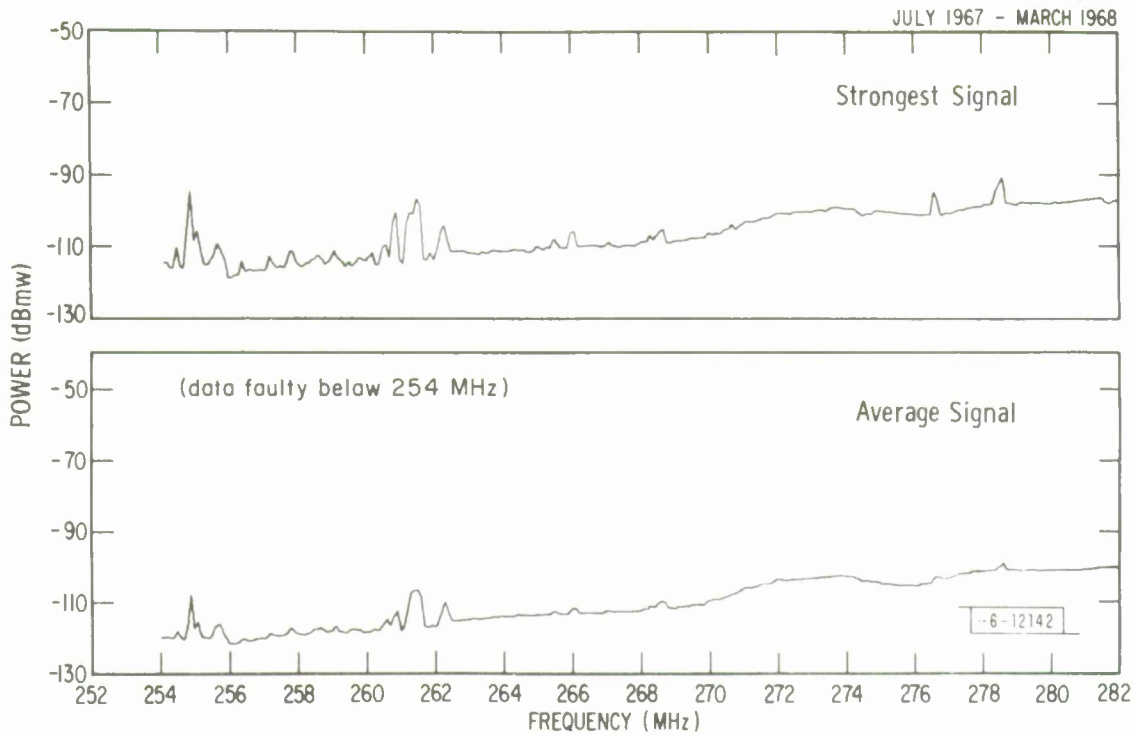


Fig. 36. RFI average power group IV (23 scans).

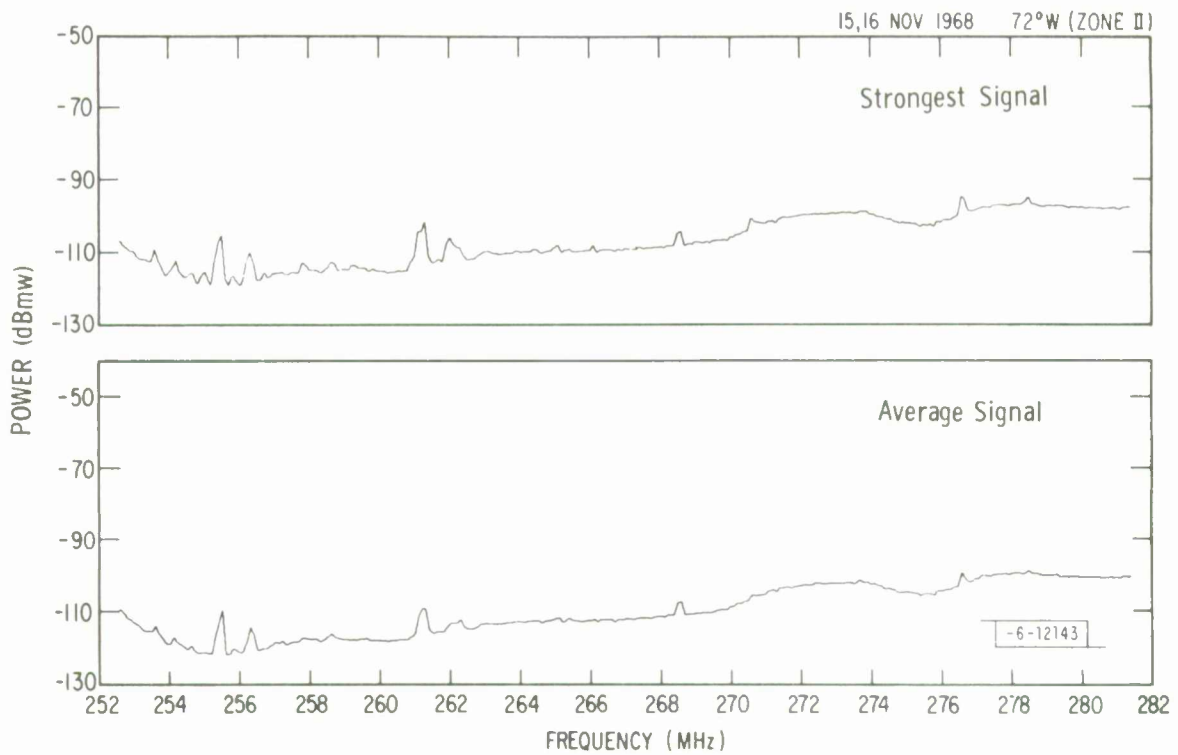


Fig. 37. RFI average power group V (8 scans).

VIII. CONCLUSIONS

The LES-5 and LES-6 RFI experiments have successfully met their objectives. Within the limitations imposed by occasional malfunction of other spacecraft equipment, the RFI instruments perform as designed. The calibration procedures and computer-processing routines for telemetered data yield output information that is in good agreement with what would be expected for certain known transmitters. The output information shows indications of many other signals. These indications are believed to be valid and to be quantitatively correct within the limits of measurement accuracy.

The conclusions to be drawn from the RFI experiments fall into two classes. In the first category, we have seen and can continue to see just how busy things are in these segments of the military UHF band. Some strong signals do show up (from the TDDL's, for example). However, there does not appear to be much, if any, of the sometimes-hypothesized piling-up of signals from many small common-channel transmitters to yield a signal equivalent to that from a large transmitter. The RFI environment within these specific bands is, if anything, quieter than might have been anticipated. Within the limits of measurement sensitivity, some portions of these bands show very little usage.

The conclusions of the second class are somewhat more general. The success of these RFI experiments demonstrates the feasibility of monitoring the level of activity* in the military UHF band (or almost any other band) from a satellite in (quasi-) geosynchronous orbit. There have been some changes in spectrum allocation during recent years, and there is talk of making still more changes. Frequency allocations in certain bands are very hard to come by. It may ultimately become imperative for the national and international regulatory agencies to adopt a "use it or lose it" approach to the issuance and reconfirmation of frequency allocations.¹⁶ In that event, the technical means, generically similar to these RFI experiments, are available to provide, from satellites, the necessary monitoring functions over broad areas of the Earth.

*Monitoring in this fashion is not the same thing as eavesdropping or listening in. For equivalent spectrum coverage, that nosy task requires a great deal more in the way of spacecraft equipment.

ACKNOWLEDGMENTS

The success of the LES-5 and LES-6 RFI experiments has resulted from the efforts of many people in the Aerospace Corporation, Lincoln Laboratory, and other organizations and agencies.

Within the Aerospace Corporation, where the RFI instrument was designed and built, special recognition is due: D. E. Kind (VCO circuits), W. A. Johnson (RF and IF amplifiers, mixers) and W. A. Garber (crystal oscillators), all (together with the Aerospace authors of this report) being members of the Electromagnetic Techniques Department of the Electronic Research Laboratories.

The initial participation of Lincoln Laboratory in the LES-5 RFI experiment was the responsibility of N. B. Childs, J. D. McCarron, W. A. McGonagle, and R. E. McMahon. John B. Connolly contributed substantially to the LES-6 effort. Their continued assistance to the Lincoln Laboratory authors of this report in the interpretation of in-orbit data has been most helpful.

The reduction of RFI-instrument data requires much programming and computer support. The patience of R. A. Anderson, Sally Hornig, Suzana V. S. Igel, and Ellen S. Swenson in supplying (and re-supplying) this support is gratefully acknowledged.

A special tribute is gladly paid to the people in Group 62, Lincoln Laboratory, who manned the terminals at unusual hours to gather the in-orbit data.

The cooperation of the Air Force Tracking Station on Guam in gathering LES-5 telemetry data is gratefully acknowledged.

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NOTE: A much more detailed account of the joint Aerospace Corporation/Lincoln Laboratory LES-5 RFI experiment is in preparation.

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13. ABSTRACT <p>The RFI environment near synchronous orbital altitude in the band 255-280 MHz was measured by subsynchronous Lincoln Experimental Satellite-5 (LES-5). Similar measurements covering the band 290-315 MHz have been made by station-kept LES-6. These experiments are a joint effort between the M. I. T. Lincoln Laboratory and the Aerospace Corporation.</p> <p>The nominal sensitivity of the LES-5 RFI instrument (signal-noise) corresponds to Earth-surface transmitter EIRP of 50 to 100 w (RHCP) near 255 MHz. LES-5 sensitivity is 20 db poorer toward the high end of its band (280 MHz). The nominal sensitivity of the LES-6 RFI instrument corresponds to EIRP of 10 to 25 w (RHCP) across the band 290-315 MHz.</p> <p>The success of the LES-5 and -6 RFI experiments shows that it is practical to monitor the level of activity in selected bands of the communication spectrum, throughout wide portions of the Earth, from synchronous orbit. This capability may be useful in the management of portions of the electromagnetic spectrum where frequency allocations are at a premium.</p>			
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